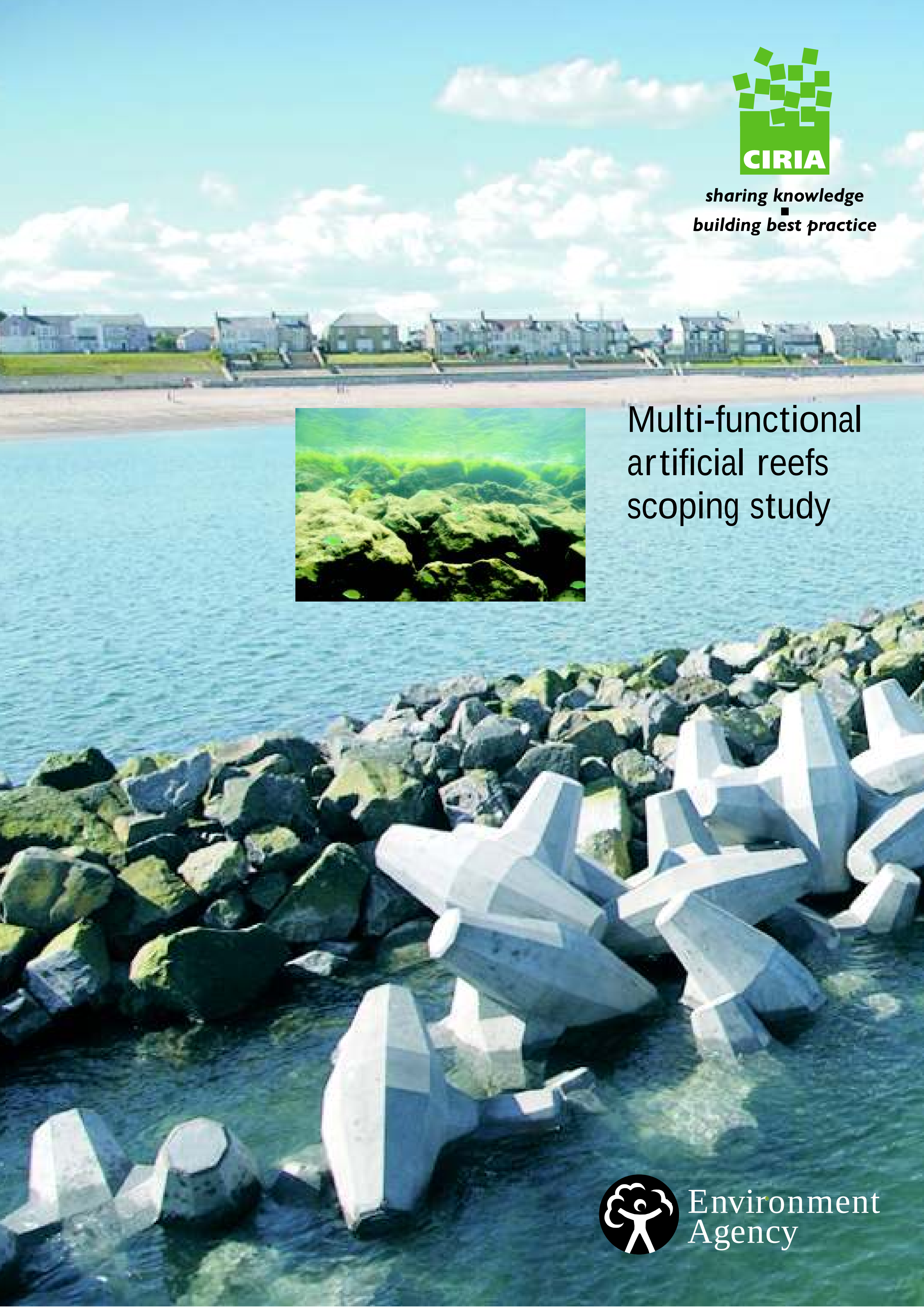

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# Multi-functional artificial reefs scoping study

Environment Agency

CIRIA C673 London, 2008

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**S Challinor** Royal Haskoning

**H Hall** Royal Haskoning

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Classic House, 174–180 Old Street, London EC1V 9BP
TELEPHONE 020 7549 3300 FAX 020 7253 0523
EMAIL enquiries@ciria.org WEBSITE www.ciria.org

**Multi-functional artificial reefs scoping study**

Challinor, S and Hall, H

*CIRIA*

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# Summary

Multi-functional artificial reefs offer an opportunity for coastal defence structures to deliver ecological and/or amenity benefits, and in doing so, support drivers for sustainable development. This scoping study focuses on artificial reef structures used for coastal defence (ie detached nearshore breakwaters) and identifies the opportunities and constraints to adding marine habitat (eg biodiversity, fisheries) and/or amenity (eg sea angling, diving, surfing). Some similarities are apparent between artificial reefs used for coastal defence and artificial reefs used for habitat and amenity, suggesting that multi-functional artificial reefs need not be substantially more difficult to achieve than a traditional detached breakwater. However, by examining existing information and using case studies, this scoping study has identified various knowledge gaps that could be addressed by dedicated guidance about design and materials requirements, economic evaluation and funding, planning and policy drivers, and health and safety issues.

# Acknowledgements


## Authors

**Steve Challinor BSc, DIC, MSc**

After gaining his masters degree from Imperial College in 1992, Steve joined Royal Haskoning (then Posford Duvivier) and has spent the past 15 years undertaking environmental impact assessments and other studies for coastal and marine infrastructure projects. He is particularly interested in marine sediment quality, dredging, port development, renewable energy from waves, and artificial reefs.

**Hamish Hall BEng, CEng, MICE**

Hamish graduated from Plymouth University in 1992 and joined Royal Haskoning (then Posford Duvivier). He has undertaken a broad range of projects in the fields of coastal and river engineering, small ports and harbours, and severe weather impacts. He is particularly interested in coastal and river management issues including funding and economic evaluation.

## Steering group

Following CIRIA's usual practice, the research project was carried out under contract to CIRIA by Royal Haskoning. The project was guided by the CIRIA project steering group comprising:

## Members

| | |
|---|---|
| Nick Lyness (chair) | Environment Agency |
| Ron Gardner | Westminster Dredging |
| Ben Hamer | Halcrow |
| Matt Hosey | Westminster Dredging |
| Jonathon Kemp | HR Wallingford |
| Paul Leonard | Department for Environment, Fisheries and Rural Affairs |
| Tom Wilding | Scottish Association of Marine Science |

## CIRIA managers

CIRIA's research managers were Nick Bean and Simon Vilarasau.

## Project funders

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# Contents

## Boxes



## Case studies

## Figures

## Tables

# 1 Introduction

## 1.1 BACKGROUND

Natural reefs occur throughout the world's coastal regions and they provide a host of recognisable functions and benefits. To capitalise on the benefits that natural reefs can provide, it is also possible to create artificial reefs that mimic characteristics of natural reefs in order to deliver desirable functions, such as:

- coastal defence (eg flood protection, erosion control)
- marine habitat (eg biodiversity, fisheries)
- amenity (eg angling, diving, surfing).

This scoping study starts from the concept that multi-functional artificial reefs offer an opportunity for one structure to deliver more than one function and benefit, and in doing so, support more sustainable development.

The study focuses on artificial reef structures used for coastal defence in the UK (ie detached nearshore breakwaters) and identifies opportunities to add either a marine habitat or an amenity function to derive an additional ecological or socio-economic benefit. The focus on coastal defence reflects the following background conditions:

- the likelihood that the UK's expenditure on coastal defence structures will increase in response to climate change and sea level rise
- government policy encouraging sustainable flood and coastal defences, including multi-functional coastal defences (eg MAFF, 2001)
- government promotion of local strategic partnerships (LSPs) as non-statutory, multi-agency partnerships that work to improve the quality of life by funding the same project for multiple benefits.

This scoping study was devised following a CIRIA led workshop on artificial reefs and a CoastNET conference in association with CIRIA on *Offshore development – new frontiers of opportunity* (2005). The conference contained three successive papers each concerning the opportunities for artificial reefs delivering coastal defence (Stive, 2005), marine habitat (Sayer and Wilding, 2005) and surfing amenity (Challinor and Weight, 2005) functions in isolation.

CIRIA launched the *Multi-functional artificial reefs scoping study* to examine artificial reefs as a viable alternative to traditional forms of coastal defence in the UK, and investigate the additional benefits to marine habitat creation and amenity that can be provided by them.

## 1.2 OBJECTIVES

The principal objective of the study was to compile existing information and to identify the gaps in current understanding of the provision and funding of multi-functional artificial reefs in the UK. The results may then be used to inform future CIRIA guidance to assist engineers, scientists and funders in supplying multi-functional artificial reefs.

In order to undertake the scoping study it has been necessary to:

- identify and explain the different applications of artificial reefs for coastal defence, habitat and amenity, internationally and nationally, by identifying their drivers and benefits, and lessons learnt concerning implementation with respect to their structures, designs and materials
- explore the potential for multi-functional artificial reefs in the UK by identifying the opportunities and constraints that may promote and/or hinder their development
- identify where collaboration and consensus between current research initiatives is needed for the development of multi-functional artificial reefs
- identify relevant science, designs and case studies.

A second objective of the scoping study is to raise the general awareness of the benefits of multi-functional artificial reefs. In this way it is intended that these structures can include the portfolio of options considered for shoreline management plans (SMPs), coastal strategies and coastal management schemes.

The final objective of the scoping study is to link with other CIRIA publications. By focusing on opportunities for coastal defence, the *Multi-functional artificial reefs scoping study* is an intermediary for *The rock manual* (CIRIA/CUR/CETMEF, 2007 – an update of CIRIA/CUR, 1991) and the *Beach management manual* (CIRIA, 1996). *The rock manual* describes the various nearshore breakwater structures that can be used to provide coastal defence, and offers guidance on the use of rock in their design and construction. The *Beach management manual* describes how detached nearshore breakwaters are used as beach control structures and gives information on the considerations for their correct design.

## 1.3 TERMINOLOGY

The term artificial reef has been applied to all the various structures for coastal defence, habitat and amenity. An artificial reef is assumed to have one intended function (ie either coastal defence or habitat or amenity) unless it is referred to as a multi-functional artificial reef. A multi-functional artificial reef is assumed to have more than one planned and designed function (ie coastal defence and either habitat and/or amenity).

Apart from the terms artificial reef and multi-functional artificial reef, the terminology for structures, designs and materials is generally in accordance with the glossaries of terms provided in *The rock manual* (CIRIA/CUR/CETMEF, 2007) and the *Beach management manual* (CIRIA, 1996).

## 1.4 THE GUIDE

The contents of this guide effectively fall into two parts:

Chapters 2 to 5 gives an overview of artificial reefs used for coastal defence (Chapter 2), marine habitat (Chapter 3), amenity (Chapter 4) and multi-functional artificial reefs (Chapter 5) in terms of their drivers and benefits, structures, designs and materials. These chapters include a range of case studies of artificial reefs in the UK and other locations.

Chapters 6 to 8 provides a review of the opportunities for and constraints to multi-functional artificial reefs in the UK with regard to coastal defence planning, coastal defence policy, economic evaluation and funding, health and safety, and structures, designs and materials (Chapter 6), and includes a detailed case study of a proposed multi-functional artificial reef in the UK (Chapter 7). Finally, the scope of further research and information needed for multi-functional artificial reefs to develop in the UK is examined (Chapter 8).

# 2 Artificial reefs for coastal defence

## 2.1 INTRODUCTION

Artificial reefs (in the form of detached nearshore breakwaters) are widely used for coastal flooding protection and erosion control purposes. They can perform a number of functions such as reducing wave energy reaching a foreshore, promoting accretion of beach material or assisting the retention of beach recharge/nourishment schemes. They can be chosen in preference to raising sea walls and providing hard defences along a coastline as they interfere less with beach amenity. They can enhance amenity by promoting or sustaining foreshore material.

The use of detached nearshore breakwaters in the UK began around 1980 (CIRIA, 1996). Their design can vary significantly to suit the local conditions (eg tidal range) and they are usually constructed of rock or concrete armour units over a core of smaller material. Their use is limited to a few sites in the UK (see Case study 2.1) where they are used in isolation eg Newbiggin Bay (Figure 2.1) or in a series eg Happisburgh (Figure 2.2), and/or used in association with other coastal defence structures and/or beach nourishment eg Jaywick and Sidmouth (Figures 2.3 and 2.4). Their use elsewhere in the world includes the Mediterranean Sea, Japan and the US, but can be highlighted by recent constructions in Dubai (see Case study 2.2).

**Figure 2.1**

*Newbiggin Bay breakwater*
(courtesy Westminster Dredging)

**Figure 2.2**

*Happisburgh breakwaters*
(courtesy Westminster Dredging)

**Figure 2.3**

*Jaywick detached breakwater*
(courtesy Royal Haskoning)

**Figure 2.4**

*Sidmouth detached breakwater*
(courtesy S Challinor)

## 2.2 DRIVERS AND BENEFITS

Coastal defences are created to protect existing and new assets at risk from damage due to coastal flooding and erosion. Evans *et al* (2004) calculated that the UK has £130 000 million worth of assets at risk of coastal flooding and £10 000 million at risk of coastal erosion. Halcrow *et al* (2001) predict the total capital value of annual average damage to property, agriculture and traffic assets at risk from coastal flooding and coastal erosion to be £1637 million and £84.3 million respectively under a do nothing scenario. With large numbers of people living along the UK's coastline and such large asset values at risk of flooding or erosion there is a clear need for coast and erosion management schemes. This need is predicted to grow in the future. For example, Defra (2004b) notes that flood and coastal erosion risks are likely to increase in the future as a result of "a combination of climate change, development pressures and other social and economic factors".

## 2.3 STRUCTURES, DESIGN AND MATERIALS

### 2.3.1 Structures

The *Beach management manual* (CIRIA, 1996) provides a good overview of the suitability of breakwater structures to different locations noting that "in general, breakwaters are suited to coastlines that require higher levels of protection at sensitive points and do not have sensitive down-drift beaches, as long-term predictions of transport response is uncertain. They are particularly well suited to frontages where the development of additional beach area can be justified for recreational/amenity purposes".

#### Conventional breakwaters

Conventional detached nearshore breakwaters are (typically) short, shore parallel structures that are not connected to the shore. They comprise raised reefs, and their crests are typically set above mean high water that are permanently exposed throughout the tidal cycle. CIRIA (1996) notes that these breakwaters "can be effective on micro and meso-tidal sand beaches, but can be used with any tidal range on shingle beaches. Under macro-tidal conditions, particularly in areas affected by significant storm surges, the structures can be very high and consequently can have a serious visual impact".

The main purpose of detached breakwaters is to reduce beach erosion by promoting the deposition of sediment or by holding in place a nourished beach. Detached breakwaters reflect and dissipate wave energy to reduce wave heights and erosion on the shore. Beach material deposits on the shore in the lee of the breakwaters due to the reduced wave energy and, in combination with the nearshore wave pattern, often creates salients or tombolos and crescent shaped beaches.

Isolated breakwaters can be used to protect shorelines where the net longshore transport rate is higher than adjacent shorelines. In these cases, the breakwaters work by reducing the net longshore transport rate to make it similar to rates at adjacent shorelines. Series of detached breakwaters are used to protect long shorelines, such as at Elmer (West Sussex) and at Happisburgh (Norfolk).

### Low-crested and submerged breakwaters

Low-crested and submerged breakwaters are (typically) shore-parallel structures that are not connected to the shore. They comprise raised reefs and their crests are submerged for part of the tidal cycle. These breakwaters break larger, less frequent waves but have little effect on normal daily waves (CIRIA/CUR/CETMEF, 2007). CIRIA (1996) notes that "submerged reef structures can be used in meso-tidal conditions, though their effectiveness at reducing wave energy may be limited, particularly in the event of a storm surge".

Reef-like breakwaters may use a similar design to conventional breakwaters but tend to have a lower crest level and a higher porosity (HR Wallingford, 2003). As noted by Pilarczyk (2003), "their purpose is to reduce the hydraulic loading to a required level that maintains the dynamic equilibrium of the shoreline. To attain this goal, they are designed to allow the transmission of a certain amount of wave energy over the structure by overtopping and also some transmission through the porous structure (low crested breakwaters) or wave breaking and energy dissipation on shallow crest (submerged structures)."

## 2.3.2 Design

Coastal defence breakwaters are typically designed as rubble-mound structures and comprise some or all of the components shown in Figure 2.5. Pre-cast concrete is sometimes used in place of, or in addition to, rock armour but tends to be more expensive.

A breakwater's components deliver the primary function of the structure (eg to attenuate wave transmission) and/or maintain the integrity of the structure (eg to prevent undermining). The core gives the breakwater its overall stability and prevents or attenuates wave transmission. The underlayer acts as a filter and prevents erosion of the core. The armour layer prevents erosion of the underlayer and dissipates wave energy. The toe and scour protection prevents undermining. The berm attenuates wave transmission. The crest attenuates wave overtopping and can be designed to provide access along a breakwater. The design of each breakwater component depends on performance requirements and associated structural loadings.

Conventional breakwater designs do not allow the materials to move in response to extreme waves conditions. However, some breakwaters – known as reshaping berm breakwaters – have berms that are reshaped when the armourstone is redistributed by waves to form a new stable profile (eg see USACE, 2006 and HR Wallingford, 2003).

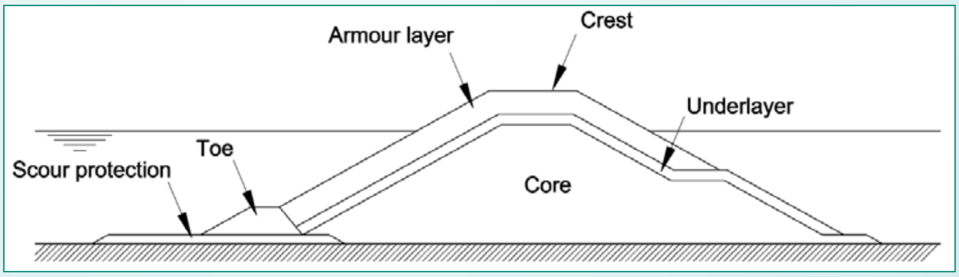



Figure 2.5 *Cross-section of a typical rubble mound breakwater* (courtesy CIRIA/CUR/CETMEF)

Low-crested and reef breakwaters may be the preferred design where tidal ranges are low because their crest levels are set close to the (normal) water level, making them less visually intrusive. Conversely, emerged breakwaters may be the preferred design where tidal ranges are high because their crest levels are set close to high water levels, but this makes them more visually intrusive at low water levels (Allsop *et al*, 1995).

Where low-crested breakwaters are required to stabilise beaches subject to strong dominant sediment drift direction, successful design depends on matching geometries to natural drift rates (Coates and Simm, 1995). The resultant development of salients and tombolos influences the efficiency of low-crested breakwaters and needs to be taken into account in design. Coates and Simm (1995) recommend not to over design breakwaters but to allow for minor modifications after construction based on monitoring.

More information concerning the design of detached breakwaters can be found in *The rock manual* (CIRIA/CUR/CETMEF, 2007), the *Beach management manual* (CIRIA, 1996) and the *Coastal engineering manual* (USACE, 2006). Design reviews of low-crested breakwaters can be found in Pilarczyk (2003) and DELOS (2001).

**Case study 2.1** ***UK detached breakwaters for coastal defence***

There are various coastal defence schemes around the UK that include one or a series of detached breakwaters. Notable examples comprising a series of detached breakwaters include the schemes at Happisburgh (Norfolk) and Elmer (West Sussex) (Figure 2.6). Other examples form part of a combination of coastal defence structures (eg detached breakwater and groynes or beach nourishment) such as at Jaywick (Essex), Sidmouth (south Devon), Newbiggin Bay (north-east England) and Monk's Bay (Isle of Wight). Table 2.1 summarises the UK's detached breakwaters in terms of their numbers per site, lengths at crest level, gaps between breakwaters, offshore distances from shoreline to centreline, freeboards from crest level to mean low water, widths at crest level, water depth at mean low water and tidal range.

Table 2.1 *Summary of UK detached breakwaters* (derived in part from DELOS, 2001)

| Site | No. | Length (m) | Gap (m) | Offshore distance (m) | Free-board (m) | Width (m) | Depth (m) | Tidal range (m) |
|---|---|---|---|---|---|---|---|---|
| Elmer 1 | 3 | 140 | 65–130 | 130 | 4.3 | 4.0 | 6.0 | 6.3 |
| Elmer 2 | 5 | 80 | 80–175 | 130 | 2.8 | 4.0 | 6.0 | 6.3 |
| Monk's Bay | 1 | 75 | | 40 | 2.2 | 4.0 | 1.5 | 3.6 |
| Sidmouth | 2 | | | | 3.6 | | 4.5 | 4.2 |
| Rhos-on-Sea | 1 | 250 | | 150 | | | | 7.0 |
| Leasowe Bay 1 | 1 | 240 | | 140 | | 5.0 | | |
| Leasowe Bay 2 | 1 | 210 | | 140 | | 6.0 | | |
| Newbiggin Bay | 1 | c200 | | c300 | | | | |
| Happisburgh | 16 | 220 | 280 | 200 | 3.5 | | 3.5 | 2.0 |
| Jaywick | 1 | | | | | | | |

Figure 2.6

*Elmer breakwaters* (courtesy Environment Agency/Arun District Council)

## 2.3.3 Materials

Materials provide three main functions within a coastal defence structure

1 Filling.

2 Filtering.

3 Armouring.

In the UK, the typical core material is rockfill. Filtering is typically provided by granular materials or geotextiles, or a combination of the two (ie geosystems). Armouring is provided by quarried rock or concrete armour units (Figure 2.7). Recycled aggregates and secondary granular materials (eg crushed concrete and dredged materials) may be used where they are sufficiently durable and economically available in the size necessary (CIRIA, 1996).

Figure 2.7 *Quarried rock and concrete armour units being placed in Newbiggin Bay* (courtesy Westminster Dredging)

Alternative materials include sand-filled geotextiles (or geosystems) in the form of bags, mattresses, tubes and containers. Sand-filled geotextiles can be used as permanent submerged structures where direct wave forces are reduced by submergence, or as core material to other structures (Pilarczyk, 1998). The tubes are typically 30 m to 300 m long and 2.5 m to 14 m in diameter (Jones *et al*, 2006).

There are two principal construction methods for breakwaters comprising geotextiles:

1 Filling them with sand when they are laid out in position on the seabed.

2 Filling them when they are laid out inside a split-hull hopper dredger and subsequently dropping them into position on the seabed.

Although geotextile fabrics are designed to be sufficiently durable and retain their integrity, they can be adversely affected when in place by fabric weakening and tearing (due to abrasion of fibres by overlying material or debris), puncturing (due to impact loading by waves, vessels and other objects), deterioration (due to exposure to ultra-violet radiation such as sunlight) and damage (due to vandalism) (Hughes, 2006). Nevertheless, geotextiles can be cost-effective and simple construction materials so long as design issues such as integrity during placement, accuracy of placement and stability under wave loading are addressed (Pilarczyk, 1998). In terms of cost-effectiveness, the use of sand-filled geotextiles for an artificial reef in Australia cost 50 per cent of the conventional rock alternative (Quirk *et al*, 2002), although in places that have good rock supplies, the cost effectiveness of sand is less clear cut.

More information concerning the materials used to construct coastal defence structures can be found in *The rock manual* (CIRIA/CUR/CETMEF, 2007) and the *Coastal engineering manual* (USACE, 2006).

**Case study 2.2** ***Breakwaters for the Palm Islands and The World, Dubai***

While there are many cases that can be drawn upon from outside the UK, the detached breakwaters of Dubai provide large-scale examples of these structures. The open and flat Jumeirah coast between Dubai City and the port of Jebel Ali is the site of three of the world's largest island development projects (Palm Jumeirah, Palm Jebel Ali and The World). The islands extend into 10 m to 15 m of water and require protection from the Shamal wave attack and wind surge water levels during winter. Continuously curving low-crested detached breakwaters protect the three island projects.

Palm Jumeirah and Palm Jebel Ali are protected by approximately 11 km and 15 km of breakwaters respectively. The outer edges of the Palm islands' breakwaters (Figure 2.8) are designed as rock mounds over sand cores with emerged crests (3 m to 4 m for Palm Jumeirah excluding the retaining wall and 4.25 m for Palm Jebel Ali).

Figure 2.8

*Palm Island breakwater construction, Dubai* (courtesy Royal Haskoning)

The World is protected by approximately 25 km of breakwaters. There are three reefs all designed as rock mounds over sand cores. The maximum rock size is four tonnes. The Shamal breakwater is the largest and is designed as a detached breakwater with a 9 m wide low crest which emerges 2 m above mean sea level. At 2.5 m below mean sea level, the Shamal breakwater's submerged berm is 32 m wide and initiates wave breaking under design storm conditions. The other two breakwaters have a crest designed at mean sea level (Stive, 2005).

Figure 2.9

*The World breakwater, Dubai* (courtesy M Aurora)

Figure 2.10

*The World breakwater, Dubai* (courtesy M Budd)

# 3 Artificial reefs for marine habitat

## 3.1 INTRODUCTION

Artificial reefs are widely used around the world to improve and protect marine habitat, particularly inshore fisheries. They comprise various designs including deployment of natural materials (eg rock), manufactured materials (eg cement stabilised concrete blocks) and materials of opportunity (eg decommissioned vessels, oil platforms and rigs, and tyres). Most importantly, designs have to be made for target species based on their habitat preferences and incorporating their supporting community. This is important because artificial reefs with non-specific design features do not automatically attract or increase productivity of desired species (Pickering and Whitmarsh, 1996).

There is substantial research and examples of artificial reefs with specific fisheries functions such as mollusc cultivation, protection from damaging fishing practices and crustacean stocking. The existing level of knowledge is such that the efficacy of artificial reefs for fisheries purposes is supported by an increasing body of evidence (Sayer and Wilding, 2005).

There is less research and examples of artificial reefs for direct ecological and conservation benefit, such as biodiversity, presumably because there is less economic incentive to create artificial reefs for this purpose. Artificial reefs can be used to replace habitats under threat from development (eg land reclamation), activities (eg dynamite fishing at coral reefs) and/or environmental change (eg coral bleaching).

The use of artificial reefs in the UK is limited to a few sites including Loch Linnhe (west Scotland, see Figure 3.1 and Case study 3.1), Poole Bay (Dorset, see Figure 3.2 and Case study 3.2), Torness (south-east Scotland) and Salcombe (south Devon). Reviews of European artificial reef sites, including many case studies from the UK, Mediterranean Sea and north-east Atlantic Ocean, are given in Jensen and Collins (1995), Jensen *et al* (2000) and Jensen (2002).

**Figure 3.1**

***Loch Linnhe artificial reef – crab on concrete blocks*** **(courtesy T Wilding, Scottish Association of Marine Science)**

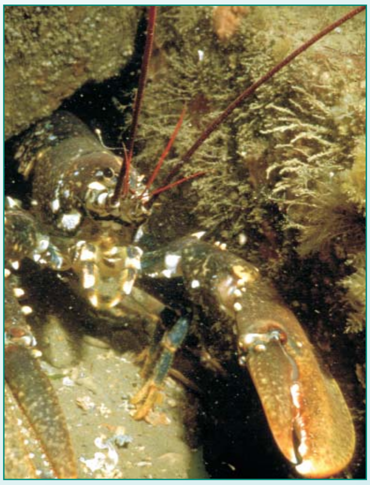


**Figure 3.2**

***Poole Bay artificial reef – lobster on cement stabilised PFA blocks*** **(courtesy K Collins, National Oceanographic Centre)**

## 3.2 DRIVERS AND BENEFITS

Maintaining and improving biodiversity appears to offer a key driver for creating artificial reefs to provide new habitat for nature conservation benefit, or for providing mitigation or compensation to offset damage to nature conservation. For example, the artificial reef at Salcombe was built in 2002 to replace habitat lost to dredging and is reported to be colonised by various anemones, sponges, sea squirts and cup coral.

To be effective in artificial reef creation, this driver requires the targeting of specific habitats and/or species, particularly habitats and species related to hard substrata given the nature of materials (see Section 3.3.3). Jensen (1998) identifies that "a high level of habitat diversity is considered essential to promote a high biological diversity in a reef" and notes that artificial reef creation for nature conservation "should seek to maximise niche diversity based on an understanding of the requirements of a number of species".

Economic return is the primary benefit and, is the driver for developing artificial reefs that support commercial fisheries in the UK. According to the Marine and Fisheries Agency (MFA), in 2005 approximately 708 000 tonnes of sea fish were landed into the UK and abroad by the UK fleet with a total value of £571 million, while a further £1686 million of fish was imported (James, 2006). Artificial reefs may have the potential to increase production of commercial fisheries for target species such as lobster and other shellfish, and are the subject of extensive development (eg in Japan) and some research (eg in the UK).

### 3.2.1 Production artificial reefs

Production artificial reefs aim to provide more habitat to increase fish biomass (ie numbers and growth), and to transform non-productive fishing areas into productive areas (Kingsford, 1999). For example, in Japan, production artificial reefs have been constructed from concrete blocks to standard techniques for many years in order to increase the abundance and biomass of target species such as abalone and lobster (Sahoo and Ohno, 2000).

Artificial reefs aim to provide habitat for commercial shellfish species, notably crustacean fisheries (including juvenile restocking), to deliver benefits to inshore fisheries using static gear (eg pots). They can provide habitat for algae or mollusc cultivation (ie production artificial reefs in Bombace, 1996). Studies on lobster indicate that artificial reefs can be used to enhance local stocks where habitat availability is a limiting factor by providing new larval settlement and nursery habitat. However studies on experimental artificial reefs have not shown that lobster stocks can be enhanced beyond the local area (French McCay *et al*, 2003).

Finfish may benefit from artificial reefs by providing spawning sites for species requiring hard substrate on which to lay eggs, or by providing habitat for prey species, or shelter from predators. However, artificial reefs do not support all commercial species and so they cannot be considered as a cure-all solution for commercial fisheries; for example, many species of flatfish and some pelagic fish do not utilise hard substrate (Jensen *et al*, 2000). Substantial uncertainty also remains about the efficacy of artificial reefs as mitigation or compensation for damaged or lost fish resources. For example, Powers *et al*, (2003) note that "the probability that any enhancement in fish production resulting from artificial reefs would vary both spatially and temporally, and by species, increases the large uncertainty that the construction of artificial reefs could meet quantitative mitigation goals".

Box 3.1 *Production versus attraction*

Fishery productivity with regard to artificial reefs assumes that a structure provides additional habitat which increases the local environment's carrying capacity (eg by providing more shelter or more food) and thereby increases the local environment's biomass. The production versus attraction debate concerns whether artificial reefs only serve to attract and aggregate existing fish resources or serve to increase and produce more fish resources. If artificial reefs only serve to attract and aggregate fish, then they could facilitate and expedite exploitation of resources. However, if artificial reefs produce fish then they could enhance resources. Bohnsack *et al*, (1997) provide a detailed review of this debate, while Pickering and Whitmarsh (1996 and 1997) consider productivity's influence on artificial reef design and policy.

### 3.2.2 Protection artificial reefs

Artificial reefs can restrict fishing where stocks require protection (ie protection artificial reefs in Bombace, 1996). Protection artificial reefs can be used to create and simultaneously protect surrounding habitat, particularly habitat that is under threat from damaging fishing activity, such as trawling (ie anti-trawling reefs). Protection can be provided for designated marine areas, ecologically sensitive habitats and species, and fish habitat. Jensen (2002) notes that most European artificial reefs are situated in the Mediterranean Sea and are in place to protect sea grass beds from trawling while also providing some fisheries function.

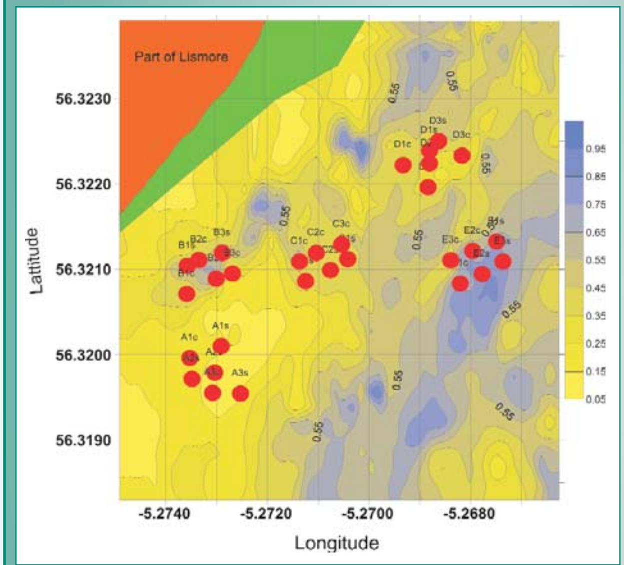
### 3.2.3 Research artificial reefs

Artificial reefs are also used for research purposes. The Loch Linnhe artificial reef provides a facility for many research areas (see Case study 3.1). Research is particularly important for establishing design and materials information for artificial reefs. For example, in the UK, tyre units were deployed at the Poole Bay artificial reef to study the environmental impact of tyres as an artificial reef construction material by monitoring colonisation of epibiota and heavy metals and organic compounds in the epibiota. This research addresses the concern that tyres may leach toxic substances into the organisms that colonise the artificial reef (eg Collins *et al*, 2002). Similar examples can be drawn from elsewhere in the world. For example, in Florida, USA, species richness on artificial reefs has been monitored to test concern that materials manufactured from stabilised oil and coal ash may leach heavy metals (Vose and Nelson, 1998).

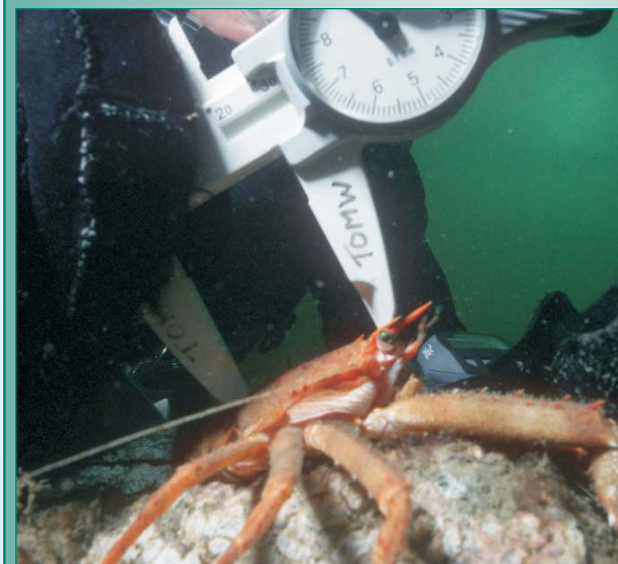
Case study 3.1 *Loch Linnhe artificial reef*

The Loch Linnhe artificial reef is located on Scotland's west coast. It comprises five groups of six artificial reef modules (Figure 3.3a) spread over a predominantly sedimentary seabed area of 0.4 km² in water depths from 12 m to 30 m. Each artificial reef is made of 4000 simple (ie solid) or complex (ie with voids) concrete block units. The blocks were dropped from a barge onto the seabed so the resulting random nature of deployment maximises habitat complexity. The artificial reef was designed and built to facilitate research concerning the development and stability of reef-associated biological communities, with particular focus on commercially important fishery species. In particular, monitoring of the artificial reef is expected to provide a unique data set on the environmental requirements of lobster species (eg squat lobster, Figure 3.3b). The artificial reef is being used for the following areas of research:

- the effect of artificial reefs on their receiving environment
- differential flow patterns over the reef area
- the effect of pre- or post-settlement processes determining sub-tidal community structure
- modelling habitat complexity on artificial reefs
- the potential for artificial reefs in augmenting artisanal fisheries
- epifaunal colonisation with reference to substratum influence on epifaunal assemblage structure
- a comparison of colonisation of natural and artificial reefs.




(a)




(b)

Figures 3.3

*Loch Linnhe artificial reef module distribution (a) and biological research (b)* (courtesy T Wilding, Scottish Association of Marine Science)

## 3.3 STRUCTURES, DESIGNS AND MATERIALS

### 3.3.1 Structures

A key objective of an artificial reef structure is to mimic conditions created by natural reefs. Typically, this entails a protrusion from the seabed of a hard substrate feature that avoids uniformity such as straight lines around the perimeter or along the crest, or materials of the same size and/or surface roughness. In terms of marine biology, a simple guideline is that more habitat diversity promotes more biodiversity. Figures 3.4a and 3.4b demonstrate the shape of modules in the Loch Linnhe artificial reef. High topographical relief is important to some species, particularly fish exploiting turbulent areas behind reefs placed in currents.


Figure 3.4 *Loch Linnhe artificial reef module structure multi-beam image (a) and physical model* (b) (courtesy T Wilding, Scottish Association of Marine Science and Z Aston, School of Marine Science and Technology, University of Newcastle)

### 3.3.2 Designs

Effective artificial reef designs focus on specific ecological and/or commercial fishery objectives for target species and their supporting community.

The European Artificial Reef Research Network (EARRN) reported that designs vary according to local environmental conditions and aims, and it is unlikely that one best design exists. Designs need to consider the habitat requirements of target species and be informed by further research into the habitat and behaviour of species, hydrodynamics and scale (Jensen, 1998a). Colonisation depends on shelter, food and hydrodynamic conditions (Spanier, 1996), and artificial reef design depends on a combination of biology, engineering and ocean physical sciences (Seaman, 1996). Overall, the following design factors should be considered if an artificial reef is to meet its objectives:

- structure, including the composition and arrangement of its materials
- location, including its depth and surrounding seabed and hydrodynamic environment.

An artificial reef's structural complexity influences colonisation and the diversity of the resulting biological community. Artificial reef designs can include various numbers, shapes and sizes of crevices, holes, overhangs and walls to increase structural complexity and increase shelter, shading and total surface area. Surface area influences the total biomass that can be supported by an artificial reef since it influences the availability of surface habitats and food sources. Shelter and shading can increase the biomass of an artificial reef's target species by increasing hiding spaces to reduce predation. Shelter is particularly important for species such as lobster which are vulnerable to predators and currents, and designs may need to incorporate a range of cavity sizes to accommodate the different life stages of juveniles and adults.

Exterior surface angles and vertical profiles influence an artificial reef's overall fish species composition and biomass. Exterior surface angles can be designed to reduce sedimentation and increase colonisation (Jensen, 1998a). Low profile artificial reefs appear more successful in providing a suitable habitat for demersal fish, while high profile artificial reefs appear more successful for pelagic fish by providing shelter from currents. A combination of high and low profiles can be used to create an artificial reef targeting a potentially more diverse fish assemblage (Joint Artificial Reef Technical Committee of the Atlantic and Gulf States Marine Fisheries Commissions, 1998). Structures need to be sufficiently open to allow better utilisation of surfaces (eg by sessile invertebrates), improve access for fish and motile invertebrates, and to allow some water circulation to prevent stagnation.

Most artificial reefs for marine habitat are located at depths below the water surface that minimise risks to structural integrity and material stability due to wave action and storm damage. Research by Gregg (1995) established shallow artificial reef sites at less than 15 m and deep artificial reef sites at more than 15 m. Artificial reefs in the UK have been deployed in water depths of 10 m (eg Poole Bay artificial reef) and 12 m to 30 m (eg Loch Linnhe artificial reef).

### 3.3.3 Materials

Various materials are used to construct artificial reefs including natural materials (eg quarried rock), manufactured materials (eg concrete units) and materials of opportunity (eg scuttled vessels and tyres). Physical and chemical stability influences the choice of materials for reasons of durability and environmental acceptability. Cost also influences the choice of materials – for example, there are few examples of artificial reefs developed for fish stock enhancement that have proved economically viable (Wilding and Sayer, 2002) – and drives the use of cheap construction materials including waste products and structures (ie materials of opportunity).

Figure 3.5

*Reef Ball™ units* (courtesy L Harris, Florida Institute of Technology)

Figure 3.6

*Concrete units, Oman* (courtesy M Aurora)

Figure 3.7

*Loch Linnhe artificial reef concrete blocks* (courtesy T Wilding, Scottish Association of Marine Science)

Figure 3.8

*Poole Bay artificial reef tyre modules* (courtesy K Collins, National Oceanographic Centre)

## Natural materials

Although most coastal defence structures are constructed from quarried rock, worldwide examples of artificial reefs for marine habitat tend to be constructed from manufactured materials or materials of opportunity. Nevertheless, physical and chemical stability issues still apply to the use of natural rock. While the physical stability of rock is well covered in coastal engineering literature (eg CIRIA/CUR/CETMEF, 2007) some rock contains leachable toxic metals that can be bio-accumulated by marine life (Jensen *et al*, 1998). Of the UK's artificial reefs, the Torness and Salcombe artificial reefs comprise quarried rock.

## Manufactured materials

Manufactured materials can be developed with the desired characteristics of a substrate for a specific artificial reef objective and/or end result. The initial costs in procuring manufactured materials may be higher than those involved in obtaining natural materials or materials of opportunity but may be offset by less cleaning or preparing costs. Specific qualities of stability, durability, structural integrity, transportability and biological effectiveness can be engineered into a manufactured material design. This gives the resulting artificial reef structure a potential advantage over some natural materials and most materials of opportunity which are limited in how they can be modified or deployed (Joint Artificial Reef Technical Committee of the Atlantic and Gulf States Marine Fisheries Commissions, 1998).

Various materials have been manufactured for use and/or trial as artificial reef materials. Concrete appears to be a suitable material given its durability and potential to be manufactured into different sizes and shapes, including specifically designed concrete vessels, blocks, pipes and units such as Reef Balls™ (Figure 3.5) and other similar structures (Figure 3.6).

Concrete materials may be manufactured by cement-stabilising low-value aggregates or waste materials. For example, the concrete blocks used for the Loch Linnhe artificial reef in west Scotland (Figure 3.7) comprise low-value granite quarry products, five per cent cement and five per cent fly-ash, and were shown to be physically and chemically stable (Wilding and Sayer, 2002). Also in the UK, cement stabilised pulverised fuel ash (PFA) blocks were deployed to create an artificial reef in Poole Bay (Figures 3.10a and 3.10b, and Case study 3.2). Research has shown that apart from records of a very minor amount of cadmium leaching (Jensen and Collins, 1995), in general, heavy metals are not released from the blocks (Jensen, 2002).

Manufactured materials can be deployed in any quantity, pattern and profile required (as can natural rock) and can be designed, manufactured and deployed as units. These factors maximise opportunities for efficient use in achieving the artificial reef's objectives.

## Materials of opportunity

Materials of opportunity is the term used to cover a vast range of waste materials that are considered for artificial reef construction, particularly in the US and Australia. The US in particular pursues the use of materials of opportunity that include decommissioned oil rigs, platforms, ships, aircraft, cars, tanks, trains, tyres, wood, shell, white goods, or concrete from razed structures (eg Lukens, 1997).

The re-use of materials poses potential environmental benefits (eg re-use of waste offsetting non-renewable resource consumption) and risks (eg leaching of toxic chemicals). Key criteria for the selection of materials of opportunity include physical stability and chemical stability, and associated environmental and health and safety risks. The philosophy proposed by EARRN stated that "re-use is acceptable if materials have been shown to be environmentally benign and that reef creation is for a positive reason, not just the disposal of material" (Jensen, 1998b).

**Box 3.2** ***Materials of opportunity – the UK position***

**Compared to the US, the UK's position on the use of materials of opportunity for artificial reef construction is more restrained, particularly through legislation concerning the placement of construction materials on the seabed. In the context of habitat enhancement, Sayer and Wilding (2005) note that "from the position of fit for purpose, any re-use of materials primarily designed for a non-reef use will generally be deficient for reef construction", citing the sinking of the frigate HMS Scylla to be illustrative of the development having the principal purpose of diving amenity (see Case study 4.1) rather than having any significant use in fishery protection or enhancement.**

Tyres are popular artificial reef construction materials outside of the UK because they are readily available at little or no cost, are durable and come with large void spaces (Collins *et al*, 2002). The use of tyres for artificial reefs is popular in south-east Asia, the US and the Middle East. Physical stability is an issue in the marine environment, particularly with respect to wave action. There are a number of cases where artificial reefs incorporating tyres have failed due to their physical instability, including the Osborne artificial reef in Florida where two million tyres were subject to mobilisation by tropical storms after the steel bands holding them together corroded and failed. A clean-up programme is underway.

HR Wallingford (2005) recommend that "tyre modules should be linked together with steel cable or chain, ballasted with concrete and if required secured to the seabed with anchor poles/piles or equivalent" to increase the stability artificial reefs and to reduce the risk of tyre loss and scattering. In the UK, the only artificial reef constructed from tyres is situated in Poole Bay (Figure 3.8 and Figure 3.9, and Case study 3.2).

Figure 3.9 *Poole Bay artificial reef tyre modules* (courtesy K Collins, National Oceanographic Centre)

Case study 3.2 *Poole Bay artificial reef*

The artificial reef in Poole Bay (Figures 3.10a and 3.10b) was initially constructed in 1989 using cement stabilised PFA blocks (0.2 m × 0.2 m × 0.4 m). It is situated in 12 m of water and comprises eight conical pile units in two rows with centres 10 m apart, covering a seabed area of 15 m × 35 m. Each pile is approximately 1 m high and has a 5 m diameter comprising six tonnes of randomly stacked blocks. About 25 per cent of the structure's volume is void space. The structure's randomness provides a large surface area and a range of crevices and galleries (Jensen and Collins, 1995). Three different PFA/cement block formulations (and standard concrete blocks as controls) were used to determine the environmental compatibility of these materials through chemical and biological monitoring. Chemical monitoring showed that metals are not leached from the blocks in significant amounts (Jensen and Collins, 1995, and Jensen, 2002). Biological monitoring of lobster behaviour was conducted and included electronic tracking (Smith *et al*, 1998).


Figures 3.10 *(a) and (b) Poole Bay artificial reef cement stabilised PFA blocks* (courtesy K Collins, National Oceanographic Centre)

The artificial reef was extended in 1998 by the placement of tyre modules (and standard concrete blocks as controls). As for the cement stabilised PFA blocks, the tyre modules were arranged as eight separate units. Each tyre module is approximately 1 m high and has a 5 m diameter. Three tyre modules were installed from 500 scrap tyres arranged as rubber rocks (stacks of car tyres forming a cylinder filled with concrete), open lattice tetrahedra (using either four or 13 tyres bound by stainless steel bolts and with basal tyres filled with concrete), and concrete-filled single car and lorry tyres (Figures 3.8 and 3.9). Chemical monitoring showed that leaching is not significant. Biological monitoring showed that colonisation is similar to colonisation of concrete materials (HR Wallingford, 2005).

# 4 Artificial reefs for amenity

## 4.1 INTRODUCTION

Artificial reefs present various amenity opportunities although there are few UK examples of artificial reefs that have been designed and built specifically for amenity. Outside the UK, most artificial reefs for amenity are in the form of sunken vessels and provide for recreational sea angling and diving. Some countries, notably the US, have well-established large-scale artificial reef programmes in place, while UK legislation concerning the placement of materials on the seabed restricts the use of materials of opportunity.

It is now possible to design artificial reefs to create good quality surfing conditions. Unlike the many artificial reefs that are in place for sea angling and diving, at present there are only a few artificial reefs worldwide with a dedicated surfing function. Compared to artificial reefs for sea angling and diving, the design of artificial surfing reefs more closely resembles the design of detached submerged breakwaters for coastal defence, so it is not surprising that some of the best examples of multi-functional artificial reefs combine coastal defence and surfing amenity (see Chapter 5).

The use of artificial reefs for amenity in the UK is limited to one example for diving (HMS Scylla, south Cornwall, see Case study 4.1), one well-developed proposal for surfing at Boscombe (Dorset, see Case study 4.2), and one, currently on-hold, proposal for surfing at Newquay (Cornwall). Worldwide, there are numerous artificial reefs for recreational angling and diving, notably in the US, and a few examples of artificial reefs for surfing.

## 4.2 DRIVERS AND BENEFITS

Artificial reefs present an opportunity for direct amenity benefit by providing a new facility and/or improved conditions at which the amenity can be undertaken and contribute to social well-being. Artificial reefs also have the potential to generate considerable expenditures that support local economies. For example, there are large programmes of artificial reef development for amenity (sea angling and diving) in some States of the US, notably in the south-east US and California. A socio-economic study of artificial and natural reefs in south-east Florida, USA (Hazen and Sawyer, 2001) illustrates the potential benefits of large-scale artificial reef development by reporting 9.8 million person days of amenity use (principally sea angling, diving and snorkelling) generating an annual use value of US$84.63 million.

### 4.2.1 Artificial reefs for recreational sea angling

Recreational sea anglers desire opportunities to catch fish but are motivated by more than the size of their catches. A survey of sea angling charter boat skippers identified that sea anglers value catch quantity (55 per cent), sporting attributes (33 per cent), species availability and fishing location (22 per cent) (North Eastern Sea Fisheries Committee, 2006). Also, sea angling is perceived to have a positive health effect on its participants (Drew Associates, 2004).

It is estimated that, of the combined population of England and Wales, three million people aged 12 and over have been sea angling (Simpson and Mawle, 2005). Expenditure on recreational sea angling in the UK is estimated to be £1 billion per year (Cabinet Office, 2004). Drew Associates (2004) report that sea angling in England and Wales is undertaken from the shore (54 per cent), private boats (23 per cent) and from charter boats (22 per cent) and is worth between £600 million and £1300 million per year. They also note that "around half of the [resident anglers'] expenditure (52 per cent) was by own-boat anglers and reflects the importance of capital expenditures on boats and equipment". Recreational sea angling is estimated to contribute £28.7 million to the Welsh economy and provide 471 full-time equivalent jobs (Nautilus Consultants, 2000), and is estimated to contribute £165 million to south-west England's regional economy (Invest In Fish, 2005).

Future prospects for sea angling in the UK appear to depend on demand, fish stocks and facilities, and may be related to an increasing use of own boats and charter boats (Drew Associates, 2004). A survey of sea angling charter boat skippers in north-east England identified that 55 per cent of skippers thought that an artificial reef (in Bridlington Bay) would be beneficial to local charter fishing (North Eastern Sea Fisheries Committee, 2006). Overall, there appears to be a role for artificial reefs as fish attraction devices to support sea angling as an amenity with socio-economic benefits.

### 4.2.2 Artificial reefs for diving

Divers desire dive locations that are interesting for a variety of reasons and often dive on wrecks and/or at sites where there is marine life. Crowding at dive sites can reduce the enjoyment of diving and is an increasing risk as the sport becomes more popular.

The economic benefits of HMS Scylla, an ex-Royal Navy frigate sunk off Whitsand Bay in south-east Cornwall are reported to include an additional expenditure of £1 million per year as a result of increased diving activity, and more employment of 37 full-time equivalent jobs. The average expenditure associated with diving on a vessel sunk as an artificial reef in the US is US$3.4 million per year (Hess *et al*, 2001). Overall, artificial reefs for recreational diving can potentially provide a large economic resource (Pendleton, 2004) and offset pressures on adjacent natural reefs while still increasing income and employment in the local economy (Leeworthy *et al*, 2006). They may also offer an opportunity to extending the diving season. Extending the season for visiting divers may be a key factor in the future growth of the diving industry.

**Figure 4.1** *Diving on an artificial reef, UAE*

## 4.2.3 Artificial surfing reefs

Surfers desire consistent good quality surf and will travel considerable distances to access it. Artificial surfing reefs can deliver better surfing conditions by increasing the number of days that surfing can occur and by improving wave quality. In addition to improved surfing conditions, artificial surfing reefs are predicted to generate economic benefits by increasing surfing activity and associated expenditure. For example, an economic impact study predicts that an artificial surfing reef proposed at Opunake, New Zealand will increase visitor numbers by 800 and generate additional expenditure of NZ$225 120 five years after construction (Tourism Resource Consultants, 2002).

The potential benefit of artificial surfing reefs to local economies in the UK can be illustrated by the importance of surfing to the Cornish economy where an assessment by Arup (2001) predicts the annual expenditure on surfing in Cornwall to be £21 million, and notes that improved surfing conditions are the largest single factor that would attract more surfing to Cornwall. Weight (2003) has predicted an annual income of £1.32 million for an artificial surfing reef at Newquay. ASR Ltd (2002) suggests that an artificial surfing reef at Newquay would provide a local economic payback of £1.6 million per year, paying for itself in three to four years through economic benefits derived from strengthening of surf-related industries and businesses (eg surf schools, surf equipment hire) and surf-related accommodation (eg by holding prestigious surf events and competitions). For comparison, payback for the Opunake reef is predicted to be 27 years and 24 years at the regional and district levels respectively (Tourism Resource Consultants, 2002).

In addition to economic drivers and benefits, Weight (2004) proposes that artificial surfing reefs offer various social benefits and suggests that if an artificial surfing reef was built at Newquay it could:

- promote tourism during the off-peak season thereby helping to reduce seasonal unemployment
- promote a better quality of life through physical and mental well-being
- develop Newquay and Cornwall's distinctiveness and culture
- build intellectual capital through learning and training opportunities.

# 4.3 STRUCTURES, DESIGNS AND MATERIALS

## 4.3.1 Structures

### Artificial reefs for recreational sea angling and diving

Most structures for artificial reefs for fishing and diving are decommissioned, scuttled vessels – notably steel hulled ex-naval vessels – and other materials of opportunity (see Section 3.3.3). Over 700 vessels have been sunk in US waters to create artificial reefs for sea angling and diving (Pendleton, 2004). The vessels have to be able to withstand heavy sea conditions and structural deterioration through ageing. Lukens (1997) identifies a number of vessels off Florida, USA that sustained damage as a result of hurricane conditions).

### Artificial surfing reefs

The wave breaking function of artificial surfing reefs is broadly similar to the function of detached submerged breakwaters for coastal defence, so they are broadly similar structures to low-crested breakwaters but require shallower seaward slopes and smoother surfaces to generate good quality surfing waves.

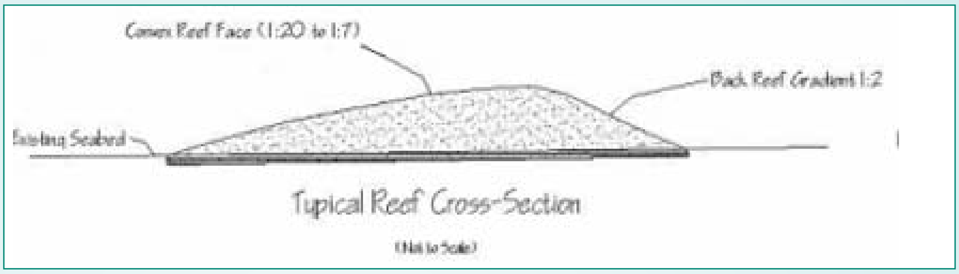



Figure 4.2 *Typical artificial surfing reef cross-section* (courtesy ASR Ltd)

Jackson and Corbett (2007) review the artificial surfing reefs that are in existence to date (2007). Table 4.1 summarises their review by identifying the key features of the artificial surfing reefs in terms of their location, date of construction, volume, construction materials, spring tidal range, wave height, wave period and crest level. Mean wave heights and wave periods are identified in the table, but they can vary considerably with seasonal trends. The Narrowneck artificial reef is a multi-functional artificial reef (coastal defence and surfing) (see Chapter 5) but is included for comparison.

Table 4.1 *Summary of artificial surfing reefs* (derived from Jackson and Corbett, 2007)

| Location | Date | Vol ($m^3$) | Material | Tidal range (m) | Wave height (m) | Wave period (s) | Crest level (m) |
|---|---|---|---|---|---|---|---|
| Bargara, Queensland, Aus. | 1997 | 300 | Rock | 2.5 | <1.0 | 6-9 | |
| Cables, WA, Aus. | 1998–1999 | 5500 | Rock | 0.8 | 2.0 | 8.8 | -1.0m LAT |
| Narrowneck, Queensland, Aus. | 1999–2000 | 70 000 | SFGCs | 1.3 | 1.0 | | -1.0m LAT |
| El Segundo, Calfornia, US | 1999–2001 | 1350 | SFGCs | 1.6 | <1.0 | | -0.9m LAT |
| Mount Maunganui, NZ | 2005–ongoing | 6000 | SFGC | >2.5 | <1.0 | | -0/4m LAT |
| Opunake, NZ 2006–ongoing | | | SFGC | >3.0 | | | |

**Note**

SFGCs = sand-filled geotextile containers

## 4.3.2 Designs

### Artificial reefs for recreational sea angling and diving

Artificial reefs created for recreational sea angling tend to take the form of sunken materials of opportunity, particularly scuttled vessels. Artificial reef creation for this purpose is particularly well-established in the US where the legislation for placing materials on the seabed is less onerous than in the UK.

Location is an important design component of artificial reefs for recreational sea angling. In addition to factors that influence fish attraction and productivity (see Chapter 3), key factors include:

- accessibility from the shore by private or charter boat
- proximity to other popular fishing areas since anglers may want to fish on more than one site and/or overcrowding may affect the fishing experience
- wave heights since this may affect accessibility by boat and angler comfort
- possible conflicts with other user groups including anglers and navigators.

Other design factors for sea angling include preventing tangling of fishing equipment (eg by eliminating overhangs (Jensen, 1998b)), but little consideration appears to be given to such factors.

Artificial reefs created for diving amenity tend to take the form of scuttled vessels to produce a site of interest for divers since they either have inherent interest (eg historic vessel) or indirectly provide an interest (eg marine life attraction). Their design has to provide safe diving conditions, particularly in the case of scuttled vessels. For example, hazards were removed, potential snagging hazards were eliminated and doors were welded shut or open to ensure safety when diving on HMS Scylla. Extra diver access holes were also created throughout the vessel to improve diving safety and interest.

Location is an important design component of artificial reefs for diving. Key factors include:

- depth since this affects bottom time and decompression risk
- water clarity since diving is largely a visual experience
- accessibility from the shore either as a shore dive or by boat
- proximity to other popular dive areas. Divers may want to dive on more than one site and/or overcrowding may affect the diving experience
- currents since divers can use them (ie drift diving) or be swept away by them
- wave conditions that may affect diver entry and exit from the water during shore dives and boat dives, and may affect accessibility by boat
- possible conflicts with other user groups including anglers and navigators.

### Artificial surfing reefs

Surfers want good quality surfing waves that allow them to ride along the clean face of a wave with progressively breaking crest (ie a peeling wave) and it is this characteristic that principally drives the design of an artificial surfing reef. Only a few dedicated artificial surfing reefs have been constructed around the world, notably in Australia and New Zealand, while others are planned at locations including the US and the UK. Surfing amenity has been incorporated into coastal defence, and this combination is one of the best examples of a multi-functional artificial reef (Chapter 5).

Good quality surfing waves need a complex combination of seabed bathymetry, swell and local wind conditions. Artificial surfing reefs cannot create better swell and wind conditions, but they can change the seabed's bathymetry to provide the breaking and peeling characteristics of good quality surfing waves and to provide suitable wave height ranges and breaking sections with lengths appropriate to surfers of different abilities.

A wave's breaking characteristic is related to an artificial reef's bathymetry, particularly the reef's slope perpendicular to the shore, and particularly in shallow water. Spilling waves are full waves with shallow take-offs which are generally the easiest to surf. Plunging waves are tubing, hollow waves with steep take-offs which offer more challenging surf. Surging or collapsing waves are very steep collapsing waves which are generally unsuitable for surfing. Surfers tend to prefer plunging waves. The breaking intensity of plunging waves is such that it is powerful enough to propel surfers forward and allow them to execute various manoeuvres and possibly ride inside a wave's curling tip (ie a barrel or tube). Mead and Black (2001) suggest a classification for wave breaking intensity and Mead (2003) provides a review of surfing wave breaking intensity.

**Figure 4.3** *Surfing at the Mount Reef (artificial surfing reef), NZ* (courtesy ASR Ltd)

Although expert level surfers can surf waves with powerful breaking intensities and large wave heights, all surfers require waves to peel. Accordingly, the peel angle is a key design issue for artificial surfing reefs. A wave's peeling characteristic is related to an artificial reef's bathymetry and can be measured as a peel angle (ie the angle between the trail of the broken white-water and the unbroken crest of the wave as it propagates forward) (Scarfe *et al*, 2003). An artificial reef's design should take into account the skill level of the surfers for whom it is intended to provide amenity. If the peel angle is very small, the peel rate is large and the wave velocity is fast. However, as the peel angle approaches 0°, the risk of close-out conditions increases (ie causing long sections of a wave to break at the same time) thereby making it less suitable for surfing. Accordingly, the need for a peeling wave means that artificial surfing reefs cannot be shore-parallel structures because their small peel angle would create a wave that closes-out. Large peel angles can be surfed but the wave velocity is slow, so the challenge they pose can limit the use of the resulting waves to more advanced surfers.

A summary of wave characteristics for different surfer skill levels is given in Table 4.1. An alternative rating system based on peel angle and wave height is given in Hutt *et al* (2001).

**Table 4.2** *Wave characteristics related to surfer skill* (Challinor and Weight, 2005a derived from Pattiaratchi, 1997 and Jackson *et al*, 2001)

| Surfer skill | Wave height (m) | Wave velocity (m/s) | Peel angle (o) |
|---|---|---|---|
| Beginner | <1.2 | <3 | 30 |
| Intermediate | <2.5 | <7.5 | 30–60 |
| Expert | <8 | <12 | 60 |

## 4.3.3 Materials

### Artificial reefs for recreational sea angling and diving

Where a vessel or alternative material of opportunity is to be sunk to create an artificial reef, it is necessary that it be prepared for its intended use. Clean-up is a key preparation activity since it is necessary to remove any materials that may be hazardous to the environment and human health including contaminants such as oils, asbestos, PCBs and other debris. An example of guidance for vessel preparation is provided by the US Environmental Protection Agency and the US Maritime Administration (2006).

For recreational sea angling, there appears to be little consideration given to use of materials to create artificial reefs other than clean-up.

In contrast, for diving, materials have to be acceptable in terms of health and safety. This means that sunken vessels such as the HMS Scylla have been adapted to be appropriate for diving but not adapted for fishery protection or enhancement (Sayer and Wilding, 2005).

Vessel preparation for diving can include measures to improve diver safety, such as:

- removing of sharp and protruding objects which could snag on divers' equipment or otherwise pose a danger to divers
- removing of doors and access hatches, and widening of openings to provide safe access for divers
- widening of corridors by removal of some wall panelling and provision of large exterior openings to allow light penetration and improve diver access
- sealing of entrances into restrictive compartments such as the boiler rooms and engine rooms (US Environmental Protection Agency and the US Maritime Administration (2006).

### Artificial surfing reefs

The materials used to construct artificial surfing reefs have been rock and sand-filled geotextile containers. Rock is the same material as often used for coastal defence structures (Chapter 2) and its use in coastal engineering is described in detail in *The rock manual* (CIRIA/CUR/CETMEF, 2007). Rock has been used to construct the Cables Station artificial surfing reef near Perth, Western Australia.

Geotextile containers for artificial surfing reefs comprise non-woven, needle punched fabrics that are pre-shaped into tubes and mattresses of various volumes (eg Heerten *et al*, 2000). Sand-filled geotextile containers have been used to construct the artificial surfing reef at Mount Manganui, NZ (Figures 4.4 and 4.5). Geotextiles are also used for coastal defence structures (Chapter 2) and their use in coastal engineering is described in *The rock manual* (CIRIA/CUR/CETMEF, 2007).

Figure 4.4

*Preparation of geotextile containers for Mount Reef, NZ* (courtesy ASR Ltd)

Figure 4.5

*Deployment of geotextile containers for Mount Reef, NZ* (courtesy ASR Ltd)

The construction of artificial surfing reefs from sand filled geotextiles is believed to offer the following benefits over rock and/or concrete units:

- their capacity for elongation facilitates distribution and dissipation of loads, and reduces the risk of damage or failure in high energy hydrodynamic environments where they may be subject to movement (Quirk *et al*, 2002)
- they can be easily topped up, modified or removed (Quirk *et al*, 2002)
- they offer a degree of improved surfer safety and reduced injury risk (Jackson *et al*, 2002)
- they can be more cost-effective (eg 50 per cent of the cost of using rock for the Narrowneck reef, Jackson *et al*, 2001, Quirk *et al*, 2002)
- they can be a more sustainable construction option, depending on transport distances and method (Challinor and Weight, 2005b).

Case study 4.1 *HMS Scylla artificial diving reef*

After decommissioning, the National Marine Aquarium purchased the HMS Scylla in 2003 in order to sink it and create an artificial reef diving facility in Whitsand Bay, south-east Cornwall. While divers use many other wrecks, HMS Scylla is the only purposefully sunk vessel that provides an artificial reef diving facility of this nature in the UK. Prior to its sinking, the vessel was cleared of all materials potentially harmful and/or hazardous to the environment. Diving hazards were removed, potential snagging hazards were eliminated, doors were welded shut or open to ensure diver safety and additional diver access holes were created throughout the vessel.

In addition to diving, this artificial reef provides a centre for education and research, and is monitored regularly to record its progressive colonisation by marine life. It is proposed that the artificial reef site becomes a voluntary no take zone to the extent that fishing does not occur and marine life develops to its full potential. While the artificial reef is predicted to increase expenditure in the local economy by c£1 million, the National Marine Aquarium's ongoing annual maintenance and diving costs exceed £40 000 to cover insurance, buoy maintenance, scientific surveys and special diving equipment.

Case study 4.2 *Proposed Boscombe artificial surfing reef*

The proposed Boscombe artificial surfing reef comprises a single-arm, right-hand reef (given the predominant swell and wind directions) designed to increase breaking wave height (given the small wave climate) with a peel angle in the range of 50° to 55°. Its design includes two levels, of which the lower level provides a low gradient conditioning platform that draws in the wave energy to increase breaking wave height and the upper level provides a steeper gradient breaking segment that breaks the wave. The artificial reef's crest height is 0.5 m above chart datum. Its footprint is 10 000 m² and its volume is 15 000 m³ (Black *et al*, 2004).

The idea for an artificial surfing reef at Boscombe was born from proposals for a multi-functional artificial reef providing coastal defence and surfing amenity. However, the coast protection provided by Boscombe Pier meant that multi-functionality could not be justified from a cost-benefit perspective so Bournemouth Borough Council proceeded with an artificial reef that is purposefully designed to provide surfing amenity. The artificial surfing reef is perceived as an amenity feature to improve the surfing potential at Bournemouth and to further develop the tourism market, particularly outside the main season.

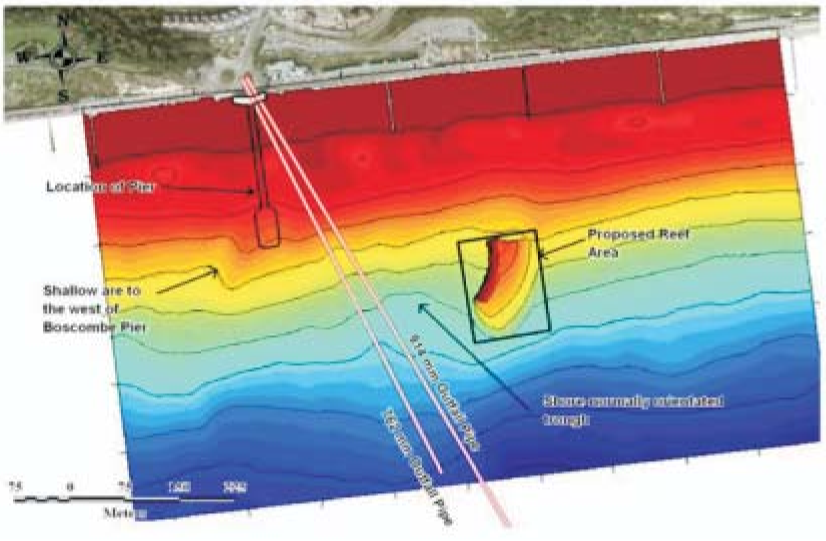



Figure 4.6 *Proposed Boscombe artificial surfing reef location and bathymetry* (courtesy ASR Ltd)

# 5 Multi-functional artificial reefs

## 5.1 INTRODUCTION

### 5.1.1 Defining multi-functionality

It is important to clarify the context in which multi-functionality is defined for this study. True multi-functionality demands purposeful planning and design to achieve its objectives, particularly with respect to coastal defences. This is important because multi-functionality needs to be demonstrable to the extent that it meets policy drivers and secures funding for functions other than coastal defen

In this context, it is reasonable to state that there are few examples of artificial reefs that have purposefully combined coastal defence with another specific function and can be considered to be truly multi-functional artificial reefs. To date, there is no example of a multi-functional artificial reef in the UK. However, there are plenty of examples of marine structures where incidental effects occur to the extent that benefits to ecology or amenity are suggested despite no obvious planning or deliberate design to deliver them. The following sections review this situation and identify why retrospectively claimed effects should not be identified as additional functions.

### 5.1.2 Incidental marine habitat functions

Artificial marine structures (eg offshore breakwaters, groynes, harbour walls, oil platforms, pipelines, wrecks) are built from hard materials and provide relief on flat or gently sloping seabed areas comprising soft substrate. These artificial structures tend to have an incidental marine habitat function. A detailed review of the ecological aspects of coastal defence structures is provided in Smith *et al*, 1998.

There are many examples of coastal defence structures (including offshore breakwaters and artificial reefs) that have an incidental ecological effect following colonisation (Figures 5.1 and 5.2). In some cases this is claimed to increase biodiversity (eg Stive, 2005 and Burgess *et al*, 2003) even though the structure is not designed to deliver it, and particularly not designed to deliver it for target habitats or species. However, the claimed benefit is not always adequately proven and research indicates that while biomass increases, abundance and species diversity "is sometimes restricted by severe wave action, turbidity or pollution characteristic of many coastal defence sites" (Halcrow Maritime *et al*, 1998). This finding is supported by research from elsewhere including Italy where very low species diversity is recorded for intertidal assemblages on detached breakwaters (Bacchiocchi and Airoldi, 2003). In addition, research indicates that artificial structures that attract foraging fish can quickly alter the epifaunal populations in the surrounding seabed, with the loss of species (eg Davis, 1998 as cited in IN EX FISH, 2006).

Figure 5.1

*Colonisation of The World artificial reef, Dubai* (courtesy M Aurora)

Figure 5.2

*Colonisation of geotextile materials at the Narrowneck multi-functional artificial reef, Australia* (courtesy International Coastal Management)

There are many examples of coastal defence structures (including offshore breakwaters and artificial reefs) that have an incidental effect on commercial fisheries and shellfisheries. An overview of commercial fishing on UK structures is provided in Halcrow Maritime *et al* (1998) and identifies that fishing (particularly potting for shellfish such as lobster, crab and prawn) takes place at various coastal defence structures around the UK, including several examples of detached breakwaters. Fishing also takes place around these structures, although some of this is recreational rather than commercial. It is difficult to determine whether artificial structures either increase habitat (eg for spawning and settlement) and resource productivity or just attract existing fish, however, the effect is incidental since the structure is not designed to deliver fisheries benefit. Overall, claimed effects including positive effects such as local scale productivity (eg Jackson *et al*, 2004) can only be considered as incidental since research suggests that design is a crucial factor to an artificial structure's production success (Pickering and Whitmarsh, 1996).

### 5.1.3 Incidental amenity functions

Despite a lack of supporting research and information, artificial marine structures appear to create incidental amenity. Recreational sea angling occurs at coastal structures around the UK (Halcrow Maritime *et al*, 1998). Fish and shellfish species are also exploited in a recreational context elsewhere around the world through activities such as sea angling and spear fishing on submerged breakwaters (eg Jackson *et al*, 2004) (Figure 5.3) and non-commercial shellfish collection from emerged breakwaters (eg Airoldi *et al*, 2005). Fish attraction to artificial structures can also promote diving amenity (eg Jackson *et al*, 2004). Nevertheless, incidental effects do not occur because artificial structures are purposefully designed to deliver amenity.

Figure 5.3 *Fishing boats and surfers at Narrowneck multi-functional artificial reef, Australia* (courtesy International Coastal Management)

## 5.2 DRIVERS AND BENEFITS

Chapters 2, 3 and 4 identify a range of drivers and benefits associated with the individual coastal defence, habitat and amenity functions of artificial reefs. The same drivers and benefits largely apply to multi-functional artificial reefs where there are significant policy drivers for coastal defences to incorporate additional benefits.

### 5.2.1 Coastal defence and marine habitat

In addition to the drivers and benefits identified in Chapter 3.2, a number of policy drivers in the UK potentially support incorporation of habitat functions into coastal defence structures through the promotion of biodiversity. Examples are summarised in the following paragraphs.

In 1999, the UK government issued high level targets (HLTs) for operating authorities in response to the Report of the House of Commons Select Committee on Agriculture published in August 1998 following the Easter floods of 1998. Operating authorities include the Environment Agency, internal drainage boards, local authorities and maritime local authorities and all are responsible for providing flood defence using differing powers and responsibilities. New targets were set in 2005 and these include HLT 4 concerning biodiversity. HLT 4 requires all operating authorities to avoid damage to environmental interest, to ensure no net loss to habitats covered by the UK biodiversity action plan (UK BAP) and to seek opportunities for environmental enhancement when carrying out flood and coastal defence works. The Environment Agency's report to Defra (Environment Agency, 2006) identifies a net gain of 165 hectares of new BAP habitat. Of the 165 hectares gained, four hectares are for coastal habitat (ie saltmarsh) and no hectares are for sublittoral habitat. It is possible that multi-functional artificial reefs could be targeted to provide environmental enhancement for broad inshore habitat types such as sublittoral rock.

Other strategic policies are in place and/or being planned to support the conservation and enhancement of marine biodiversity eg *Delivering the essentials of life* (Defra, 2004), Safeguarding sea life (Defra, 2005) and *A sea change – a Marine Bill White Paper* (Defra, 2007), and fisheries eg *Fisheries 2027 – towards a contract for the future of marine fisheries* (Defra, 2007a). These policies have less of a direct connection to coastal defences, but could promote the use of multi-functional artificial reefs to enhance marine biological resources. The most notable policies relate to the UK's actions in response to the Convention on Biodiversity, which was signed as part of the Earth Summit held at Rio de Janeiro in 1992. One of its main goals is to conserve biological diversity (ie biodiversity). The current target is to halt the loss of biodiversity by 2010 and this target is identified in the UK government's latest five year strategy for the environment *Delivering the essentials of life* (Defra, 2004b). The UK BAP is the UK's response to the Convention on Biodiversity. It describes the UK's biological resources and commits a detailed plan for the protection of these resources. It currently comprises 391 species action plans, 45 habitat action plans and 162 local biodiversity action plans with targeted actions. A number of habitat action plans and species action plans cover inshore sublittoral habitats and species. It is possible that multi-functional artificial reefs could be targeted to:

- create and/or improve habitat(s) under the habitat action plans, including broad inshore sublittoral habitat such as sublittoral rock
- create and/or improve habitat(s) for species identified under the species action plans, including various commercial marine fish species where stocks are at risk, principally from over fishing.

## 5.2.2 Coastal defence and amenity

As identified in Section 4.2, improvements to the (local) economy are the principal drivers and benefits supporting incorporation of amenity functions into coastal defence structures. No further benefits or drivers have been identified.

# 5.3 STRUCTURES, DESIGNS AND MATERIALS

Achieving multi-functionality is likely to require a degree of compromise in structures, designs and materials. In addition, achieving multi-functionality potentially leads to a cost exceeding that of a structure providing coastal defence only, but is less than the combined cost of two structures providing coastal defence and another function.

## 5.3.1 Structures

### Coastal defence and marine habitat

Given the evidence concerning incidental colonisation of coastal defence structures (Section 5.1), it appears that there is potential for combining coastal defence and marine habitat functions in truly multi-functional artificial reefs if structures can be focused on target habitats and/or species. As noted from EARRN Workshop 4 "the possibility of integrating artificial reef principles (ie habitat development) into coastal engineering such as breakwaters, marina developments and ports was discussed and found to have some merit for structures with some portion below the low water level" (Jensen, 1998a). Also, Halcrow Maritime *et al* (1998) note that "breakwaters provide habitat comparable to natural rocky habitat and can be potentially more complex in structure."

### Coastal defence and amenity

Given that coastal defence structures (notably offshore breakwaters) sometimes provide popular recreational sea angling sites in the UK and abroad where snorkelling and diving are also popular, it appears that there is potential for combining coastal defence and recreational sea angling and snorkelling/diving amenity functions in truly multi-functional artificial reefs in the UK. Uncertainties may lie in the planning and design of these structures to purposefully attract (or produce) species that benefit amenity, and to be acceptable in terms of health and safety.

While scuttled vessels are widely used to create submerged artificial reefs for recreational sea angling and diving in US waters, it is suggested that they are unlikely to prove suitable structures for multi-functional artificial reefs in the UK's inshore environment for a variety of technical reasons, including their capacity to withstand the stresses of wave action and absorb wave energy, and their long-term durability and stability in the marine environment. However, it is acknowledged that vessels are used for coastal defence in the UK, notably the silt-filled Thames lighter barges providing wave protection at the Dengie Peninsula, Essex.

Given that examples of multi-functional artificial reefs already exist where coastal defence and amenity have been successfully combined into offshore breakwater structures, there is significant potential for introducing structures of this type in the UK. One such structure is being proposed as part of a coastal defence strategy for the water frontage at Borth, Ceredigion (Chapter 7).

Figure 5.4

*Narrowneck multi-functional artificial reef, Australia* (courtesy International Coastal Management)

## 5.3.2 Design

### Coastal defence and marine habitat

For multi-functional artificial reefs, a degree of design compromise will be necessary to achieve coastal defence and habitat functions. Design compromise may result from matters such as non-negotiable coastal defence performance criteria (eg standards of service provision, design life, health and safety requirements), the local hydrodynamic conditions (particularly wave energy and currents) in which these structures are situated and operate, and/or a lack of knowledge about target habitats and species.

For an outline procedure of the design process, reference should be made to the MAFF commissioned feasibility study *Design criteria for enhancing marine habitats with coastal structures* (Halcrow Maritime *et al*, 1998). This report outlines the key considerations for the design process procedure including planning, environment, materials, physical site conditions, stability, construction, maintenance and cost.

Case study 5.1 *Coastal defence and marine habitat in the Caribbean and the US – design*

A number of multi-functional artificial reefs have been constructed in the Caribbean (eg Dominican Republic, Antigua, Grand Cayman and Mexico) and the US (eg Florida) to provide coastal defence and habitat using Reef Ball™ units. These units were originally designed for habitat enhancement but are used to construct submerged breakwaters for beach stabilisation and erosion protection. They reduce wave energy reaching the beach by attenuating waves and by generating turbulences in the interstices in and around the units.

The design of a submerged breakwater system in the Dominican Republic consisted of three segmented breakwater sections comprising three rows of Reef Ball™ units for each segment. The breakwater was installed in water depths of 1.6 m to 2.0 m, with the units 0.3 m to 0.8 m below the mean water level. Shortly after the installation of the breakwater system in autumn 1998, the breakwater withstood a direct hit by a category 3 hurricane and large waves from a category 5 hurricane with no units displaced or damaged. The beach and shoreline in the lee of the submerged breakwater is stable and accretes sand with no adverse impacts on adjacent beaches (Harris, 2003).

(a)

(b)

Figures 5.5 (a) and (b) *Submerged breakwater comprising Reef Ball™ units in Grand Cayman* (courtesy L Harris, Florida Institute of Technology)

## Coastal defence and amenity

The commentary on designs for coastal defence and marine habitat is applicable to designs for coastal defence and recreational sea angling and diving where these amenities depend upon habitat creation and associated species colonisation, attraction and production.

Designs for recreational sea angling are likely to focus on developing and maintaining fish populations. Emphasis is likely to be given to characteristics preferred by anglers. According to the North Eastern Sea Fisheries Committee (2006) charter boat skippers report that recreational sea anglers desire characteristics including catch quantity, sporting attributes and species availability (ie target species such as cod, bass tope and pollack).

Designs for diving may focus on generating interesting features for divers, including marine life with the species colonising and swimming around the structure, possibly providing a dive trail. In addition, designs need to take into account the health and safety of divers. Given the potentially extreme hydrodynamic conditions at sites requiring coastal defence, health and safety requirements may prove too restrictive to allow a satisfactory design for a diving function to be combined with the coastal defence function.

Traditional detached breakwaters designed for coastal defence break waves in a similar manner to natural offshore reefs, but do not provide good quality waves for surfing because their shore parallel alignment produces rapidly shoaling waves which close out rather than peel. Accordingly, designs for artificial surfing reefs need to incorporate bathymetry consisting of depth contours at an angle to the incident waves in order to create a peeling wave. This characteristic alone means compromise between designs for traditional coastal defences and multi-functional artificial reefs combining coastal defence and surfing. Designs also need to allow structures to focus energy as waves propagate relative to water depth. A review of the bathymetric components influencing surfing waves is provided in Mead and Black (2001). Furthermore, designs can be made to accommodate a surfer skill level (eg Hutt *et al*, 2001) based on peel angle, breaking intensity, wave height etc.

The coast protection function in existing examples of multi-functional artificial reefs with surfing amenity is largely derived from the widening of the beach in the lee of the structure due to sheltering and wave rotation. Although the shoreline oscillates back and forth due to storms and swell conditions, the shoreline remains further seaward than adjacent coast unprotected by the structure (Black and Andrews, 2001a, Black and Andrews, 2001b, Black, 2003) and designs need to avoid unwanted shoreline morphology changes (eg the formation of a tombolo between the artificial reef and shoreline).

Traditional coastal defences in the form of detached breakwaters are typically designed with slopes that are as steep and stable as possible to minimise volume and cost. However, the slope affects wave breaking characteristics and determines whether a spilling, plunging or collapsing wave breaks. Multi-functional artificial reefs incorporating surfing amenity require shallower slopes than traditional coastal defence structures. For example, the preliminary design of an artificial surfing reef at Newquay (ASR Ltd, 2002) and a multi-functional artificial reef at Borth (ASR Ltd, 2003) propose seaward slopes of up to 1:20. The slope design increases the reef's volume (and potentially its cost) over more traditional coastal defence/protection structures in the form of submerged/emerged breakwaters. Research on the Narrowneck artificial surfing reef in Australia indicates that only the upper part of the slope affects the wave break, so the lower part of the slope can be changed to reduce the artificial reef's overall volume (ie the slope can be steepened as the water depth increases) (Jackson *et al*, 2001). However, the applicability of these findings to multi-functional artificial reefs in the UK depends on tidal ranges.

**Case study 5.2** *Narrowneck multi-functional artificial reef, Australia – design*

Wave breaking occurs around 60 per cent of the time and depends on prevailing wave conditions. Under optimum conditions, the artificial reef provides two take off zones and rides of between 50 m and 250 m over long sections with varying peel angles.

The artificial reef provides good surfing waves and wave quality is not adversely affected by the roughness of the artificial reef's surface. To optimise surfing and wave breaking in small swell conditions and at high tide, the recommended theoretical reef shape had a very shallow crest level. However, the crest level was lowered during design to improve coast protection, reduce rip currents and reduce surfer safety risks. Typically, the artificial reef provides plunging waves at low tide (Figure 5.6a) and spilling waves at high tide (Figure 5.6b) (pers. comm., A Jackson).


Figures 5.6 *Plunging waves at low tide (a) and spilling waves at high tide (b) at the Narrowneck multi-functional artificial reef, Australia* (courtesy International Coastal Management)

## 5.3.3 Materials

### Coastal defence and marine habitat

As described in Chapter 3, the materials used to construct these structures include natural materials (eg rock), specifically manufactured materials (eg cement stabilised blocks, Reef Balls™), or materials of opportunity (eg tyres, ships, oil industry infrastructure). Rock and some manufactured materials appear suitable for multi-functional artificial reefs. Materials of opportunity, particularly waste materials such as decommissioned vessels are generally not considered acceptable for the reasons outlined in Chapter 3, although tyres may be suitable in certain locations (HR Wallingford, 2005).

### Coastal defence and amenity

As previously identified, the materials used for traditional coastal defence structures appear to deliver structures that create incidental recreational sea angling and diving amenity, and may be suitable for multi-functional artificial reefs. Scuttled vessels are unlikely to be suitable for multi-functional artificial reefs incorporating coastal defence.

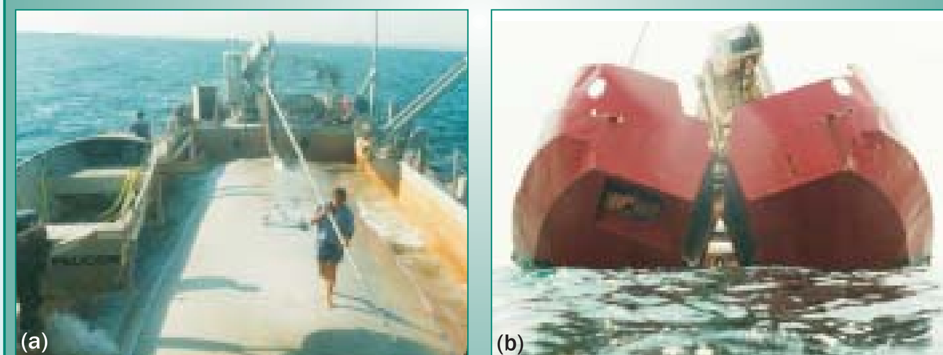
Examples already exist of multi-functional artificial reefs combining coastal defence with surfing amenity (Table 4.1). These examples use either rock or sand-filled geotextile containers.

Case study 5.3 *Narrowneck multi-functional artificial reef, Australia – materials*

The multi-functional artificial reef at Narrowneck on Australia's Gold Coast combines coastal defence with surfing amenity. Its coastal defence function is to stabilise the nourished beach in its lee. The double-arm structure was originally constructed in 1999-2000 from sand-filled geotextile containers of 150 tonnes to 300 tonnes. The geotextile containers were filled (Figure 5.7a) and dropped in place (Figure 5.7b) using a split hull hopper dredger. The sand-filled geotextile containers were often placed in a 1-3-2 order, with container 2 tending to settle into the gap between containers 1 and 3. Slight slumping of the container after placement results in improved packing of the containers.

Post-construction monitoring has demonstrated the need for subsequent construction in:

- topping up after storm events that caused expected large changes to the seabed due to on-offshore storm bar migration
- replacing damaged and failed trial urethane coated containers with new composite geotextile containers
- modifying the shape (Jackson *et al*, 2005).




Figures 5.7 *Filling (a) and placing (b) geotextile containers during construction of the Narrowneck multi-functional artificial reef, Australia* (courtesy International Coastal Management)

# 6 Multi-functional artificial reefs in the UK – opportunities and constraints

## 6.1 INTRODUCTION

This section identifies and describes the key opportunities and constraints associated with multi-functional artificial reefs in the UK with respect to:

- coastal defence planning
- coastal defence policy
- economic evaluation and funding
- structures, designs and materials
- health and safety.

## 6.2 COASTAL DEFENCE PLANNING

Multi-functional artificial reefs that include a coastal defence function are subject to the same opportunities and constraints as other coastal defence structures under the UK's planning system and the associated legislation. The following paragraphs summarise the potential permission, consent and licence requirements and environmental impact assessment (EIA) requirements for coastal defence structures. The following information is not exhaustive, is subject to future change (eg see Box 6.1) and should not be used as formal legal advice.

### 6.2.1 Permissions, consents and licences

The following paragraphs identify the principal legislation that relates to coastal defences and the permissions, consents and licences required to be in place prior to construction. The legislation may be applied and administered differently in England, Wales, Scotland and Northern Ireland.

Section 34 of the Coast Protection Act 1949 (as amended) concerns activities that may be detrimental to the safety of navigation and requires that consent be given for the following activities taking place below mean low water springs in the UK's territorial waters:

- construction, alteration or improvement of any works on, under or above any part of the seabed
- deposition of any object or materials
- removal of any object or materials.

Under the Coast Protection Act, coastal defence structures in the form of artificial reefs are likely to require consent since they typically involve one or more of the relevant activities affecting the seabed.

The Food and Environment Protection Act 1985 (Part II) is in place to protect the marine ecosystem and human health, and to minimise interference and nuisance to other users of the sea and seabed. Under the Food and Environment Protection Act 1985, construction works require licences for the placement of materials on the seabed below mean high water on spring tides, and this is likely to include placing materials on the seabed to construct coastal defences including artificial reefs.

Other legislation may come into force if a coastal defence scheme includes structures or construction above mean low water on spring tides (eg beach nourishment). For example, the Town and Country Planning Act 1989 (as amended) requires planning permission for certain types of development on land above mean low water on spring tides.

Box 6.1 *Proposed changes to marine licensing in the UK*

*A sea change – a Marine Bill White Paper* (Defra, 2007) proposes a strategic marine planning system including reforms to the existing marine licensing regime that would consolidate procedures under the Coast Protection Act and the Food and Environment Protection Act. The proposed reforms could deliver a one project: one licence approach to licensing new development in the marine environment. Accordingly, developers would make one application to one authority resulting in one decision for one licence.

The Crown Estate owns the majority of the UK's seabed as far as the 12-mile territorial limit. Various activities require consent from the Crown Estate including coastal defence works. Accordingly, coastal defence works such as artificial reefs are likely to require consent if they take place on the seabed owned by the Crown Estate. In this respect, the Crown Estate acts as a landowner and not as a regulator.

### 6.2.2 Environmental impact assessment

EIA is a process by which information about the likely environmental effects of certain projects is collected, assessed and taken into account both by the project proponent, as part of project design, and by the regulating authority in deciding whether a permission, consent or licence should be given. EIA is required to support applications for projects listed in Annexes I and II of European Council (EC) Directive 85/337/EEC (as amended by 97/11/EC) on the assessment of the effects of certain public and private projects on the environment (the EIA Directive).

Artificial reefs (including multi-functional artificial reefs) are not specifically listed in either Annex I or Annex II of the EIA Directive. However, Annex II, 10(k) of the EIA Directive on infrastructure projects includes coastal work to combat erosion and maritime works capable of altering the coast through the construction, for example, of dykes, moles, jetties and other sea defence works, excluding the maintenance and reconstruction of such works. Accordingly, a multi-functional artificial reef proposed with a coastal defence function is likely to qualify as an Annex II project.

EIA is not mandatory for projects listed under Annex II of the EIA Directive. Instead, the requirement for EIA is discretionary and, in the UK, is subject to a screening determination by the relevant authority. Screening is undertaken to determine whether an artificial reef is likely to affect a sensitive area (eg a designated site), meet applicable thresholds/criteria under UK guidance and have significant environmental effects. These aspects will depend on the particular characteristics of an artificial reef and its relation to the local environmental conditions (Challinor, 2003). A screening decision may also depend on whether an artificial reef forms part of a larger project for coastal defence. For example, the proposed multi-functional artificial reef at Borth in west Wales is one of many coastal defence structures required to protect several kilometres of frontage at risk from flooding.

The EIA Directive is transposed into UK legislation through various Regulations (and their subsequent amendments)[1] that relate to the Acts identified in Section 6.2.1, including:

1. Marine Works (Environmental Impact Assessment) Regulations 2007 for the Coast Protection Act and the Food and Environment Protection Act 1985.
2. Town and Country Planning (Environmental Impact Assessment) (England and Wales) Regulations 1999 (as amended) for the Town and Country Planning Act.

Where EIA is required, it is necessary for permission, consent and licence applications to be accompanied by an environment statement. An environmental statement should contain information that provides a systematic and objective account of the significant environmental effects to which a project is likely to give rise (ODPM, 2000). For example, the potential effects associated with multi-functional artificial reefs may be positive if coastal stabilisation protects coastal and high inter-tidal historic assets, but may be negative if damage occurs to submerged land surfaces, sediment (including peat) outcrops or fixed archaeological features (pers. comm. P Murphy, English Heritage).

### 6.2.3 Other regulations

EC Directive 92/43/EC on the conservation of natural habitats and wild flora and fauna (the Habitats Directive) is in place to maintain biodiversity of certain habitats and species through a network of protected areas (ie special areas of conservation (SACs) and special protection areas (SPAs)) known as Natura 2000 sites. The Habitats Directive introduces the precautionary principle such that a project can only be permitted where it is determined – through appropriate assessment – that it would cause no adverse effect on the integrity of a site. Accordingly, artificial reefs with the potential to adversely affect either a SAC or SPA will be subject to appropriate assessment and – depending on the effect – mitigation or compensation may be required.

From 2009, the Water Framework Directive requires that all structures to be placed in transitional and coastal waters will have to be assessed for their potential impacts on the status of the water body. Government agencies are currently developing a screening tool to assist in this process (pers. comm., C Vivian, Cefas).

## 6.3 COASTAL DEFENCE POLICY

### 6.3.1 Flood and coastal risk management

*Flood and coastal defence project appraisal guidance: overview* (MAFF, 2001) states that the UK Government's flood and coastal defence policy is "to reduce risks to people and the developed and natural environment from flooding and coastal erosion by encouraging the provision of technically, environmentally and economically sound and sustainable defence measures". This reference also provides a checklist "of aspects which may need to be considered if sustainability issues are to be addressed fully", which includes:

- "preserving and enhancing the environment…[for example]…ensuring all actions are environmentally neutral or positive, and contribute to biodiversity and other environmental targets

**Note**

1 Different regulations may apply in England, Wales, Scotland and Northern Ireland.

- using resources efficiently…[for example]…minimising the use of construction materials (especially where these are not renewable)
- ensuring design, operation and maintenance processes are efficient and flexible to long-term needs…[for example]…designing with a whole-life approach – including adaptability to natural processes, climate change impacts and other factors…designed with a dual or multipurpose functionality – eg sea wall with promenade or offshore reef providing fisheries habitat or the provision of a walkway along a river floodbank (efficient use of resources)."

Flood and coastal defence project appraisal guidance: environmental appraisal, MAFF (2000a) reiterates the strategic approach required to take account of long-term sustainability and states "ideally, a new defence scheme should be of overall benefit to people, with no significant detrimental effect on the environment, and should maximise any opportunities to contribute to biodiversity targets. This will not always be possible for individual schemes, but should be a key objective at the strategic level, in relation to both short- and long-term timescales. The overall aim of a more sustainable approach is to reduce long-term costs associated with the management of defences, particularly through mitigating against significant future adverse effects which could result from present day ill-advised or short-sighted management decisions."

Sustainability is also covered by national policy documents concerning flood risk including those relevant in England (The Stationery Office, 2006), Wales (Welsh Assembly Government, 2004) and Scotland (the Scottish Government, 2004). For example, the Scottish Office's planning policy concerning the environment states "flood prevention and alleviation measures should not lead to a deterioration in the ecological status of the watercourse or body and may provide opportunities for habitat enhancement or creation" (the Scottish Government, 2004).

Multi-functional artificial reefs provide a clear opportunity to develop sustainable coastal defence in accordance with the generic and specific flood and coastal defence project appraisal guidance, although opportunity for adding habitat and amenity functions needs to be considered against other sustainability issues, such as efficient use of (non-renewable) resources.

*Making space for water* (Defra, 2004a) is the UK Government's 20-year strategy to implement a more holistic approach to managing flood and coastal erosion risks in England.[2] The approach involves taking account of all sources of flooding, embedding flood and coastal risk management across a range of government policies, and reflecting other relevant government policies in the policies and operations of flood and coastal erosion risk management. The aim will be to manage risks by employing an integrated portfolio of approaches which reflect both national and local priorities, so as to:

- reduce the threat to people and their property
- deliver the greatest environmental, social and economic benefit, consistent with the government's sustainable development principles.

Specifically on coastal issues, *Making space for water* notes that the government will develop a more strategic and integrated approach to managing coastal flooding and erosion risks, so it provides a potential opportunity for the delivery of multi-functional artificial reefs since they have the ability to deliver sustainable environmental, social and economic benefits.

**Note**

2 A similar review is being undertaken in Wales.

Defra introduced a new set of high level targets (HLTs) for flood and coastal erosion risk management to take effect from 1 April 2005. These HLTs are not statutory requirements but are important to the delivery of UK government policy. The primary aim of the HLTs is to ensure delivery of Defra's stated policy aim for flood and coastal erosion risk management by operating authorities.

Not all HLTs are relevant to multi-functional artificial reefs. However, multi-functional artificial reefs that include a dedicated habitat function could contribute to HLT 4 (formerly HLT 9) concerning biodiversity in England and requires creation of at least 200 hectares of new biodiversity habitat per annum as a result of flood management activities (of which at least 100 hectares should be saltmarsh or mudflat). Target 4D(ii) monitors losses and gains to BAP habitats resulting from all Environment Agency flood risk management (FRM) works. The latest results (Environment Agency, 2007) show that 195.5 ha of net gain of BAP habitat was achieved in England in 2006. However, little gain was achieved for BAP habitat in the marine environment (ie only 14 ha of coastal saltmarsh and 0.1 ha of mudflat). No reference is made to the creation of inshore sublittoral habitats such as inshore sublittoral rock, which is identified as a broad habitat under the UK BAP. However, the UK BAP habitat statement for inshore sublittoral rock does not identify a habitat creation or enhancement direction for future biodiversity conservation.

### 6.3.2 Shoreline and coastal zone management

In England and Wales shoreline management plans (SMPs) have been in operation for over ten years. They form an important element of Defra's policy by highlighting issues such as the importance of coastal processes and defining strategies for the entire coast with respect to future management options.

Since the first plans, valuable lessons have been learnt and guidance has been issued for the updating of these plans (SMP2). Following several pilot projects the second round of shoreline management plans are now being prepared. These plans both update the previous studies and link together with statutory planning objectives. In the SMP2 guidance more emphasis is placed on creating a sustainable coastline by balancing the future pressures of climate change with economic, social and environmental objectives.

SMPs provide an opportunity for the consideration of multi-functional artificial reefs; indeed the guidance makes reference to the creation of habitats and the provision of tourism and amenity as opportunities in the selection of shoreline management policies. The guidance does not, however, expand upon the potential for multi-functional artificial reefs to provide a dual role in delivering policy objectives. The challenge is for the SMP authors and the operating authorities working to the plans to identify these opportunities.

In 2002 the member states of the European Union adopted a recommendation to undertake and implement integrated coastal zone management (ICZM) in Europe. The objective of ICZM, as noted on Defra's website, is to establish sustainable levels of economic and social activity in coastal areas while protecting the coastal environment. It brings together all those involved in the development, management and use of the coast within a framework that facilitates the integration of their interests and responsibilities.

As with the SMPs, ICZM provides an opportunity for multi-functional artificial reefs to be considered at an early stage of shoreline management planning. Successful integrated coastal zone management may involve adopting the following principles:

- a long-term view
- a broad holistic approach
- adaptive management
- working with natural processes
- support and involvement of all relevant administrative bodies
- use of a combination of instruments
- participatory planning
- reflecting local characteristics.

## 6.4 FUNDING AND ECONOMIC EVALUATION

### 6.4.1 Funding overview

The following sections have been written with reference to some policies and procedures which are only directly relevant to England. This scoping study recognises that there are differences in policy and procedures in Northern Ireland, Scotland and Wales but notes that the four countries' approaches to funding and justification are broadly similar.

In England, Defra has policy responsibility for coastal erosion and flood management and provides the majority of the funding works. The responsibility for delivering schemes currently rests with the Environment Agency and local authorities in relation to flood defence issues, and with local authorities in relation to coastal erosion issues.

Funding for coast protection works relate to the Coast Protection Act 1949. This Act recognised the role of central government in protecting the coast and the national importance of assets at risk from flooding and erosion. Arising from the Act was a mechanism for local authorities (coast protection authorities) to obtain financial assistance in the delivery of protection works. Until 2006, operating authorities received a percentage of the cost of scheme delivery centrally, with the remainder raised locally. It is now the case that authorities receive 100 per cent assistance in the eligible costs of scheme delivery, subject to meeting various priorities and planning criteria.

Given their funding and delivery roles, Defra and the Environment Agency are interested in opportunities to reduce the costs of coastal defence structures. For example, research such as *Low cost rock structures for beach control and coast protection* (HR Wallingford, 2003) identifies measures to reduce costs including fewer materials and more efficient construction. These measures are likely to be in contrast to the additional materials and more complex construction required by multi-functional artificial reefs.

Since the emphasis of the Act is in the protection of assets at risk, national assistance in the delivery of the environmental, social and economic benefits that can be derived through adding habitat and amenity functions is not a primary objective. The Act neither precludes nor accommodates incorporating habitat and amenity into coast protection schemes, which means that alternative justification and funding is often needed for adding functions that do not directly contribute to coast protection.

Recent changes in government policy and the roles and responsibilities of organisations in managing the coast, particularly in relation to long-term sustainability, are resulting in opportunities for more innovative ways of managing risk, including opportunities for multi-functional artificial reefs. Nevertheless, the additional cost of habitat improvement or amenity provision over the cost of a standard coastal defence structure is a key constraint to developing multi-functional artificial reefs.

### 6.4.2 Scheme assessment and prioritisation

The primary driver for a coast protection schemes is the reduction of risks associated with assets and a well tested and widely used framework is in place for assessing the needs and options of individual schemes. *Flood and coastal defence project appraisal guidance notes 1 to 6* (FCDPAG 1-6) (eg MAFF, 2000a, 2000b and 2001) give guidance on the appraisal of flood and coastal defences schemes. Along with supplementary notes updating the guidance (eg the latest understanding and use of climate change forecasts) and companion guides (eg Penning-Rowsell *et al*, 2003), it is possible to systematically and consistently appraise schemes. Benefit cost assessment approaches and tools are becoming more standardised. This allows an objective assessment of an individual scheme's benefits and facilitates comparison between schemes in different areas of the country.

With a standardised system of appraising schemes Defra implemented a priority score system in order to prioritise national funds. The priority score is based on three key factors: economics, social and environment. The priority scores of potential schemes across the country are collated and a threshold set each year in order to prioritise the most needed schemes. The priority score system is recognised as having a number of shortfalls including being disproportionately weighed toward economic benefit cost ratios, which is a potential constraint in relation to coastal defence schemes incorporating multi-functional artificial reefs.

In line with *Making space for water* (Defra, 2004a) and the UK Government's commitment to better address social and environmental objectives, there is now a commitment to change the way schemes are prioritised nationally. In March 2007 Defra held a stakeholder event for the consultation on outcome measures and prioritisation approaches for flood and coastal erosion risk management. Although still being developed it is thought that outcome measures will become a better tool for scheme prioritisation that contain environmental, social or amenity benefits.

### 6.4.3 Funding

In order to deliver a multi-functional reef project it is likely that additional funding will be required over that provided at a national level for coastal defence. While the funding process for coastal defence schemes is well defined, additional sources of funding to deliver the added amenity, social or environmental benefits of a multi-functional artificial reef is less well understood. This lack of knowledge presents a potential constraint as it is perceived as difficult and time consuming to obtain co-funding for projects.

*Making space for water* (Defra, 2004a) identifies the opportunity that co-funding presents and a number of Defra research initiatives are underway to highlight co-funding opportunities and mechanisms. A non-exhaustive list of potential co-funding opportunities includes:

- private investment and contributions
- direct developers' funding
- direct local authority investment
- Town and Country Planning Act Section 106 agreements (developer contributions)

- regeneration funding (such as from regional development agencies)
- European regional development funds (eg structure funds)
- fisheries grants
- lottery funding.

A particular funding issue is that of separating coastal defence and other functions. Accordingly, the mechanisms for delivering co-funded schemes – where risks such as cost over-runs, future maintenance responsibility and costs are complex – often require innovative approaches to justification and procurement.

## 6.5 STRUCTURES, DESIGNS AND MATERIALS

### 6.5.1 Structures

As noted in previous sections, there is a diverse range of breakwater structures that can be classed as artificial reefs but it is important to note that the requirements of these structures in terms of coastal defence (for this scoping study) are limited to four main functions:

1. Reducing wave energy along a foreshore by creating a structure that either prevents wave energy reaching the foreshore or more typically reduces wave energy by forcing waves to break offshore.
2. Promoting sediment accretion to reduce erosion risk and absorb wave energy.
3. Retaining imported beach material to reduce erosion risk and absorb wave energy.
4. Refracting wave energy away from high risk areas.

#### Coastal defence and marine habitat

In simple opportunistic terms, the fact that an artificial reef provides hard substrate protruding from a predominantly flat, sedimentary seabed means that it may make a positive contribution to local marine habitat for ecological and fisheries benefit. In essence, a more complex habitat invariably leads to more biological diversity.

Box 6.2 ***Influence of an artificial reef's scale***

Scale can be a key constraint for artificial reef structures seeking to derive benefit, particularly for commercial fisheries. An artificial reef's benefit to a commercial fishery will depend on its size. Currently, there is a lack of evidence about the efficacy of artificial reefs because the size of experimental structures is too small (Jensen *et al*, 2000). Japanese experience indicates that an artificial reef is ineffective for commercial fishing if its volume is less than 2500 $m^3$ and, in fact, most Japanese artificial reefs have volumes of c50 000 $m^3$ (Simard, 1995). The UK's detached breakwaters are of a size somewhere in between those identified by Simard (1995). For example, the Newbiggin structure comprises 22 000 $m^3$ of core material, 3600 $m^3$ of toe material and 1230 pre-cast concrete armour units. However, larger volumes are provided by series of detached breakwaters, such as at Happisburgh and Elmer. The scale of a series of structures can be enhanced by placing additional hard substrate on the seabed in the gaps between the structures.

#### Coastal defence and amenity

Fundamental differences between the principal structures for coastal defence (ie detached breakwaters) and recreational sea angling and diving (ie sunken vessels) are a key constraint to combining functions. However, most recreational sea angling and diving benefits from the presence of marine life, so it is suggested that the principles applied to structures combining coastal defence with marine habitat also be applied through design to combining coastal defence with recreational sea angling and diving.

In contrast, fundamental similarities between the principal structures for coastal defence and surfing are a key opportunity for combining functions through design, as shown by existing multi-functional artificial reefs (eg Narrowneck, Australia, Case study 5.2) and proposed multi-functional artificial reefs (eg Borth, Wales, Chapter 7).

### 6.5.2 Designs

With coast protection as the primary driver in designing an artificial reef there are numerous design issues that need to be considered. The key technical factors in the choice of, and suitability for, offshore structures are normally only decided after assessing the following:

- existing wave climate (to determine reef suitability and construction materials)
- seabed condition (to assess capacity for additional structure loads)
- water depth ( to assess structure type)
- normal tidal range and extreme water levels (to assess the height of the structure)
- existing sediment transport regime
- availability of materials
- potential secondary impacts through wave reflection or transformation
- potential secondary impacts though changing the existing sediment transport regime.

#### Coastal defence and marine habitat

The current level of knowledge suggests that although a standard design for a coastal defence structure provides habitat that generates incidental biodiversity, a modified design can provide a more complex habitat that generates higher biodiversity with potential benefits for ecology and/or fisheries. With the right level of biological knowledge, it is possible that a design can be modified for a target habitat or species.

#### Coastal defence and amenity

Since most recreational sea angling and diving benefits from the presence of marine life, it is suggested that these amenities could benefit from designs incorporating more complex marine habitat.

While there are some similarities between artificial reefs for coastal defence and surfing (eg both break waves), combining these functions is not straightforward and requires detailed investigation in order to achieve both satisfactorily. An understanding of the design requirements for generating surfing waves is fundamental to creating a multi-functional artificial reef of this nature.

### 6.5.3 Materials

Traditional materials in the construction of artificial reefs for coastal defence are quarried rock and specifically designed concrete units. These are generally preferred as they are durable, easy to place and can be placed at relatively steep angles to reduce the structure's size and footprint. The most exposed locations of the structures usually contain the largest rock and block sizes, with less exposed and buried areas containing smaller and cheaper material. Exposed faces are usually porous as this allows for a degree of wave absorption. The cost of rock and concrete is high and is often a factor in adopting other defence methods (eg beach nourishment and groynes).

Alternative construction materials include sand filled geotextile containers and materials of opportunity, such as tyre bales. Durability is a key issue in the selection of construction materials and this often precludes some of the lower initial cost materials. The planning requirements (eg under the Food and Environment Protection Act) and use of waste is also a key consideration in choosing construction materials.

### Coastal defence and marine habitat

Rock and concrete materials are typically used to construct coastal defence structures. These materials can provide hard substrate in various shapes and sizes with positive ecological benefits, including benefits for biodiversity and target species. Accordingly, they appear to be suitable for combining coastal defence and marine habitat functions. As for designs, the current level of knowledge suggests that although the standard rock and concrete materials in coastal defence can provide marine habitat that generates incidental biodiversity, a modified specification can provide a more complex habitat that generates higher biodiversity and accommodates target species. For example, materials modifications to increase habitat complexity may include:

- replacing materials of one or two sizes with a range of sizes across the structure
- replacing smooth surfaced materials with rough surfaced materials.

Sand filled geotextile containers are also used to construct coastal defence structures but less is known about their ecological benefits. Further information is necessary to demonstrate that these materials can provide positive ecological benefits and are suitable for combining coastal defence and marine habitat functions.

HR Wallingford's (2005) research into the use of tyres reports that colonisation of tyres is similar to colonisation of concrete, indicating that they can provide positive ecological benefit when used as materials to construct artificial reefs for this purpose. However, this research also reports that tyre bales are unsuitable for use as primary armour materials where they are subject to wave action. Accordingly, tyres and tyre bales appear to be unsuitable for combining coastal defence and marine habitat functions. In addition, it can be assumed that the use of tyres and other materials of opportunity will be constrained by legislation which restricts the placement of waste materials on the seabed.

### Coastal defence and amenity

As for structures, there are fundamental differences between the principal materials used in coastal defences (ie rock, pre-cast concrete armour units) and the materials used to provide artificial reefs for recreational sea angling and diving (ie materials of opportunity).

Rock is used to construct coastal defence structures and has been used to construct artificial surfing reefs. Sand filled geotextile containers are already used to construct multi-functional artificial reefs that combine coastal defence and surfing amenity functions.

Materials of opportunity, notably sunken vessels and possibly other large decommissioned structures (eg oil platforms) are likely to be less compatible for coastal defence and amenity functions.

## 6.6 HEALTH AND SAFETY

### 6.6.1 Background

Health and safety is a key consideration for the construction of new projects including multi-functional artificial reefs. The following sections outline some of the health and safety issues associated with multi-functional artificial reefs, although similar issues may arise with coastal defence structures or artificial reefs with one function.

### 6.6.2 Intended and unintended uses

Artificial reefs are used by various interest groups and individuals including professionals (eg researchers, commercial fishermen), formal and informal recreation sectors (eg sea anglers, divers, surfers, bathers) and the public (eg beach visitors). Artificial reefs are designed for a target audience. The Loch Linnhe artificial reef (Chapter 3) is used by researchers because it has a research programme concerned with the design, impacts and productivity of artificial reefs in relation to benefits for fisheries and biodiversity.

Sometimes artificial reefs are not used for their intended function. For example, Jackson *et al* (2005) note that Narrowneck artificial reef has become popular for amenity including sea angling, spear fishing, diving and snorkelling from the beach, although its intended amenity function is for surfing. In addition, coastal structures are not always used for their intended function. For example, coastal defence structures are used for activities such as commercial fishing and recreational sea angling (eg Halcrow Maritime *et al*, 1998) and personal harvesting of shellfish (eg Airoldi *et al*, 2005).

### 6.6.3 Risks to water users

The following paragraphs highlight some of the health and safety risks to water users (eg surfers, swimmers, divers, bathers, anglers) relating to the intended and unintended uses of multi-functional artificial reefs.

Corbett *et al* (2005) identify three risks associated with physical interactions between water users and an artificial reef's structure:

1. The first risk is associated with surfers impacting with structures when diving or falling off their boards, noting the water depth above the crest (ie where the wave breaks) to be the key safety factor in this respect, such that crest height can become an important design consideration. For example, the Narrowneck multi-functional artificial reef was originally designed with a crest height of only 0.5 m below low water to optimise surfing for very experienced surfers, however, the safety risk was considered too high and the crest level was lowered to 1.5 m below low water level but still provides improved surfing condition and hosts surf events (Jackson *et al*, 2002).
2. The second risk is associated with surfers and other water users impacting with structures when caught in turbulent water, particularly breaking waves, noting that the greatest risk "generally corresponds to the largest wave to break on or very near the crest of the structure" (Corbett *et al*, 2005).
3. The third risk is associated with surfers and other water users becoming trapped underwater (and potentially drowning) due to gaps between materials used to construct an artificial reef's structure, noting that the size and shape of gaps associated with large sand-filled geotextile containers generally pose a minor risk. This risk also applies to and could be greater with other construction materials. For

example, *The rock manual* (CIRIA/CUR/CETMEF, 2007) notes that the risks associated with rock structures include trapping in voids and injuries associated with unstable materials. In addition, where decommissioned vessels are used to create artificial reefs for recreational diving they tend to undergo preparations to reduce trapping hazards (eg removing doors, widening accesses, sealing entrances to restrictive compartments).

*The Beach management manual* (CIRIA, 1996) identifies that rip currents can occur around breakwaters in certain tidal conditions. Corbett *et al* (2005) identify the risk associated with water users becoming caught in rip currents (and potentially drowning) and note that the flow of water over submerged artificial reefs can create rip currents in the lee of these structures. The feasibility study for an artificial surfing reef at Newquay (ASR Ltd, 2002) predicts rip currents around the artificial reef to be similar to naturally occurring rip currents at the beaches, but predicts that rip currents east of the artificial reef may be exacerbated if flows are compressed. Measures to reduce this risk include either moving the structure seawards or reducing the length of the artificial reef's left arm, which can be addressed by detailed design.

Corbett *et al* (2005) also identify other risks including conflict between water users, noting that the potential for conflict between user groups is minimised by the relative needs of the user groups (eg recreational sea anglers (with vessels) and divers prefer calm sea conditions while surfers prefer conditions when waves break).

### 6.6.4 Risks to navigation

Multi-functional artificial reefs are unlikely to have a navigation function but intended and unintended uses can involve navigation. Intended uses may require the use of a vessel to either conduct a use (eg research, commercial fishing, recreational sea angling) or to provide access for a use (eg diving). Principal risks to navigation include vessel collision, grounding and/or capsizing, and the associated risks to human health and safety, and are unlikely to be significantly different from the risks associated with other coastal defence structures and artificial reefs. For example, Corbett *et al* (2005) note that vessels anchored at artificial reefs "are vulnerable to the passage of larger waves that are substantially increased in height over a small distance due to shoaling over the reef, capsizing the vessel".

In addition, a multi-functional artificial reef may affect navigation by interfering with the safe passage of commercial and recreational vessels. For example, concerns raised against the proposed Newquay artificial surfing reef concern the risk it may pose to the safe access and egress of Newquay harbour, to vessels grounding or being swamped by waves, and to interference with the local rowing course for pilot gigs (traditional Cornish six-oared rowing boats) – although waves are predicted to break some 100 m away from the course (ASR Ltd, 2002).

### 6.6.5 Construction design and management

It is possible that some of the risks associated with multi-functional artificial reefs may be relevant to the requirements of the amended *Construction (Design and Management) Regulations 2007* (CDM 2007), which integrates health and safety into the planning and management of construction projects from design concept onwards. Further information is provided in the Health and Safety Executive's Approved Code of Practice for CDM 2007, *Managing health and safety in construction* (HSE, 2007). More information concerning the construction of structures in the coastal and marine environment is given in CIRIA/CUR/CETMEF (2007).

# 7 Multi-functional artificial reefs in the UK – Borth case study

## 7.1 INTRODUCTION

This chapter provides a case study for the proposed multi-functional artificial reef at Borth, west Wales. The multi-functional artificial reef forms part of the proposed preferred option for a larger coastal defence project for the Borth frontage.

Arguably, this is the UK's first truly multi-functional artificial reef in terms of the definitions used for this scoping study, because it is purposefully intended to deliver a coastal defence function (ie beach protection) and an amenity function (ie surfing), and will be designed, managed and funded accordingly. This case study is used to illustrate how a multi-functional artificial reef can be developed in the UK in relation to the headline opportunities and constraints identified in Chapter 6.

Information for this chapter is provided by a series of study outputs concerning future coastal defences at Borth (Royal Haskoning, 2001, 2004 and 2006, and ASR Ltd, 2003 and 2006). At present, the proposed preferred option is undergoing further refinement and outline design.

## 7.2 BORTH MULTI-FUNCTIONAL ARTIFICIAL REEF

### 7.2.1 Project background

Borth is situated at the centre of Cardigan Bay in west Wales. Its frontage (Figure 7.1a) consists of a gently sloping sandy beach with shingle and cobbles at high water mark and at the crest of the beach. The steep shingle bank along the back of most of the beach forms the principal defence line. The shingle is currently held in place with timber groynes (Figure 7.1b). The existing coastal defences are fast approaching the end of their effective life. It is predicted that the entire Borth frontage and the assets behind it would be lost within about 20 years due to progressive deterioration of the structures and loss of the shingle bank (Royal Haskoning, 2006). So Ceredigion County Council – the coast protection authority – is planning a new scheme to provide flood protection and prevent coastal erosion.


(a) (b)

Figures 7.1 *Borth's frontage (a) and timber groynes (b)* (courtesy Royal Haskoning)

Being conscious of the important interrelation between the village and the sea, Ceredigion County Council is looking for opportunities to enhance the amenity and recreational value of the beach and the village environment. The Borth coastal study (Royal Haskoning, 2001) initially identified a preferred option including recharging of the shingle bank in front of Borth village and controlling this through the use of rock structures. In addition, it recommended examination of further economic, amenity and environmental enhancement of the area, including consideration of ways to improve water and beach use in the southern part of the frontage. Members of the local community contributed to discussions about the inclusion of an artificial reef in order to improve surfing conditions at Borth. Subsequent studies by ASR Ltd (2003) and Royal Haskoning (2004 and 2006) recommended a preferred option comprising construction of rock breakwaters, an offshore artificial reef and beach nourishment (Figures 7.2 and 7.3).

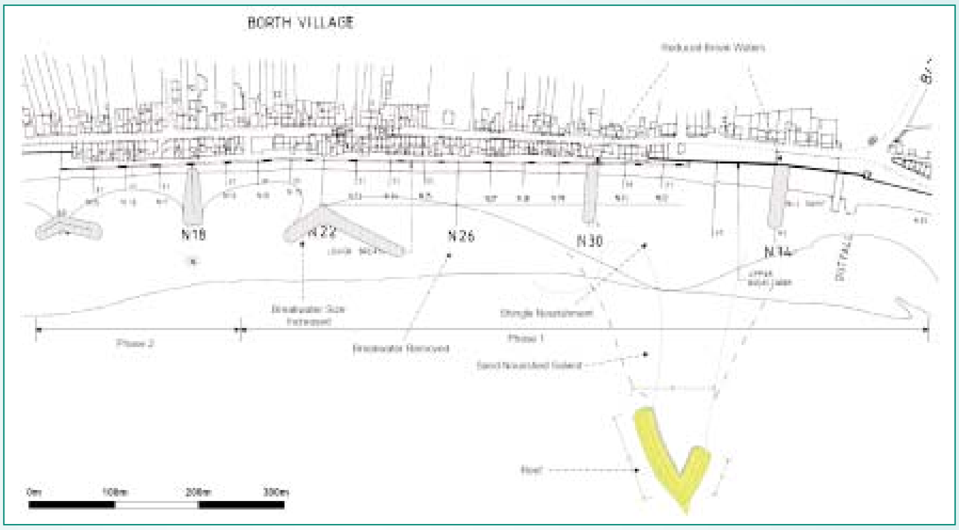



**Figure 7.2** *Preferred option for Borth coastal defences* (courtesy of Ceredigion County Council)

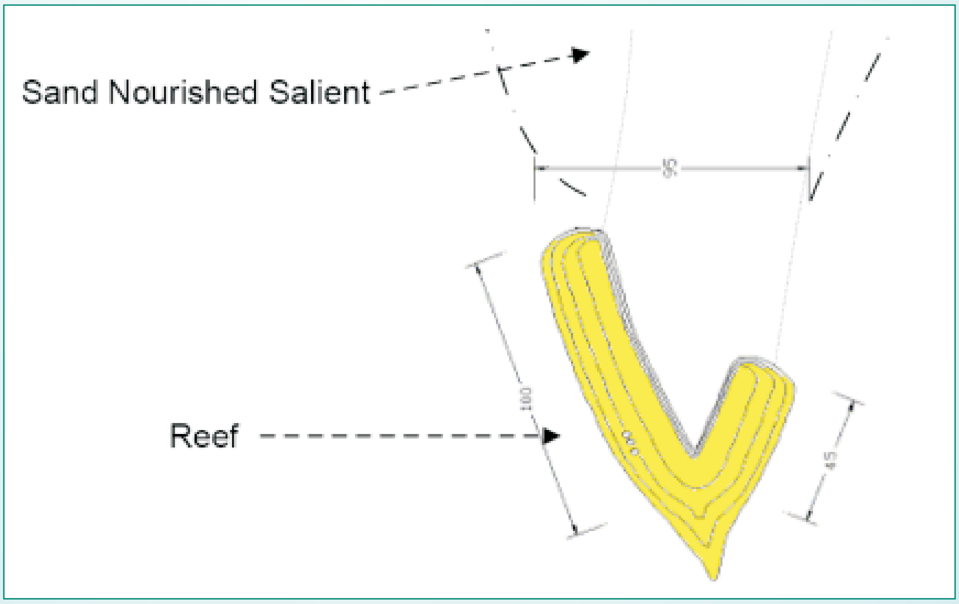



**Figure 7.3** *Borth multi-functional artificial reef dimensions* (courtesy of Ceredigion County Council)

## 7.2.2 The multi-functional artificial reef

Detailed investigations (ASR Ltd, 2003) show that it is practical to construct an artificial reef approximately 400 m offshore at the southern end of the Borth frontage (Figure 7.2). The long-shore and cross-shore position of the artificial reef is based on various studies that recommend a location close to the south end of the beach between existing timber groynes.

The optimum arrangement for the artificial reef is identified in Table 7.1 and shown in Figure 7.4. It comprises a double-arm structure with a northern arm giving a left-hand surfing wave and a shorter southern arm giving a right-hand surfing wave (Figure 7.4). Between the two arms, the seaward tip is the artificial reef's wave focusing component (Figure 7.4), which locally increases wave height to create a take-off zone for surfers (ASR Ltd, 2003). The artificial reef's crest level is set at 1.5 m above chart datum.

**Table 7.1** *Borth artificial reef characteristics*

| | Northern arm | Southern arm | Total / average |
|---|---|---|---|
| Gradients | 1:20 to 1:17 | 1:20 to 1:17 | n/a |
| Surface area ($m^2$) | 3100 | 1300 | 4400 |
| Volume ($m^3$) | 6900 | 3100 | 10 000 |
| Long axis (max.) (m) | 100 | 45 | 125 (across shore) |
| Width (max.) (m) | 25 | 25 | 95 (along shore) |
| Distance offshore* (m) | n/a | n/a | 380 |
| Depth of offshore toe (m) | n/a | n/a | 2.8 |

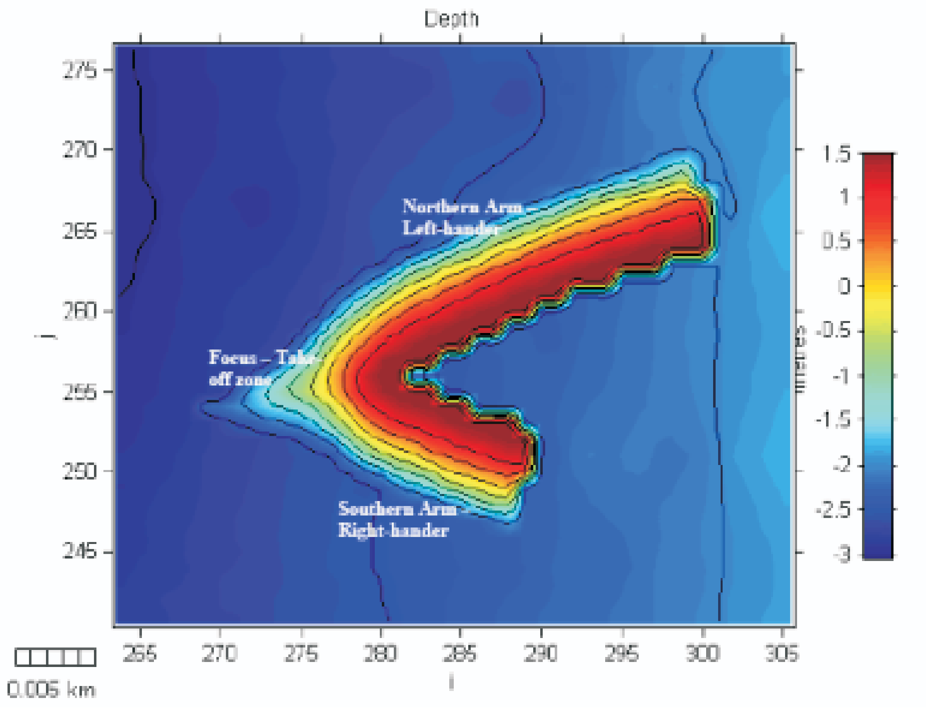



**Figure 7.4** *Borth multi-functional artificial reef components* (courtesy ASR Ltd)

### 7.2.3 Coast protection function

The artificial reef forms part of the preferred option for providing coastal defence to the Borth frontage. In combination with the construction of rock breakwaters, the artificial reef is predicted to control untoward movement of the shingle bank in the area of Borth village providing flood defence to a 1:100 year storm event standard. The length of coastline influenced by the artificial reef is approximately 300 m to 400 m. Within this zone, the artificial reef is predicted to provide a degree of coast protection but would not, by itself, give adequate coast protection during more extreme water level and wave events to the required flood defence standard. A sand and shingle salient is predicted to develop inshore of the artificial reef and to contribute to flood and coastal erosion protection. Sand and shingle nourishment is required to feed the anticipated salient formation (Royal Haskoning, 2004).

The proposed rock control structures' function is to limit the natural redistribution of the shingle away from the erosion zones, particularly during high energy storm events, by providing a physical obstruction that retains the nourished shingle beach material in crescent shaped bays. They also provide some physical defence to the extreme storm waves that would otherwise overtop the shingle bank and result in the flooding of Borth village. The artificial reef offsets the need for more rock structures, as shown by the alternative coastal defence option without the artificial reef (Figure 7.5) (Royal Haskoning, 2006). For example, the need for four fish-tail groynes is replaced by the artificial reef, a larger fish-tail groyne, two smaller breakwaters and some nourishment (Figure 7.2).

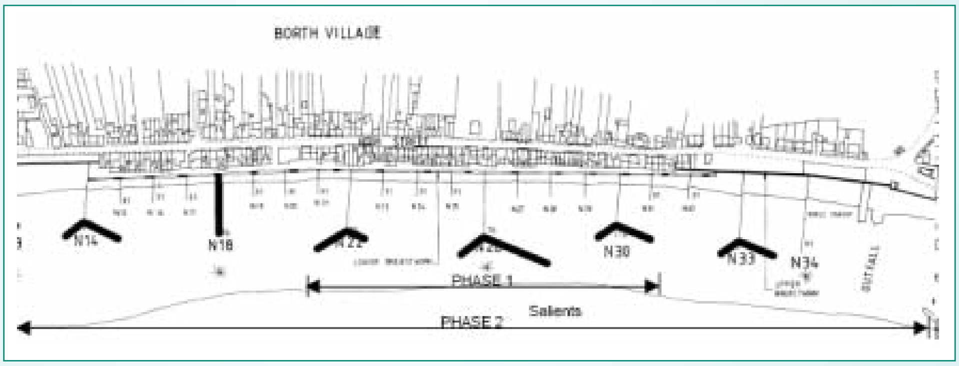



Figure 7.5 *Borth's coastal defence option without the artificial reef* (courtesy Ceredigion County Council)

### 7.2.4 Surfing function

ASR Ltd (2003) reported the following surfing characteristics based on the preliminary design of the artificial reef:

- surfing difficulty – equivalent to a difficulty rating of 3-6 based on the classification system of Hutt *et al* (2001), depending on the wave height and stage of the tide, giving a steep surfing wave to provide a challenging ride for intermediate surfers and to allow good surfers to complete powerful manoeuvres
- peel angles – averaging 60° on the left-hand breaking northern arm and 55º on the right-hand breaking southern arm, although in reality changes in the swell direction, wave height and phase of the tide result in a range of peel angles for each side of the artificial reef
- wave breaking intensity – medium/high to high and possibly very high to extreme at low tide based on the classification system of Mead and Black (2001), generally greater on the right-hand section of the reef and at lower phases of the tide

- wave height – increased by an average of 1.5 times by the focus (eg a 1 m high wave offshore is focused to 1.5 m at the take-off) and decreasing along the length of the arms to an average of 0.7 times and 0.78 times the wave height at the take-off at the inshore ends of the northern arm and southern arm respectively
- number of surfing days – increased by 36 per cent, from 95 to 129 days.

## 7.3 OPPORTUNITIES AND CONSTRAINTS

The following paragraphs provide examples of potential opportunities and constraints of multi-functional artificial reefs in the UK by applying the findings of study outputs concerning future coastal defences at Borth (Royal Haskoning, 2001, 2004 and 2006, and ASR Ltd, 2003 and 2006).

### 7.3.1 Coastal defence planning

The proposed coastal defence project including the multi-functional artificial reef requires planning permission under the Town and Country Planning Act, consent under the Coast Protection Act and a licence under the Food and Environmental Protection Act.

If the preferred coastal defence option is rejected at its planning stage, then at best the construction would be delayed during appeal and at worst would be unable to proceed. Consultation found that visual impact and changes in character or setting of the village are likely to be key factors in avoiding objections at the project's planning stage. Given these findings, to minimise the risk of project objection and subsequent refusal of planning consent, the preferred coastal defence option should not adversely impact on the character and setting of the village. Accordingly, the project's planning objective is to optimise the solution to ensure that it blends in with the existing setting and character of the area.

The multi-functional artificial reef offers the opportunity to reduce the scale and height of structures on the beach in front of the village and the associated potential visual impact of the coastal defence project. For example, with the crest height proposed by the preliminary design at 1.5 m above chart datum, ASR Ltd (2003) predict that the artificial reef is emerged for 14 per cent of the time: on spring tides it is 3.5 m below mean high water level and emerges by up to 0.8 m at mean low water level, while on neap tides it remains underwater. Because the artificial reef remains underwater on most states of the tide, it is much less visible if compared to the alternative option using rock structures (Figure 7.5).

### 7.3.2 Coastal defence policy

As the responsible bodies for the implementation of the UK government's coastal defence policy, the aim of both Defra and the National Assembly of Wales is to reduce risks to people and the developed and natural environment from flooding and coastal erosion by encouraging the provision of technically, environmentally and economically sound and sustainable defence measures.

Accordingly, the *Borth strategic appraisal* (Royal Haskoning, 2006) states the project's aim is to protect life, the public and property in a manner that is economically justified, environmentally sensitive and sustainable. This aim is maintained throughout the appraisal of the various options identified to deliver the preferred coastal defence option for Borth. Initially 11 options were identified including do nothing which were subject to multi-criteria analysis. Options were initially eliminated if unacceptable (in terms of the strategy's aims) and then eliminated on the basis of cost benefit. Three options (including the multi-functional artificial reef option) were found to provide a sustainable coastal defence strategy by virtue of:

1 Remaining flexible enough to accommodate the uncertainty of climate change and sea level rise.
2 Sustaining the weak but important supply of shingle to the north, without interfering with the more major sand movement system extending into the Dyfi Estuary.
3 Working within the broader aspirations for the development of the area and village by creating the opportunity for enhancement beyond that merely of coastal defence.

However, the coastal defence option incorporating the artificial reef is preferred at Borth because:

- it offers the most potential to enhance amenity and facilitate beach management due to the additional surfing function
- it reduces the scale of coastal defences in front of the village by offsetting the need for additional rock structures
- it best balances coastal defence requirements with environmental and socio-economic factors, based on consensus emerging from consultation.

Given the above benefits, the multi-functional artificial reef proposed at Borth appears to address the UK government's coastal defence policy concerning sustainable development (eg MAFF 2000a, 2000b and 2001) and a more holistic approach to risk management including delivery of the greatest environmental, social and economic benefit (eg Defra, 2004a).

### 7.3.3 Funding and economic evaluation

A key constraint to developing multi-functional artificial reefs is the additional costs over a standard coastal defence structure including:

- capital and maintenance works
- additional habitat or amenity functions.

The Borth project's economic objective is to adopt the most economically efficient approach to addressing the problems of the Borth frontage, taking into account the whole-life costs and impacts upon adjacent frontages. This approach uses a cost benefit analysis of potential options based on MAFF (2000b). It evaluates the potential damages arising from loss and/or flooding of Borth and nearby Ynyslas, and the land in between, and compares them with the potential cost of constructing and subsequently maintaining coastal defence structures to the whole frontage.

The *Borth strategic appraisal* (Royal Haskoning, 2006) reports that the capital cost of providing the multi-functional artificial reef does not differ significantly from the alternative option (Section 7.3.1) because it offsets the need for other coastal defence structures (Figure 7.5). However, the multi-functional artificial reef is predicted to incur larger maintenance costs, particularly due to uncertainty associated with the long-term performance (eg accidental or purposeful damage) of sand-filled geotextile containers (although there is scope for reducing future maintenance costs by using rock instead of sand-filled geotextile containers). The additional maintenance cost does not appear to significantly affect the overall cost benefit performance of Borth's coastal defence option, possibly because its cost effect is diluted by the costs and benefits given to the other structures included under this option. However, this may not be the case if a multi-functional artificial reef were compared to an alternative coastal defence structure on a like for like basis because costs and benefits are only assessed in relation to coastal defence.

**Box 7.1** *Borth multi-functional artificial reef co-funding opportunity*

In Wales, the Welsh Assembly Government (WAG) provides the majority of funding for coastal defence projects. For the Borth project, it is likely that WAG would provide funding for coastal defence only, and that other sources of funding would be required to cover the additional cost of providing amenity associated with the proposed multi-functional artificial reef.

The European Regional Development Fund (ERDF) is one alternative funding opportunity under consideration for providing amenity within the coastal defence project at Borth. The ERDF contributes towards the financing of investment in creating sustainable jobs, new infrastructure and measures which support regional and local development. The ERDF's objective is to help reinforce economic and social cohesion by redressing regional imbalances across the European Union.

Two regions within the UK are eligible for funding from the ERDF's structural funds under the convergence objective from 2007 to 2013: west Wales and the Valleys, and Cornwall and Isles of Scilly. Borth is situated within the west Wales and the Valleys region. The National Assembly for Wales is responsible for the structural funds programme in Wales and has set up the Welsh European Funding Office (WEFO) as a division of the Department of Enterprise, Innovation and Networks within WAG to take responsibility for the preparation of the programme and its focus and operation.

The programme comprises three priorities. Each priority has a set of themes. For example, ERDF priority 2 (*Creating an attractive business environment*), Theme 4 (*Tackling environmental risks to economic growth*) aims to tackle environmental barriers in economic development by supporting investment in infrastructure that will improve resource productivity and manage environmental risks and constraints. This will be achieved through adaptation measures and mitigation measures. One of the adaptation measures is to improve inland and coastal flood defence infrastructure.

This highlights the potential to co-fund projects and achieve multiple benefits. The mechanisms for delivering co-funded schemes where risks such as cost over-runs, future maintenance responsibility and costs are complex and often require innovative approaches to justification and procurement.

### 7.3.4 Structures, designs and materials

In terms of materials, the multi-functional artificial reef proposed at Borth could be constructed either from sand filled geotextile containers or from rock.

*Costs associated with the maintenance of a multi-purpose reef at Borth* (ASR Ltd, 2006) compared the costs of maintaining the artificial reef constructed from sand-filled geotextile containers and rock, and made the following conclusions:

- both sand-filled geotextile containers and rock are suitable materials for reef construction
- sand-filled geotextile containers are expected to survive the 50 year design life for the project in terms of degradation and instability, but are at risk of potential mechanical damage from floating debris or human activities such as vandalism, boat propellers and boat anchors
- rock is expected to survive the 50 year design life from the project and is at very little risk from mechanical damage
- ongoing maintenance costs are expected to be higher for the sand-filled geotextile containers.

While maintenance costs are expected to be lower if rock is used to construct the artificial reef, this is not the only factor concerning the choice of materials for a multi-functional artificial reef that incorporates a surfing function. At Borth, ASR Ltd (2006) suggests that it is necessary to use reasonably large rocks (4 tonnes to 7 tonnes) in order to ensure the stability of the artificial reef during storm events. With rock of this size, it is difficult to achieve the artificial reef's design tolerances concerning the surfing function. For example, an irregular crest would degrade the quality of the surfing wave during small wave conditions.

### 7.3.5 Health and safety

Different materials may result in different levels of risk associated with surfing over artificial reefs (eg impact and trapping, see Section 6.5). However, at present, the existing timber groynes at Borth are a significant hazard to surfers. The construction of the preferred option including both surfing amenity and rock structures (ie groynes) in close proximity also has health and safety implications which will need careful consideration during design. It may also be appropriate to identify advisory safe surfing tidal windows, when the risk of impact and trapping is less.

In addition, water recreation at Borth includes surfing, wind-surfing, swimming and the use of powered craft such as jet-skies. To avoid conflict and risks, it may be appropriate to develop beach zones for different recreational activities.

# 8 Scoping for the future

## 8.1 CURRENT SITUATION

### 8.1.1 Coastal defence planning

Planning legislation is in place to cover coastal defence development including multi-functional artificial reefs.

### 8.1.2 Coastal defence policy

There is plenty of policy and support through SMPs and ICZM concerning sustainable development, biodiversity and socio-economic benefits to encourage the intentional addition of habitat and amenity functions to coastal defence structures. However, it appears that operating authorities and the associated construction industry are either unaware of the policy and/or discouraged to apply it due to uncertainties concerning non-coastal defence functions – particularly design requirements, maintenance costs and funding options.

### 8.1.3 Funding and economic evaluation

Funding and economic evaluation (eg from Defra and the WAG) are perceived to be key constraints to the development of multi-functional artificial reefs because they only concern the coastal defence function. Therefore habitat and amenity functions need to be funded separately.

### 8.1.4 Structures, designs and materials

The knowledge necessary to design multi-functional artificial reefs for coastal defence and surfing appears to be available to the extent that there is significant potential in the UK for integrating coastal defence and surfing amenity into one structure that intentionally and acceptably delivers both functions. This is not surprising given the commonalities (eg wave braking and salient formation) of submerged breakwaters and artificial surfing reefs.

The knowledge necessary to design a multi-functional artificial reef for coastal defence and habitat and other amenity functions appears to be less available. The work of Halcrow Maritime *et al* (1998) initiates the knowledge necessary to integrate habitat for one target species (ie lobster) into the UK's coastal defence structures. This study found no examples of a coastal defence structure intentionally providing habitat with a planned, designed and funded, protection and/or production function.

The situation is summarised by Jensen *et al* (2000) "whilst surfing reefs are always likely to remain specialist structures to promote wave breaks (possibly integrating with coastal protection schemes) the concept of multipurpose artificial reefs that would serve the need of commercial fishermen, anglers, divers and nature conservation is an attractive one from an economic and social view and a considerable design challenge for artificial reef scientists and engineers."

### 8.1.5 Health and safety

There are health and safety risks associated with coastal defence structures and with artificial reefs for habitat and amenity. At present, knowledge about risks and how to address them are largely known in relation to structures with one function – many of which are very different to coastal defence structures (eg scuttled vessels for diving).

## 8.2 FUTURE DEVELOPMENT

The current situation indicates that multi-functional artificial reefs can be constructed in the UK and can provide significant benefits at an increased cost. Given that no multi-functional artificial reefs have been constructed in the UK, it is recommended that the potential multi-functional artificial reef at Borth be tracked through outline design, detailed design, planning, funding, construction and post-construction in order to highlight lessons learned about these structures' feasibility.

To realise their potential, further guidance is required, particularly because multi-functional artificial reefs deliver more than one type of benefit. The following recommendations are suggested to progress knowledge concerning the opportunities and constraints affecting multi-functional artificial reefs.

### 8.2.1 Coastal defence planning

Guidance on the planning of coastal defences including multi-functional artificial reefs should be provided to operating authorities and the associated construction industry following changes to legislation as outlined under *A sea change – a Marine Bill White Paper* (Defra, 2007). Guidance would be used by those involved in coastal planning, management and the preparation of SMPs, and should be cross-referenced with other CIRIA publications such as the *Beach management manual* (CIRIA, 1996) and *The rock manual* (CIRIA/CUR/CETMEF, 2007).

### 8.2.2 Coastal defence policy

Guidance on coastal defence policy and management encouraging multi-functional artificial reefs should be provided for operating authorities and associated construction industry where it specifically encourages adding habitat and amenity functions to coastal defence schemes. For example, guidance should raise awareness and clarify the potential for the use of multi-functional artificial reefs for applications to SMPs, such as either advancing the line or holding the line.

### 8.2.3 Funding and economic evaluation

Funding and benefits are key to the provision of multi-functional artificial reefs. Because the benefits and funding can be derived from a number of sources, guidance on funding and economic evaluation should be provided. The guidance should be directed toward operating authorities and the associated construction industry to facilitate the adoption of multi-functional artificial reefs as preferred options for future coastal defence schemes. It is recommended that guidance considers the following aspects of funding and economic evaluation:

- proposed and confirmed changes to the grant and payment processes
- current and future funding opportunities
- justification of social, environmental and amenity benefits in relation to assessments accepted by potential funding sources

- lessons learnt from previous projects where co-funding and multiple benefits have been realised, including a review of the current and potential future justification approaches.
- opportunities to fund, co-fund and remove funding constraints for multi-functional reef projects
- the attitude of funders, licensing authorities, conservation agencies and NGOs to the multi-functional artificial reef concept.

It is also recommended that the potential adoption of outcome measures for scheme prioritisation be tracked and influenced (through consultation) to facilitate the adoption of multi-functional structures as preferred options for future coastal defence schemes by encouraging outcome measures to give higher priority to those delivering social and environmental benefits.

Assessing and justifying social, environmental and amenity benefits is less well defined than for direct economic flood and costal defence benefits. A wide range of methods from willingness to pay to assessing the area of environmental enhancement have been used in the past.

Guidance should provide a robust framework for assessing benefits and attracting funding. It is, however, important to note that sources of funding and the conditions attached to funding frequently change, particularly within the private sector, and so detailed and specific funding guidance is unlikely to be produced.

### 8.2.4 Structures, designs and materials

#### Coastal defence and marine habitat

While there is significant knowledge about the design of coastal defence structures and about the use of structures to develop biodiversity and fisheries, there remains little work that draws both these aspects together (Jensen *et al*, 1998). Despite the work of Halcrow Maritime *et al* (1998), this statement remains correct in 2007. Additional information and guidance should be provided to inform operating authorities and the associated construction industry about the potential for creating multi-functional artificial reefs by modifying traditional designs for coastal defences.

It is recommended that additional studies be undertaken to provide design knowledge for target habitats and species:

- identified under the UK BAP in order to contribute to biodiversity, including HLT 4
- that contribute to local commercial fishery resources
- that promote recreational sea angling and/or diving.

In order to inform operating authorities and the associated construction industry, it is recommended that design examples are produced to illustrate the requirements of adding simple habitat functions into coastal defences. This work could entail taking the designs of existing detached breakwaters (eg Happisburgh, Elmer, Jaywick, Newbiggin and Sidmouth (Chapter 2)) and revising them to improve their habitat function. Note this recommendation could be extended to include other marine structures, particularly rock structures, such as coastal defences attached to the shore, harbour walls and the scour protection bases to offshore wind turbines. As a basic premise, the following design modifications should increase complexity to deliver increasing biological performance:

- increasing shape variability (eg change design from straight lines to include more curvy and sinuous lines)
- adding materials to the seabed in the vicinity of the main structure(s) (ie small intermediary artificial reefs)
- varying the height of protrusion (eg by varying crest height)
- increasing material variability (eg change design from uniform to include various rock sizes).

By taking this approach (Box 8.1), it may be possible to achieve simple habitat functions with minimal design changes and cost increases.

More defined habitat functions (eg for a target habitat or species under HLT 4 or the UK BAP) may incur more significant design changes and cost increases. Halcrow Maritime *et al* (1998) note "there may be scope for modifying the design of coastal defence structures to accommodate particular reef species of interest, without compromising the primary coastal defence function. However, there is insufficient information about habitat requirements of many likely target species and about the influence of physical habitat on interactions with other species, such as predation and competition, to allow the ecological properties of structures to be optimised rationally." It is recommended that design examples are produced to illustrate the requirements of adding selected target habitat functions into coastal defences. This recommendation should build upon existing design information including the work of Halcrow Maritime *et al* (1998), the application of software such as modelling of artificial reefs (MAREEF) and the European Community sponsored work on the environmental design of low-crested breakwaters (DELOS). In this respect, it is suggested that design examples focus on habitat for target species where some information on requirements already exists, such as lobsters.

For materials, it is recommended that a desk study (or a more detailed study including existing monitoring data) be undertaken to examine and demonstrate the biological value of sand-filled geotextiles. This study would provide evidence to support decisions about materials when combining coastal defence and marine habitat functions. Monitoring data is available from the existing Narrowneck multi-functional artificial reef, Australia, but would be more relevant to UK conditions if the proposed Boscombe multi-functional artificial reef is monitored.

**Box 8.1** *Key criteria for example designs for simple habitat functions*

Coastal defence structures are usually designed with simple shapes and constructed from uniform materials in order to minimise costs. In contrast, natural rocky reefs are more complex in shape and materials, so provide a more diverse range of habitat niches. Since habitat complexity invariably leads to biological diversity, variations to traditional engineering designs and materials could increase the biological value (eg species diversity, fisheries potential) of a coastal defence structure (pers. comm. K Collins, National Oceanographic Centre).

To start, the following criteria should be examined through example designs:

- shape – examine the use of irregular dimensions associated with structures' toes, berms, crests etc
- materials – examine use of a range of rock sizes associated with armour layers, scour protection etc
- coastal defence – functional performance
- habitat/biology – functional performance
- costs – examine the financial implications of adding a habitat function to a structure's coastal defence function, with particular reference to cost-benefit analysis and funding mechanisms.

### Coastal defence and amenity

Since most recreational sea angling and diving benefits from the presence of marine life, it is suggested that the principles applied to structures combining coastal defence with marine habitat may be also applied through design to combining coastal defence with recreational sea angling and diving. It is recommended that guidance produced for coastal defence and marine habitat also consider amenity functions and benefits relating to marine life.

To combine coastal defence with surfing amenity, a structure's design needs to create a profile that would promote surfable waves. Since both structures for coastal defence and surfing are designed to break waves, the multi-functional artificial reef requires a broadly common design requirement, although alterations will be necessary to create wave breaking conditions suitable for surfing by surfers of one particular or a range of abilities. It is recommended that guidance be prepared to inform the construction industry of surfing related aspects such as wave climate, wind climate, peel angles, breaking intensity, wave height, wave velocity, construction materials and methods, health and safety etc.

## 8.2.5 Health and safety

Guidance concerning health and safety risks associated with multi-functional artificial reefs should be provided to operating authorities and the associated construction industry. Guidance should be provided with regard to the requirements of CDM 2007 through, for example, CIRIA publications C632 *Construction work sector guidance for designers* (CIRIA, 2007a) and C633 *Workplace "in use" guidance for designers* (CIRIA, 2007b).

# References

AIROLDI, L, BACCHIOCCHI, F, CAGLIOLA, C, BULLERI1, F and ABBIATI, M (2005)
"Impact of recreational harvesting on assemblages in artificial rocky habitats"
*Mar Ecol Prog Ser*, vol 299, 1 Sep, pp 55–66

ALLSOP, N W H, JONES, R J and BRADBURY, A P (1995)
"Design of beach control structures on shingle beaches"
In: J E Clifford (ed) *Proc advances in coastal structures and breakwaters conf, London, 27–29 April*, Thomas Telford, London

ARUP, JOHN PATTISSON and CREST NICHOLSON MARINAS (2001)
*Assessment of the potential contribution of marinas and watersports to increasing prosperity in Cornwall. Final report*
Cornwall Enterprise, UK

ASR LTD (2002)
*Developing a surfing reef at Newquay Bay: feasibility study*
Prepared for Newquay Artificial Reef Company (copyright 2001)

ASR LTD (2006)
*Costs associated with the maintenance of a multi-purpose reef at Borth*
Prepared for Royal Haskoning by ASR Ltd, Raglan, New Zealand

BLACK, K P (2003)
"Numerical prediction of salient formation in the lee of offshore reefs"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

BLACK, K P and ANDREWS, C (2001a)
"Sandy shoreline response to offshore obstacles Part 1: Salient and tombolo geometry and shape"
*Journal of Coastal Research*, **Special Issue 29**, pp 82–93

BLACK, K P and ANDREWS, C (2001b)
"Sandy shoreline response to offshore obstacles part 2: discussion of formative mechanisms"
*Journal of Coastal Research*, **Special Issue 29**, pp 94–101

BLACK, K, BLENKINSOPP, C, and MEAD, S (2003)
*Borth multi-purpose reef for coastal protection and amenity*
Prepared for Royal Haskoning by ASR Ltd, Raglan, New Zealand

BLACK, K, BLENKINSOPP, C, BEAMSLEY, B, JOHNSON, D, MEAD, S, MATHEW, J (2004)
*Field data and initial design report. Boscombe surfing reef*
Prepared for Bournemouth Borough Council by ASR Ltd, Raglan, New Zealand

BACCHIOCCHI, F and AIROLDI, L (2003)
"Distribution and dynamics of epibiota on hard structures for coastal protection"
*Estuarine, Coastal and Shelf Science*, **56**, pp 1157–1166

BOMBACE, G (1996)
"Protection of biological habitats by artificial reefs"
In: A C Jensen (ed) *Proc 1st EARRN Conference, Ancona, Italy, March*

BOHNSACK, J A, ECKLUND, A-M and SZMANT, A M (1997)
"Artificial reef research. Is there more than an attraction-production issue?"
*Artificial Reef Management*, **22** (4), pp 14–16

BURGESS, S C, BLACK, K P, MEAD, S T and KINGSFORD, M J (2003)
"Considerations for artificial surfing reefs as habitat for marine organisms"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

CABINET OFFICE (2004)
*Net benefits. A sustainable and profitable future for UK fishing*
Prime Minister's Strategy Unit, Cabinet Office
<http://www.cabinetoffice.gov.uk/upload/assets/www.cabinetoffice.gov.uk/strategy/netbenefits.pdf>

CHALLINOR, S (2003)
"Environmental impact assessment for artificial surfing reefs: a United Kingdom perspective"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

CHALLINOR, S and WEIGHT, A (2005a)
"Artificial surfing reefs"
In: *Proc CoastNET/CIRIA Offshore Development – New Frontiers of Opportunity, London, 15 Sep*

CHALLINOR, S and WEIGHT, A (2005b)
"Environmental sustainability of constructing the Newquay artificial surfing reef"
In: *Proc 4th int surfing reefs symposium, Manhattan Beach, California, USA, 12–14 Jan*

CIRIA/CUR/CETMEF (2007)
*The rock manual. The use of rock in hydraulic engineering. 2nd edition*
CIRIA, C683, London

COATES T T AND SIMM J D (1995)
"Shingle beach response in the lee of detached breakwaters"
In: J E Clifford (ed) *Proc Advances in coastal structures and breakwaters conf, Institution, of Civil Engineers, London, 27–29 Apr,* Thomas Telford, London

COLLINS, K J, JENSEN, A C, MALLINSON, J J, ROENELLE, V and SMITH, I P (2002)
"Environmental impact assessment of a scrap tyre artificial reef"
*ICES Journal of Marine Science: Journal du Conseil 2002*, **59**, (supp), Elsevier Science Limited, pp S243–S249

COMMUNITIES AND LOCAL GOVERNMENT (2006)
*Planning policy statement 25: development and flood risk*
The Stationary Office, London

CORBETT, B B, TOMLISON, R B and JACKSON, L A (2005)
"Reef breakwaters for coastal protection – safety aspects and tolerances"
In: *Proc 17th Australasian coastal and ocean engineering conf, 21–23 Sep, Adelaide, Australia*

DEFRA (2004a)
*Making space for water. Developing a new Government strategy for flood and coastal erosion risk management in England. Physical drivers behind flood and coastal erosion risks*
Flood Management Division, Defra

DEFRA (2004b)
*Delivering the essentials for life. Defra's five year strategy*
HM Government, Available from:
<http://www.defra.gov.uk/corporate/5year-strategy/5year-strategy.pdf>

DEFRA (2007)
*A sea change – a Marine Bill White Paper*
CM 7047, The Stationary Office, Norwich (ISBN 978-0-10170-472-4)

DELOS (2001)
*LCS inventory statistics*
EVK3-CT2000-0041, no 5 for WP1.1, second draft, Dec

DREW ASSOCIATES (2004)
*Research into the economic contribution of sea angling*
Report to the Economics and Statistics Group, Defra. Available from:
<http://statistics.defra.gov.uk/esg/reports/seaangling/finalrep.pdf>

ENVIRONMENT AGENCY (2001)
*High Level Target 9. Biodiversity*
Report to Defra, EA. Available from:
<http://www.defra.gov.uk/environ/fcd/hltarget/hlt9report1.pdf>

ENVIRONMENT AGENCY (2007)
*High Level Target 4. Biodiversity*
Report to Defra, EA. Available from:
<http://www.defra.gov.uk/environ/fcd/hltarget/hlt42006.pdf>

EVANS, E, ASHLEY, R, HALL, J, PENNING-ROWSELL, E, SAUL, A, SAYERS, P, THORNE, C and WATKINSON, A (2004)
*Foresight future flooding. Scientific summary: Volume I. Future risks and their drivers*
Office of Science and Technology, London

FRENCH MCCAY, D P, GIBSON, M and COBB, J S (2003)
"Scaling restoration of American lobsters: combined demographic and discounting model for an exploited species"
*Mar Ecol Prog Ser*, vol 264, pp 177–196

GILBERTSON, A (2007b)
*CDM 2007 – workplace "in use" guidance for designers*
CIRIA, C663, London

GREGG, K L (1995)
"Comparisons of three manufactured artificial reef units in Onslow Bay, North Carolina"
*North American Journal of Fisheries Management*, **15**, American Fisheries Society, pp 316–324

HALCROW, HR WALLINGFORD and JOHN CHATTERTON ASSOCIATES (2001)
*National appraisal of assets at risk from flooding and coastal erosion, including the potential impact of climate change. Final report*
Flood Management Division, Defra, July

HALCROW MARITIME, SOUTHAMPTON OCEANOGRAPHIC CENTRE and CEFAS (1998)
*Design criteria for enhancing marine habitats within coastal structures: a feasibility study*
MAFF Project OC9617, Halcrow Maritime, Southampton Oceanographic Centre and CEFAS on behalf of MAFF Chief Scientists Group.
Available from: <http://www.defra.gov.uk/research/Publications>

HARRIS, L E (2003)
"Artificial reef structures for shoreline stabilization and habitat enhancement"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

HEERTEN, G, JACKSON, A, RESTALL, S and SAATHOFF, R (2000)
"New developments with mega sand containers of non-woven needle-punched geotextiles for the construction of coastal structures"
In: B L Edge (ed) *Proc of the 27th Int conf on coastal engineering, Sydney, Australia, 16–21 Jul*

HESS, R W, RUSHWORTH, D, HYNES, M V and PETERS, J E (2001)
*Disposal options for ships*
National Security Research Division, RAND, (ISBN: 0-83303-014-0)
Available from: <http://www.rand.org/pubs/monograph_reports/MR1377/>

HR WALLINGFORD (2003)
*Low cost rock structures for beach control and coast protection. Practical design guidance*
Report SR 631, on commission by Defra and the Environment Agency, HR Wallingford, Wallingford

HSE (2007)
*Managing health and safety in construction. Construction (Design and Management) Regulations 2007 (CDM) Approved Code of Practice*
L144, HSE Books, Sudbury (ISBN: 9780717662234).
Available from: <http://www.hsebooks.com>

HUGHES, S A (2006)
"Part VI Design of coastal project elements. Chapter 4 Materials and construction aspects"
*Coastal Engineering Manual*, Coastal and Hydraulics Laboratory – Engineer Research and Development Center, USACE, New York. Available from:
<http://users.coastal.ufl.edu/~sheppard/eoc6430/Coastal_Engineering_Manual.htm>

HUTT, J BLACK, K and MEAD, S (2001)
"Classification of surf breaks in relation to surfing skill"
In: Natural and artificial reefs for surfing and coastal protection Black, K (ed), *Journal of Coastal Research*, **Special Issue 29**, pp 66–81

IN EX FISH (2006)
*The role of anthropogenic and non-anthropogenic forcing factors on the biology of exploited species*
WP 1 Deliverable – review. Incorporating extrinsic drivers into fisheries management. Proposal/Contract no. FP6–022710, University of Liverpool

INVEST IN FISH (2005)
*The motivation, demographics and views of south west recreational sea anglers and their socio-economic impact on the region*
Invest In Fish South West Report. Available from: <http://www.investinfishsw.org.uk/>

JACKSON, L A, TOMLINSON, R B and D'AGATA, M (2001)
"Combining surfing and coastal protection. What is the perfect surf?"
In: *Proc 15th Australasian coastal and ocean engineering conference, Gold Coast, Australia, 25–28 Sep*

JACKSON, L A, TOMLINSON, R B and D'AGATA, M (2002)
"The challenge of combining coastal protection and improved surfing amenity"
In: *Proc Littoral 2002, Porto, Portugal, 22–26 Sep*

JACKSON, L A, REICHELT, R E, RESTALL, S, CORBETT, B, TOMLINSON, R and MCGRATH T (2004)
"Marine ecosystem enhancement on a geotextile coast protection reef – Narrowneck reef case study"
In: *Proc 29th int conf on coastal engineering, Lisbon, Portugal, 19–24 Sep*

JACKSON, L A, TOMLINSON, R, TURNER, I, CORBETT, B, D'AGATA, M and MCGRATH T (2005)
"Narrowneck artificial reef. Results of 4 years monitoring and modifications"
In: *Proc 4th int surfing reefs symposium, Manhattan Beach, California, USA, 12–14 Jan*

JACKSON, L A and CORBETT, B B (2007)
"Review of existing multi-functional artificial reefs"
In: *Proc Australasian conf on coasts and ports 2007*

JAMES, E (ed) (2006)
*United Kingdom sea fisheries statistics 2005*
Marine and Fisheries Agency, Defra Publications, London

JENSEN A C (1998)
*Report of the results of EARRN workshop 4: Reef design and materials*
European Artificial Reef Research Network (EARRN) AIR-CT94-2144

JENSEN, A (2002)
"Artificial reefs of Europe: perspective and future"
*ICES Journal of Marine Science: Journal du Conseil 2002*, **59**, (supp), Elsevier Science Limited, pp S3–S13

JENSEN, A C, COLLINS, K J and LOCKWOOD, A P M (eds) (2000)
"Current issues relating to artificial reefs in European seas"
*Artificial reefs in European seas*, Dortrecht, The Netherlands, Kluwer Academic Publishers, pp 489–499

JENSEN, A and COLLINS, K (1995)
"The Poole Bay artificial reef project 1989 to 1994"
*Biol. Mar. Medit.*, **2** (1), pp 111–122

JENSEN, A C, HAMER B A and WICKINS J F (1998)
"Ecological implications for developing coastal protection structures"
In: N W H Allsop (ed) *Proc coastlines, structures and breakwaters conference, 19–20 Mar*, Thomas Telford, London

JOHNS, G M, LEEWORTHY, V R, FREDERICK, W BELL and BONN, M A (2001)
*Socioeconomic study of reefs in Southeast Florida. Final report*
Hazen and Sawyer in association with the Florida Fish and Wildlife Conservation Commission and the National Oceanic and Atmospheric Administration
<http://marineeconomics.noaa.gov/Reefs/02-01.pdf>

JOINT ARTIFICIAL REEF TECHNICAL COMMITTEE OF THE ATLANTIC AND GULF STATES MARINE FISHERIES COMMISSIONS (1998)
*Coastal artificial reef planning guide*
FWS Grant Agreement Nos. GS-96 and AP-98-501, US Fish and Wildlife Service. Funded by Federal Aid in Sport Fish Restoration Administrative Funds and support from the National Marine Fisheries Service

JONES, D L, DAVIS, J E, CURTIS, W R and POLLOCK, C E (2006)
*Geotextile tube structures. Guidelines for contract specifications*
Coastal and hydraulics engineering note ERDC/CHL CHETN-II-50, USACE, New York

KINGSFORD, M J (1999)
"Fish attraction devices (FADs) and experimental designs"
*Scientia Marina*, **63** (3–4) pp 181–190

LEEWORTHY, V R, MAHER, T and STONE, E A (2006)
"Can artificial reefs alter user pressure on adjacent natural reefs?"
*Bulletin of Marine Science 78* (**1**), Rosenstiel School of Marine and Atmospheric Science, University of Miami, pp 29–37

LUKENS, R (1997)
*Guidelines for marine artificial reef materials*
Artificial Reef Subcommittee of the Technical Coordinating Committee, Gulf States Marine Fisheries Commission

MEAD, S T (2003)
"Surfing science"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

MEAD, S T and BLACK, K P (2001)
"Field studies leading to the bathymetric classification of world-class surfing breaks"
*Journal of Coastal Research*, **Special Issue No 29**, pp 5–20

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (2000a)
*Flood and coastal defence project appraisal guidance: environmental appraisal*
FCDPAG5, MAFF, London
Available from: <http://www.defra.gov.uk/environ/fcd/pubs/pagn/fcdpag5.pdf>

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (2000b)
*Flood and coastal defence project appraisal guidance: strategic planning and appraisal*
FCDPAG2, MAFF, London
Available from: <http://www.defra.gov.uk/environ/fcd/pubs/pagn/fcdpag2.pdf>

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (2001)
*Flood and coastal defence project appraisal guidance: overview (including general guidance)*
FCDPAG1, MAFF, London
Available from: <http://www.defra.gov.uk/environ/fcd/pubs/pagn/fcdpag1.pdf>

NAUTILUS CONSULTANTS (2000)
*Study into inland and sea fisheries in Wales. Final report*
Prepared for the National Assembly for Wales by Nautilus Consultants in association with EKOS Economic Consultants Ltd
Available from: <http://www.nautilus-consultants.co.uk/pdfs/wales.pdf>

NORTH EASTERN SEA FISHERIES COMMITTEE (2006)
*Recreational sea angling diversification study*
Summary report, Yorkshire Forward

ODPM (2000)
*Environmental impact assessment: A guide to procedures*
Communities and local government, (ISBN 0 72 772960 8)
Available from: <http://www.communities.gov.uk>

OVE ARUP AND PARTNERS (2007a)
*CDM 2007 – Construction work sector guidance for designers*
CIRIA, C662, London

PENNING-ROWSELL, E, JOHNSON, C, TUNSTALL, S,TAPSELL, S, MORRIS, J, CHATTERTON, J, COKER, A and GREEN, C (2003)
*The benefits of flood and coastal defence: techniques and data for 2003*
Flood Hazard Research Centre, Middlesex University

PATTIARATCHI, C (1997)
"Design studies for an artificial surfing reef at Cable Station, Western Australia"
In: *Proc 1st Int surfing reef symposium, Sydney, Australia*

PENDLETON, L H (2004)
*Creating underwater value: the economic value of artificial reefs for recreational diving*
Prepared for the San Diego Oceans Foundation

PICKERING, H and WHITMARSH, D (1996)
"Artificial reefs and fisheries exploitation: a review of the 'attraction versus production" debate, the influence of design and its significance for policy"
*CEMARE Research Paper 107*, Centre for the Economics and Management of Aquatic Resources, University of Portsmouth

PICKERING, H and WHITMARSH, D (1997)
"Artificial reefs and fisheries exploitation: a review of the 'attraction versus production' debate, the influence of design and its significance for policy"
*Fisheries Research*, **31**, pp 39–59

PILARCZYK, K W (1998)
"Composite breakwaters using geosystems"
In: N W H Allsop (ed) *Proc coasts, structures and breakwaters conference, London, 19–20 Mar*, Thomas Telford, London

PILARCZYK, K W (2003)
"Design of low-crested (submerged) structures – an overview"
In: *Proc 6th Int conf on coastal and port engineering in developing countries, Colombo, Sri Lanka*

POWERS, S P, GRABOWSKI, J H, PETERSON, C H and LINDBERG, W J (2003)
"Estimating enhancement of fish production by offshore artificial reefs: uncertainty exhibited by divergent scenarios"
*Mar Ecol Prog Ser*, vol 264 pp 265–277

QUIRK, C, HEERTEN, G, SAATHOFF, F and STELLJES, K (2002)
"Artificial offshore reef construction using innovative geotextile sand containers"
In: N W H Allsop (ed) *Proc Breakwaters, coastal structures and coastlines conference, London, 26–28 Sep 2002*, Thomas Telford, London

ROYAL HASKONING (2001)
*Borth coastal study*
On behalf of Ceredigion County Council

ROYAL HASKONING (2004)
*Borth multi-purpose reef enabling study*
Final report, on behalf of Ceredigion County Council

ROYAL HASKONING (2006)
*Borth strategic appraisal. Borth strategy 2006*
Final report, on behalf of Ceredigion County Council

SAHOO D and OHNO M (2000)
"Rebuilding the ocean floor – construction of artificial reefs around the Japanese coast"
*Current Science*, vol 78, **3**, 10 Feb

SAYER M and WILDING, T (2005)
"Managing artificial reef developments to optimise benefit"
In: *Proc CoastNET/CIRIA Offshore Development – New Frontiers of Opportunity, London, 15 Sep*

SCARFE, B E, ELWANY, M H S, MEAD, S T and BLACK, K P (2003)
"The science of surfing waves and surf breaks – a review"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

SEAMAN, W (1996)
"Does the level of design influence success of an artificial reef?"
In: *Proc 1st European artificial reef research network conference, Ancona, Italy, March*

SIMARD, F (1995)
"Réflexions sur les récifs artificiels au Japon"
*Biol. Mar. Médit.*, 1995, **2** (1), pp 99–109

SIMM, J D (ed), BRAMPTON, A H, BEECH, N W *et al* (1996)
*Beach management manual*
CIRIA, Report 153, London

SIMM, J D, WALLIS, M J and COLLINS, K (eds) (2005)
*Sustainable re-use of tyres in port, coastal and river engineering. Guidance for planning, implementation and maintenance*
Report SR 669, HR Wallingford, Wallingford

SIMPSON, D and MAWLE, G W (2005)
*Public attitudes to angling 2005*
Environment Agency, Bristol

SMITH, I P, JENSEN, A C, COLLINS, K J, REEVE, D E, HAMER, B E and WICKINS, J F (1998)
*Ecological aspects of coastal defence structures*
Halcrow Maritime, Southampton Oceanographic Centre and CEFAS

Spanier, E (1996)
"Assessment of habitat selection behaviour in macroorganisms on artificial reefs"
In: *Proc 1st European artificial reef research network conference. Ancona, Italy, March*

STIVE, R J H (2005)
"Low crest breakwater design for Dubai islands projects"
In: *Proc CoastNET/CIRIA Offshore Development – New Frontiers of Opportunity, London, 15 Sep*

THE SCOTTISH GOVERNMENT (2004)
*Planning and flooding*
Scottish planning policy (SPP) 7, Scottish Executive Development Department, Edinburgh (ISBN 0-75592-439-8)

TOURISM RESOURCE CONSULTANTS (2002)
*Proposed artificial surf reef, Opunake, South Taranaki. Economic and social impact report*
Prepared for Opunake Artificial Surf Reef Committee South Taranaki District Council

USACE (2006)
*Coastal engineering manual*
EM 1110-02-1100, US Army Corps of Engineers, New York

US EPA and US MA (2006)
*National guidance: best management practices for preparing vessels intended to create artificial reefs*
US Environmental Protection Agency and the US Maritime Administration

VOSE, F E and NELSON W G (1998)
"An assessment of the use of stabilized coal and oil ash for construction of artificial fishing reefs: comparison of fishes observed on small ash and concrete reefs"
*Marine Pollution Bulletin*, vol 36, issue 12, pp 980–988

WEIGHT, D (2003)
"Economics of surf reefs"
In: K Black and S Mead (eds) *Proc 3rd int surfing reefs symposium, Raglan, New Zealand, 23–25 Jun*

WEIGHT, A (2004)
"Artificial reef in Newquay, UK"
*Municipal Engineer* 157, Institution of Civil Engineers, Jun, pp 87–95

WELSH ASSEMBLY GOVERNMENT (2004)
*Development and flood risk*
Technical advice note (TAN) 15, Planning Policy Wales, Cardiff. Available from: <http://new.wales.gov.uk/topics/planning/policy/tans/tan15?lang=en>

WILDING, T A and SAYER, M D J (2002)
"The physical and chemical performance of artificial reef blocks made using quarry by-products"
*ICES Journal of Marine Science: Journal du Conseil 2002*, 59, (supp), Elsevier Science Limited, pp S250–S257

## Acts and Directives

Coast Protection Act 1949

Food and Environment Protection Act 1985

Town and Country Planning Act 1989 (as amended)

Marine Works (Environmental Impact Assessment) Regulations 2007

European Council (EC) Directive

EIA Directive

Habitats Directive

Water Framework Directive