The Influence of Groyne Fields and Other Hard Defences on the Shoreline Configuration of Soft Cliff Coastlines

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Abstract: Building defences, such as groynes, on eroding soft cliff coastlines alters the sediment budget, changing the shoreline configuration adjacent to defences. On the down-drift side, the coastline is set-back. This is often believed to be caused by increased erosion via the 'terminal groyne effect', resulting in rapid land loss. This paper examines whether the terminal groyne effect always occurs down-drift post defence construction (i.e. whether or not the retreat rate increases down-drift) through case study analysis.

Nine cases were analysed at Holderness and Christchurch Bay, England. Seven out of nine sites experienced an increase in down-drift retreat rates. For the two remaining sites, retreat rates remained constant after construction, probably as a sediment deficit already existed prior to construction or as sediment movement was restricted further down-drift. For these two sites, a set-back still evolved, leading to the erroneous perception that a terminal groyne effect had developed. Additionally, seven of the nine sites developed a set back up-drift of the initial groyne, leading to the defended sections of coast acting as

a hard headland, inhabiting long-shore drift. Set-backs can also develop if defences are selectively removed along a heavily defended coastline, as found in an additional study site at Happisburgh, Norfolk.

Four possible post defence coastal configurations are presented, designed to support strategic shoreline management. Defences might not always be responsible for increased down-drift erosion, which has potential implications for shoreline management and litigation. Selective defence removal leading to changes in coastal configuration may become more common in the future.

Keywords: Southern and Eastern England, historical shoreline analysis, cliff retreat rate, set-back, terminal groyne.

INTRODUCTION

Erosion dominates over accretion on coastlines world-wide. With one of the longest coastlines in the Europe, the UK has over 3,100 km of soft cliffs[1] (many located on the south and east coasts of England) – the largest length of soft cliffs for any European country (Eurosion 2004). 17 % of the UK shoreline is eroding (Eurosion 2004). Long-term coastal evolution is strongly linked to human modifications (Ells and Murray 2012; Lazarus et al. 2015). Thus determining how man has caused and affected soft cliff erosion is important, as economic decisions regarding protection and management are influenced by cumulative coastal change (Lazurus et al. 2015). This is particularly

[1] Soft cliffs are formed of clays, shales, sandstone and unconsolidated sands (Jones and Lee 1994; Lee and Clark 2002).

important where there is a shift coastal management options (from hold the existing line of defence to retreat), as anticipated in England and Wales over the coming century (Nicholls et al. 2013).

For many decades, groynes, seawalls and revetments have been constructed to reduce erosion, and beaches have been nourished. This has lead to a reduction of wave attack on the cliff base, and subsequently sediment input from cliff, changing littoral drift patterns in the immediate vicinity of the defence. Adverse effects can develop down-drift due to reduced sediment volumes potentially exposing the cliff base to marine attack and erosion, thus inducing a 'set-back'[2] of shoreline position with respect to the defences (Brown et al. 2011) (Figure 1). When down-drift retreat is accelerated compared with the pre-defence rate, this is known as the terminal groyne effect[3]. The terminal groyne effect has been extensively analysed (for examples, see Table 1) on low-lying coasts adjacent to breakwaters or jetties (e.g. Indian River Inlet, Delaware, US-Keshtpoor et al. 2014; Chesapeake Bay, US–Hardaway and Gunn 2011) where the effects can extend for tens of kilometres down-drift (Bruun, 1995; Galgano, 1998). However, much less attention has been placed on cliffed coasts, hence the focus of this study. Additionally, few studies have systematically analysed whether retreat rates always increase down-drift after defence construction. This is particularly important, as if erosion accelerates there is divided responsibility for measuring and mitigating any adverse effect down-drift of protection works, such as for infrastructure and land loss (e.g. Mappleton, Holderness, England (Lands Tribunal 1999); Sandringham, Melbourne,

[2] Set-back is defined as: The cross-shore retreat between a shoreline position at the time of defence construction, and subsequent shoreline positions

[3] The terminal groyne effect is defined as: Where defences stop or dramatically reduce erosion, inducing a sediment deficit down-drift and causing a consequent increase in down-drift retreat rate.

Australia (Stephenson 2007), Paola to San Lucido, Italy (D'Alessandro et al. 2011); West Hampton Dunes, USA (NOAA 2002); North Carolina, USA (Pietrafesa 2012; North Carolina Coastal Federation 2015)). Hence the motivation for this paper is to develop a scientific framework of the possible configurations for cliffline position after defence construction on soft eroding coastlines. By taking results from three soft-cliffed case study regions in England, this paper aims to analyse post-defence construction set-backs by:

(1) Reviewing the literature and setting of the three study regions (Holderness, Christchurch Bay, Norfolk);
(2) Determining a consistent methodology to measure retreat adjacent to defences and consider problems with measuring retreat ;
(3) Analysing the type of set-backs (up and down-drift) and whether retreat rates increase down-drift after defence construction;
(4) Reviewing future coastal configurations and their wider implications.

EROSION AND DEFENCES IN CLIFFED ENVIRONMENTS: STUDY SITES

The broad consequences of building defences and subsequent down-drift erosion along English soft cliff coasts are well known, noted as far back as the 19^{th} century (Topley 1885), but the detailed geographical and temporal effects of changes to shoreline behaviour are still being understood. Some effects of down-drift erosion are long-lived and very rapid after defence construction, whereas others are short lived and localised (Brown, 2008; Barkwith et al., 2014). Engineers are now much more aware of down-drift erosion issues than half a century ago and often remediate down-drift erosion effects though nourishment (e.g. Kana et al. 2004; Dolphin et al. 2012). However, down-drift erosion still occurs, sometimes unexpectedly, bringing scientific, engineering and policy challenges.

In England and Wales, Brown et al. (2011) identified 95 sites where shoreline movement adjacent to defences had developed on cliffed coasts. Using this selection, eight sites in three study regions (Holderness, Christchurch Bay, Norfolk as shown in Figure 2) were selected for detailed analysis due to data availability (e.g. historical time series of cliff top positions, a history of defence construction), data quality (e.g. of mapping resources) and sufficient time interval since defence construction (to allow for coastal change to be clearly identified beyond the bounds of data error and broader spatial and temporal changes of coastal retreat (see Methodology)). A summary of the regional settings are as follows, with further details in Brown et al. (2014) and Brown et al. (2012a,b).

Holderness

The Holderness cliffs, on the east coast of England are part of a 60 km crenulate shaped bay (Figure 2). The cliffs, average 15 m in height along the coast, are of glacial till origin overlying Cretaceous chalk (Steers 1964; Catt 1987). On average, sands and gravels occupy 2 % to 8 % of the till and boulder clay cliff, but in places this increases to up to 50 % (Richards & Lorriman 1987; Robertson 1990), encouraging greater erosion through seepage. Beach volume is influenced by sediment input from the cliff and from longshore drift, estimated to be up to 90,000 m^3/yr in the northern third of the bay (Mason 1985). Recurring low sections of the beach are known locally as ords. These vary in length between 50 m and 3.8 km and appear to migrate down-drift (Phillips 1962; Pringle 1985; Scott 1976). Although their morphodynamics are debated (see Pethick 1996), when beach levels are low as within an ord, cliff erosion is more likely to develop. Hence it appears that waves of low and high erosion rates migrate along the coast. The northern (up-drift) section of the bay is sheltered by a headland resulting in wave refraction and lower retreat rates (Brown et al. 2012a; Pye and Blott 2015). Sand banks also partially protect parts of the coast, allowing for a regional rate of erosion. The dominant wave direction is from the north-north-east, and has a maximum fetch of 900km.

Retreat rates vary temporally, spatially and by measurement method (see Brown et al. 2012a). Past studies of retreat rates (e.g. Brown 2008, Brown et al. 2012a, Castedo et al. 2015, Furlan 2008, Pethick 1996, Pye and Blott 2015; Reid and Matthews 1906, Mason 1985, Quinn et al. 2009; 2010, Valentin 1954) include average rates of 2.7 m/yr (Reid and Matthews 1906) to 1.2 m/yr (1852-1952) (Valentin 1954) to 1.4±0.2 m/yr (1952-2005) (Brown et al. 2012a). Brown (2008) studied spatial and temporal changes south of Mappleton in detail, and found cycles of erosion spanning two decades, where a period of low rates of retreat was followed by a period of high retreat. She concluded that measuring retreat over periods of one decade could provide a false representation of long-term retreat. Episodic variations were also analysed at Low Skirlington (north of Hornsea), where Furlan (2008) found a large landslide (e.g. resulting in 6m of retreat) occurred once a decade, followed by years of less retreat (at 1 m/yr – 2 m/yr). Quinn et al. (2009) found cliff retreat periodicity was caused by geology, cliff height, slope angle, type of till, beach level and the phreatic surface level. Hence, in this paper, ‘average’ retreat (to determine whether a terminal groyne effect exists) must be measured over periods of several decades to ensure retreat periodicity is not misrepresented. Furthermore, other influencing factors (e.g. beach mining) that could also affect the retreat rate, both up and down-drift must be identified and taken into account to ensure that any increased erosion down-drift of defences is solely due to the defences, not any of natural or artificial cause.

Four study sites were investigated for set-back adjacent to the defences: Barmston, Hornsea, Mappleton and Withernsea. Details of engineering works and cliff top retreat at each site are detailed in Figure 2. In this paper, due to their long and complex histories (> 100 years) of defence extensions, set-backs were measured over two different time periods at Hornsea and Withernsea (referred to as case 1 and case 2).

Christchurch Bay

Christchurch Bay is a 14 km long crenulate shaped bay on the southern coast of England (Figure 2). The cliffs, up to 35 m high comprise unlithified Palaeogene and Lower Headon Formation sand and clay deposits overlaid by Pleistocene gravel terraces (Bristow et al. 1991; Allen & Gibbard 1993; Velegrakis et al. 1999). The beaches grade from sand in the west (up-drift) to shingle in the east due to the increased exposure. The bay has an easterly littoral drift of between 3,000 m^3/yr and 20,000 m^3/yr, with material lost offshore at four points around the bay (Bray et al. 1995; Carter et al. 2004; Nicholls 1985). Waves enter the bay from the west-south-west and are refracted around a headland, and by the sand and shingle banks within the bay. The maximum fetch (east of Barton-on-Sea) is thousands of kilometres across the Atlantic Ocean, providing large storm waves (Lacey 1985). In 2005 (the last year of cliff retreat data used in this study), the mean significant wave height and period derived from a wave buoy in the eastern half of the bay was 0.5 m and 7.5 s respectively, where the mean tidal range varied between 1.0 m and 2.2 m (Channel Coastal Observatory 2005).

The cliffs erode at a variable rate around the bay, averaging 0.6±0.5m/yr from 1963 to 2005 (with spatial variations during this time period of 0.2m/yr to 0.8m/yr), and temporal variabilities of 0.1±0.2 m/yr (1932-1963) to 1.0±0.4 m/yr (1872-1932) (Brown, 2008). Each rate is associated with a large error being attributed to mapping uncertainties (Brown et al. 2012b and see Methodology section). The bay has a long and complex history of human interference due to quarrying of ironstone nodules from the shingle beach and cliff, plus the building of substantial defences. Brown (2008) and Brown et al. (2012b) found it challenging to attribute periodicity of retreat a similar way to the Holderness coast due to the continued long-term effects of human interference on the coast. Hence, expert judgement (based on many years' of experience by the authors) was used to determine an appropriate length of time to be analysed prior to and subsequent to defence construction, bound by historic data availability, to determine if retreat rates had changed.

Three study sites were investigated where set-backs arise: Highcliffe, Barton-on-Sea and Becton, whose defence schemes are described in Figure 2.

Norfolk

North Norfolk, eastern England has one study site, Happisburgh (Figure 2). The region is underlain by Chalk, with the cliffs (10 m high at Happisburgh) composed of weak Pleistocene glacial tills including layers of sand and clay (Owen 1976; Hart 1999; Ohl et al. 2003). The beaches are formed of sand and gravels from the cliff, and longshore transport is 260,000 m^3/yr towards the south-east (Clayton et al. 1983; Clayton 1989). Waves direction is from the north and north-east, where the fetch can exceed 500 km (Dickson et al. 2007). In recording waves, 15 km of coast around Happisburgh received the highest wave and energy between 2006 and 2009 with a mean significant wave height of 0.6 m and period of 6.1 s (Environment Agency 2014). The spring tidal range at Walcott (2 km north-west of Happisburgh) is 3.4 m (Environment Agency 2014).

The coast originally eroded at approximately 1m/yr (Clayton, 1989), before being defended in the late 1950s and 1960s by wooden groynes and revetments (Clayton 1989; Coastal Concern Action Group 2008) (noted in Figure 2) which resulted in a sediment starved coastal system. At Happisburgh, due to lack of sediment input, funding, management and safety reasons (HR Wallingford 2001), after 1991 900m of defences were partially removed creating a 100m set-back on the coast over 14 years (Brown 2008).

In summary, eight cliffed study sites with transitions from defence construction to defence removal have been investigated, with two (Hornsea and Withernsea) developing over long time periods (>100 years), creating a total of ten case studies. In nine of these cases, a set-back resulted after defence construction, and in one case, by removing the defences.

METHODOLOGY: DETERMINING PAST AND FUTURE CLIFF RETREAT

To evaluate set-backs, cliff top positions based on historic maps, aerial photographs and field surveys (total station Electric Distance Measurement (prior to 2000) and differential Geographical Positioning Surveys (DGPS) (after 2000)) were mapped in a Geographical Information System (GIS). Each method resulted in mapping errors in the position of the cliff top, due to, for example, georectification, difficulty in positioning a common point, pen thickness, survey errors (e.g Crowell et al. 1991; Moore 2000). Errors in georectification of ±10 m in the cliff top position were used based on comparing known points (minimum of four) from Ordnance Survey maps and aerial photos over a number of years. For example, in Christchurch Bay, rural areas and a golf course were more challenging to georectify from aerial photos as there were fewer fixed points. Errors of ±2 m were assumed for surveys. Whilst a DPGS is much more accurate (within centimeters), surveying practice (e.g. not walking too close to a cliff edge due to an overhang as found down-drift of Barton-on-Sea) would not always allow for this accuracy. Again, known points were contrasted to maps and aerial photographs.

Once shoreline positions were established, retreat rates were calculated. Numerous methods are available to calculate shoreline change (Moore, 2000), with each method appropriate to different temporal and spatial scales of the study required (French et al. 2015). To project retreat, it was assumed that the past rates would continue, as this provided a quick and simple methodology. To determine the pre-defence rate of retreat, a time period was carefully selected for each site depending on data availability, quality, human interference, storm conditions and potential decadal scale tidal cycles (e.g. see

Lee 2011) where conditions appear to be 'stable' and independent of periodic fluctuations (as described for each case study region). To achieve this for each case study site, a regional study of retreat was undertaken (presented in Brown, 2008 and Brown et al. 2012a,b) to determine spatial and temporal variations of erosion. Different time periods were considered over a range of spatial scales. Too long a period, spanning a century, encountered factors irrelevant to future retreat (e.g. mining of beach sediment in Christchurch Bay), while too short an amount of time (e.g. less than ten years) included episodic event unrepresentative of longer-term conditions (e.g. Holderness). Given data availability, it was found a period of 30 to 50 years was representative (see Brown et al. 2012a,b for further details).

The authors are acutely aware that short-term variability has potentially mislead retreat analysis in the past, as seen in a land tribunal at Mappleton (Lands Tribunal 1999). Here, a 6-year record of higher than average retreat measurements was argued to be a result of down-drift erosion, whereas records of at least decadal length indicate this to be partly due to periodic landslide activities (Brown et al. 2012a). Spatial and temporal variation of retreat has also been found in other soft cliffed coast environments, such as Suffolk, UK (Brooks and Spencer 2010). A further step could involve detailed process based models (e.g. Nicholls et al. 2015; Barkwith et al. 2014; Dawson et al. 2009) for each region and site to project future shoreline positons taking account a wider range and interaction of physical processes affecting retreat. However, these did not exist at the time of publication or were not appropriate to use, such as for scaling reasons as down-drift erosion can be highly localised.

Once shorelines were mapped, three pieces of information (defined in Figure 1) were collated to evaluate set-back from each study site:

(1) Whether the up-drift or down-drift coast was set-back, and if so, by how much;

(2) Whether retreat rates increased down-drift after defence construction assuming that the retreat remain constant, taking account the uncertainties due to errors in mapping (if so, this was known as the cross-shore component of excess retreat);

and

(3) If excess retreat resulted, how far down-drift this was observed (termed the longshore component of excess retreat).

The dates of defence construction, and the time passed since the last engineering intervention were also recorded (see Figure 2). Initial retreat and the magnitude of set-back up- or down-drift of the defences was measured by calculating the retreat between successive transects, placed 10m apart in the area affected by erosion (Figure 3). Transects were positioned perpendicular to the cliff using the Digital Shoreline Analysis System (Thieler et al. 2003). Average retreat was measured between 300 m to 6,200 m down-drift of each case study site to a point where the defences had no discernable influence on retreat. To calculate whether excess retreat resulted, the following calculations were made:

$$\dot{R}_{BDC} = \frac{C_{DC} - C_i}{\Delta t_{BDC}} \qquad \text{(Equation 1)}$$

Where:

$\dot{R}_{BDC}$ = Retreat rate before defence construction; C_{DC} = Cliff position at time of defence construction; C_i = Cliff position at initial time, I; Δt_{BDC} = time elapsed between successive cliff top positions before defence construction.

Following the construction of defences, cliff retreat resulted when:

$$R_{ADC} = C_t - C_{DC} \qquad \text{(Equation 2)}$$

Where:

R_{ADC} = Retreat after defence construction; C_t = Cliff position at time, t; C_{DC} = Cliff position at time of defence construction

To establish the retreat after defence construction, assuming the original retreat rate was maintained:

$$R_M = \dot{R}_{BDC} . \Delta t_{ADC} \qquad \text{(Equation 3)}$$

Where:

R_M = Maintained retreat if no defences were constructed; $\dot{R}_{BDC}$ = Retreat rate before defence construction; Δt_{ADC} = time elapsed between successive cliff top positions after defence construction.

After uncertainties due to errors in shoreline mapping were accounted for, excess retreat was recognised and unambiguously resulted when:

$$\left(\mathrm{R}_{\mathrm{ADC}} > \mathrm{R}_{\mathrm{M}}\right) \qquad \text{(Equation 4)}$$

Where:

R_{ADC} = Retreat after defence construction; R_M = Maintained retreat if no defences were constructed.

CASE STUDY RESULTS

Results for the ten case studies are listed in Table 2. Set-backs down-drift after defence construction were dominant in all case studies regardless of the age of defences, with retreat rates potentially increasing by 10 % (Hornsea) to 500 % (Becton). Set-backs also occurred up-drift, but often by only a few metres. One set-back developed due to defence removal. These outcomes are discussed.

(i) Set-backs developing down-drift after defence construction

Set-backs developing down-drift of defences arose in nine case studies. Once the bounds of mapping uncertainty (i.e. ±10 m or ±2 m depending on the data source) were taken into account, case studies were divided into three categories based on the rate of retreat (as illustrated in Figure 4):

a) Retreat rates increased down-drift after defence construction (7 case studies);
b) Retreat rates were maintained down-drift after defence construction (2 case studies);
c) Retreat rates decreased down-drift after defence construction (0 case studies)

On average, for the Holderness case studies, retreat rates increased by 60 % after defence construction, but for Christchurch Bay, increased by 320 %. Five of the seven case studies in part a) showed down-drift limits to the excess retreat beyond mapping uncertainty (Barton-on-Sea, Becton, Mappleton, Withernsea (case 2), Barmston). For example, at Barmston, other hard defences limited the longshore extent of excess erosion as 650 m down-drift a drainage pipe debouched onto the beach limiting sediment transport). At Becton large beach volumes 650m down-drift of the defence dominated the down-drift response.

For the two case studies in part b) (Highcliffe and case 2 at Hornsea), down-drift retreat rates did not accelerate (once data uncertainties described in the Methodology section were taken into account). At Highcliffe, this was due to the Barton-on-Sea defences located 1.25 km down-drift acting as a hard headland restricting sediment movement (Figure 5). At Hornsea, this may be due to defences which were extended on a coast that was already locally sediment starved as extensive engineering works have been present for over 100 years. Therefore the additional protection works did not make a notable difference to reducing the sediment budget on the down-drift coast.

(ii) Set-backs developing up-drift after defence construction

Set-backs resulted up-drift of the defences as there was insufficient sediment retained by defences to completely halt cliff retreat, or that non-marine processes were still active. This arose in seven case of the studies presented in Table 2, even when mapping uncertainties were accounted for. Thus, up-drift set-back resulted from:

a) An increase in retreat rates caused by another defence up-drift aggravating retreat (1 case study);
b) The continued retreat of the cliff in the absence of other defences up-drift, due to the continuation, albeit reduced volume of littoral drift (3 case studies);
c) The decrease in the cliff rate of retreat relative to the protected section of cliff (3 case studies).

The up-drift set-back is virtually always more subtle or gradual than a down-drift set-back as retreat is slower (e.g. at Barmston, the down-drift coast set-back 15±13m, whereas the up-drift coast was set-back half this amount). If another defence scheme is present up-drift this can aggravate up-drift retreat. For instance, this occurred at Becton (where the down-drift coast set-back 33±29 m), as the Barton-on-Sea defences are located 550m up-drift. Highcliffe and Mappleton did not show set-backs up-drift as there was sufficient sediment to reduce cliff top retreat.

(iii) Set-backs developing after defence removal

Set-backs developing after defence removal will develop due to:

a) A selection of defences being removed whilst the adjacent coast remains.

This occurred in Happisburgh, Norfolk. Due to the being defended for thirty years, cliff retreat was rapid after defence removal (100m of retreat in 14 years), compared with the pre-defence rate (0.5±0.4 m over 59 years).

SET-BACKS: MEASUREMENT, CONFIGURATION AND MANAGEMENT OPTIONS

For down-drift set-backs, the rate of retreat determines whether a terminal groyne effect occurs or not (i.e. by definition it only results from accelerated retreat). Central to this, is the assumption that pre-defence retreat rates would have continued irrespective of the construction (for factors that determine this rate, see Methodology).

Projecting Retreat

Although a pre-defence retreat rate is presumed to continue, in reality, environmental conditions vary and change in respect of:

- wave heights and storms;
- wave direction and subsequent longshore sediment movement;
- lithology and geological exposure influencing retreat and the amount of sediment provided (although over the time scales studied this is probably a small factor); and
- sediment availability due to human interference (e.g. historical beach mining or other defence works).

Whilst it is not possible to fully understand how past environments or human interferences have affected erosion due to lack of historical data, or how they will in the future (e.g. through additional effects, such as sea-level rise), simple projections of past rates provide an indicative value to aid our understanding. Numerical modeling (e.g. as shown in Dickson et al. 2007; Barkwith et al. 2014) may help to project retreat under different management conditions, but would need to be detailed due to the geographical scale, which many if the present geographical models are lacking. Additionally, following earlier analysis (e.g. Nicholls et al. 2000) and quantification of data sets used in these studies, large uncertainty bands developed due to map errors and some natural variation. However, with greater time elapsed since defence construction, the relative error in shoreline position decreases, and will lead to a greater confidence in the results.

Categorisation of set-backs

These ten case studies illustrated that sediment budgets and coastal planforms change due to human interference on the natural environment. With only ten cases studies, limited conclusions can be drawn, so to classify coastal cliff configurations, further study sites have been considered. This includes non-cliffed sites as published studies on cliffed sites subject to down-drift are limited in number. Four configurations that result due to the building or removal of defences are listed in Table 3. This includes three new definitions (perceived terminal groynes effect, initial terminal groyne effect and abandoned groyne effect) which describe the possible behaviour of cliffs after defence construction. These typologies may already appear apparent to practicing engineers, but the authors can find no collective reference to such possibilities in the academic literature. Very often protection works are a mix of many defence types, so the above categories may not just be caused by groynes, but can also be applied to the 'end effects' of defence, such as from sea walls. The term 'terminal groyne effect' is well established in the literature, so this phrase was retained, but these more precise categorisations are related to the nature of set-back and the rate of down-drift retreat.

Few references in the literature refer to a perceived terminal groyne effects or initial groyne effects, presumably as these configurations caused less coastal engineering problems compared with the terminal groyne effect. Initial groyne effects are more common where shore parallel armouring is present as it helps an artificial headland to form. Additionally, on low-lying coasts where the beach is the principal shoreline indicator, the up-drift shoreline may also be set-forward due to excessive sediment accumulation. As cliffs cannot move forward, this configuration is not considered here.

Ongoing, frequently periodic erosion of the shore platform and cycles of set-backs leading to defence extensions mean that set-backs and groyne effects are not fixed features, but are continuously evolving, shaping the shoreline and coastal processes. Rapid retreat after defence construction may induce a terminal groyne effect, but over longer periods sediment recovery could lead to a reduction in retreat rates, shifting the site to be defined as a perceived terminal groyne effect. Even if retreat rates increased after defence construction, evidence may still be sought to determine that the defences were the cause, and not the result of natural environmental processes, particularly over short time scales where natural variability can dominate. This can cause litigation where down-drift landowners request compensation from those responsible for the up-drift defence (e.g. Mappleton (Lands Tribunal 1999); West Hampton Dunes (NOAA 2002)). It would seem likely that such litigation will increase as data, monitoring and modelling capacities rise.

Management, planning and engineering implications

As set-back continues, particularly where the down-drift coast is subject to accelerating retreat, defences will become less effective and more difficult to maintain, leading to outflanking (Brown et al. 2014). Coastal managers have four options of response, as listed in Table 5. Commonly, it is a combination of the options available. With continued erosion of the undefended hinterland together with defence extensions, the protected coast increasingly becomes an artificial headland, protruding into the sea along its entire frontage, as seen at Cromer (Cromer's predecessor, Shipden had been defended prior to 1391 (Steers, 1964)) and Overstrand, Norfolk (from at least 1907 evidenced through Ordnance Survey maps) (see Brown et al. 2014). Hence these defences are subject to greater wave heights, due to refraction effects (Brown et al. 2014), and defence standards need to be progressively increased and strengthened with rising costs (Brown and Barton 2007; Townend and Burgess 2004). Although artificial headland formation was recognised as early as 1922 (by Ward 1922), engineers remained committed to this protection strategy, so in effect, engineers today are locked-in by decisions made in the past. Any removal of headlands (rather than smaller sections of coast) is a step-change in policy that has major engineering and planning challenges.

One possible option is to totally or partly abandon defences, a process known in shoreline management planning as managed realignment. This could produce the abandoned groyne effect, as seen in Happisburgh, Norfolk. In England and Wales, shoreline management policies project greater realignment of shorelines, including cliffed coasts, so this typology could become more common in the future.

CONCLUSIONS

Coastal defences constructed on an eroding soft cliff coast alter the sediment budget, frequently resulting in a set-back of the adjacent shoreline. Using ten studies on English soft cliff coasts where set-backs were found, together with examples from the wider literature, it was found, that even once historic temporal and spatial variations in retreat were accounted for, that:

a) Set-backs can develop up and down-drift of defences regardless of any measureable change in retreat rates;
b) Up-drift set-backs also occur widely, but are smaller and less problematic than down-drift set-backs so are less described in the literature;
c) Retreat rates do not always increase down-drift after defence construction and therefore a terminal groyne effect does not always develop;
d) Set-backs can develop by selectively removing defences whilst maintaining adjacent protection.

Based on these findings, in addition to the well-known *terminal groyne* effect, three additional shoreline behaviours down-drift are recognised and defined as the: (1) *perceived terminal*, (2) *initial* and (3) *abandoned* groyne effects. These are useful to distinguish for long-term shoreline management purposes.

Determining the type of defence effect can be challenging as temporal and spatial variations in historic retreat can be influential, and thus difficult to account for. Additional influencing factors include defence type and its efficiency at retaining sediment, magnitude of long-shore drift or whether a down-drift barrier is present that could block further sediment transport. Down-drift set-backs evolve throughout time from a terminal groyne effect to a perceived terminal groyne effect, or vice versa, as a new sediment balance develops. Set-backs can also lead to the development of artificial headlands which in the long-term may have important consequences for coastal defences, and longer term shoreline management issues.

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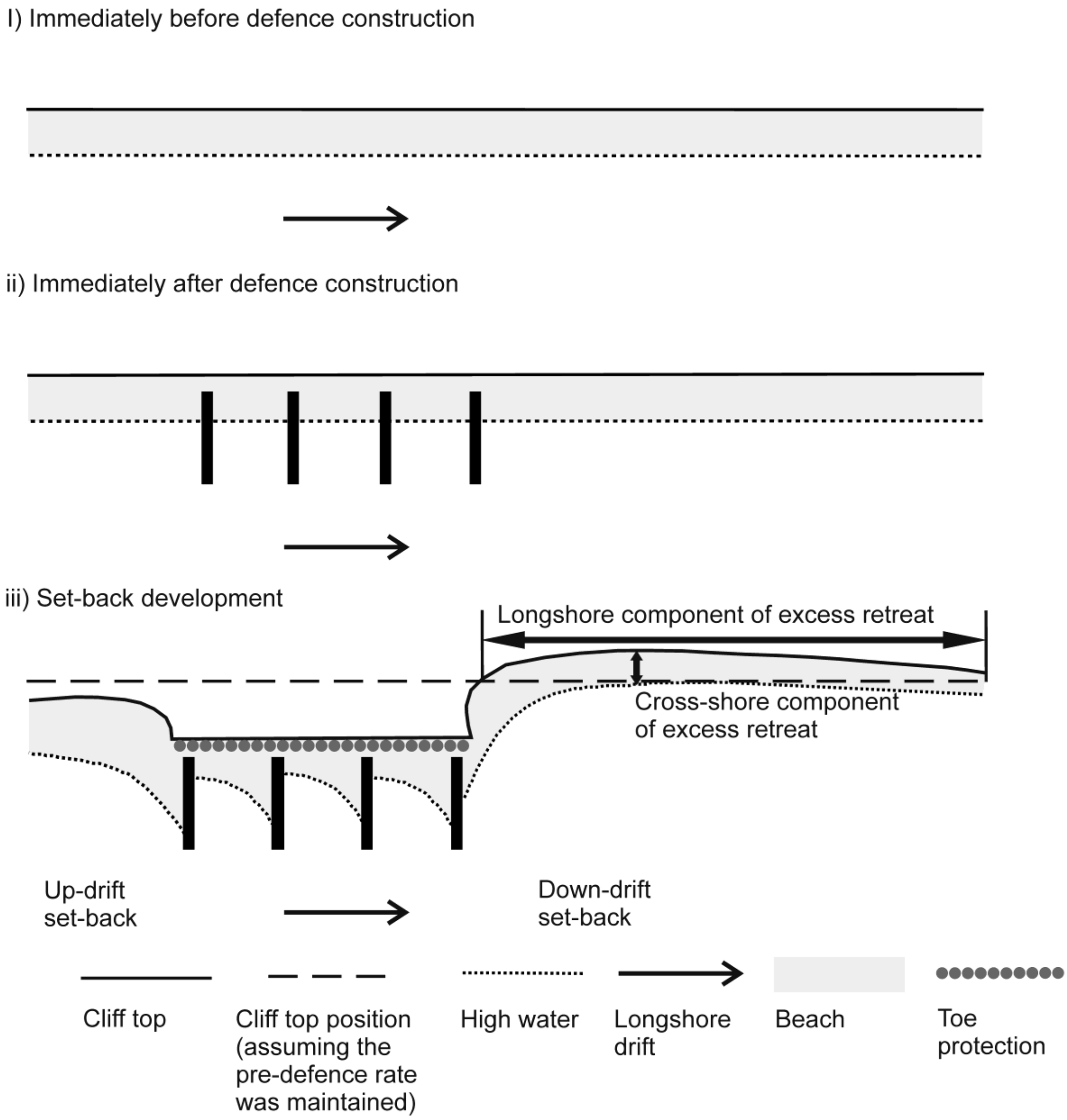

I) Immediately before defence construction
ii) Immediately after defence construction
iii) Set-back development
Longshore component of excess retreat
Cross-shore component of excess retreat
Up-drift set-back
Down-drift set-back
Cliff top
Cliff top position (assuming the pre-defence rate was maintained)
High water
Longshore drift
Beach
Toe protection

Figure 1.

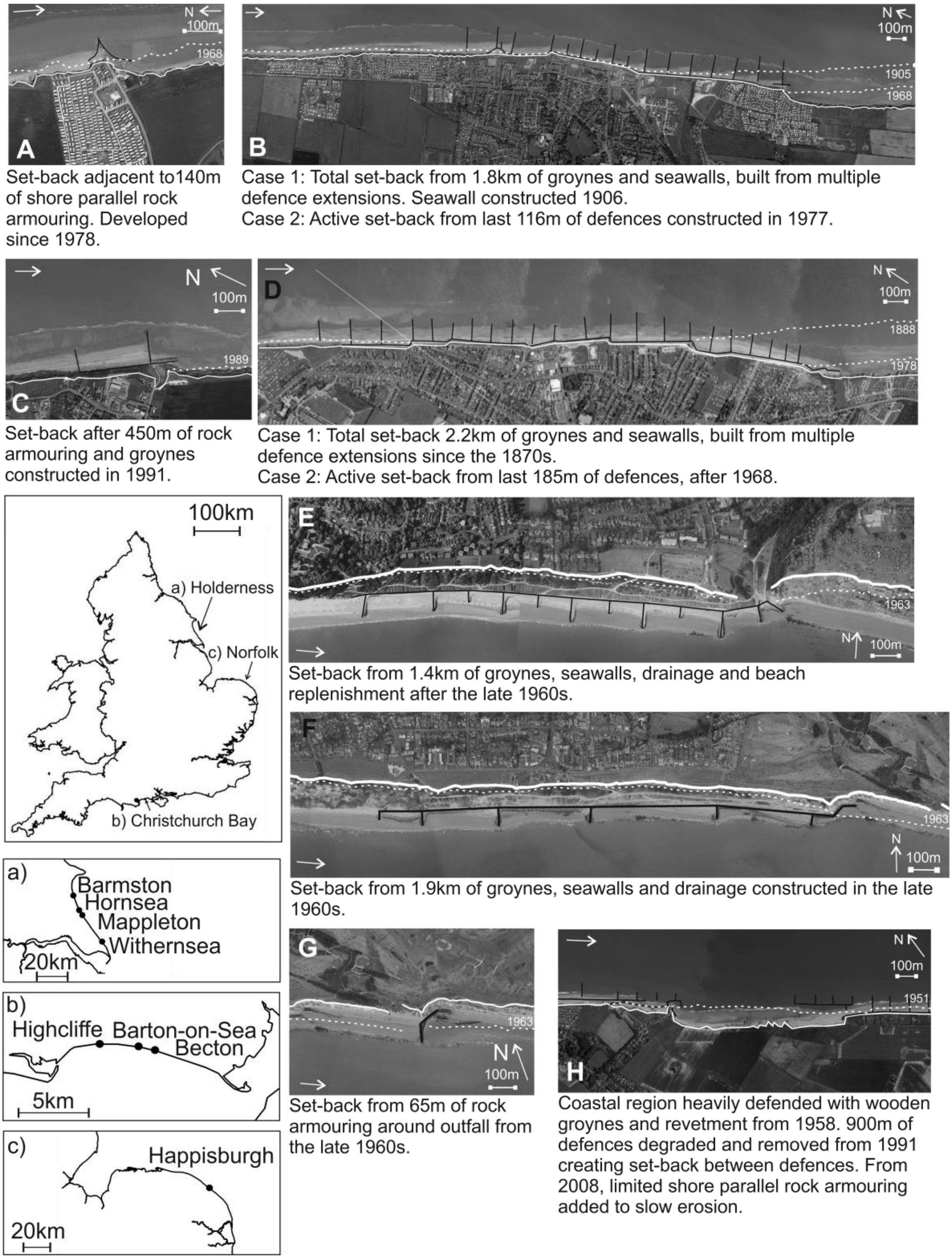

N
100m
1968
A
Set-back adjacent to140m of shore parallel rock armouring. Developed since 1978.
1905
B
Case 1: Total set-back from 1.8km of groynes and seawalls, built from multiple defence extensions. Seawall constructed 1906.
Case 2: Active set-back from last 116m of defences constructed in 1977.
1989
C
Set-back after 450m of rock armouring and groynes constructed in 1991.
D
1888
1978
Case 1: Total set-back 2.2km of groynes and seawalls, built from multiple defence extensions since the 1870s.
Case 2: Active set-back from last 185m of defences, after 1968.
100km
a) Holderness
c) Norfolk
b) Christchurch Bay
a)
Barmston
Hornsea
Mappleton
Withernsea
20km
b)
Highcliffe
Barton-on-Sea
Becton
5km
c)
Happisburgh
20km
E
1963
Set-back from 1.4km of groynes, seawalls, drainage and beach replenishment after the late 1960s.
F
1963
Set-back from 1.9km of groynes, seawalls and drainage constructed in the late 1960s.
G
1963
Set-back from 65m of rock armouring around outfall from the late 1960s.
H
1951
Coastal region heavily defended with wooden groynes and revetment from 1958. 900m of defences degraded and removed from 1991 creating set-back between defences. From 2008, limited shore parallel rock armouring added to slow erosion.

Figure 2.

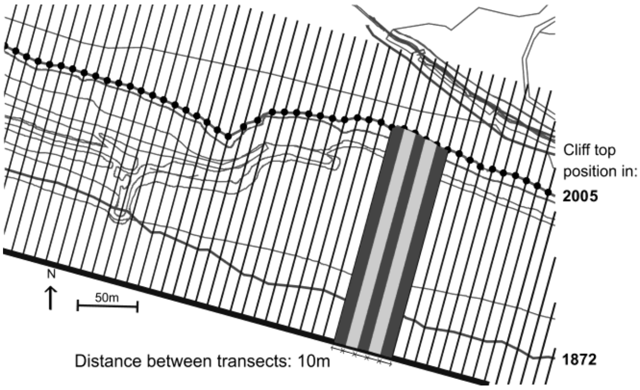

Cliff top
position in:
2005
1872
N
50m
Distance between transects: 10m

Figure 3

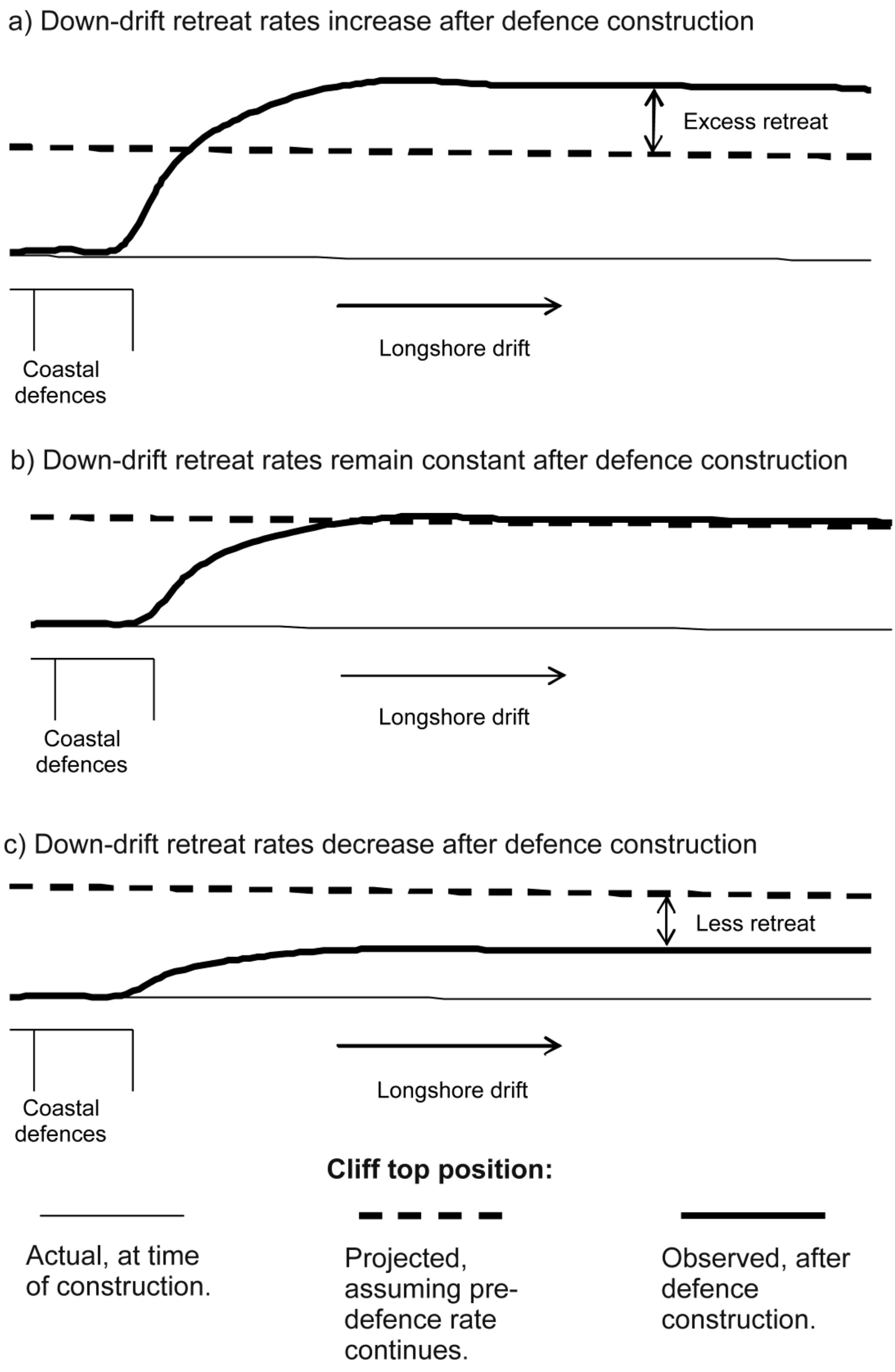

a) Down-drift retreat rates increase after defence construction
Excess retreat
Longshore drift
Coastal defences
b) Down-drift retreat rates remain constant after defence construction
Longshore drift
Coastal defences
c) Down-drift retreat rates decrease after defence construction
Less retreat
Longshore drift
Coastal defences
Cliff top position:
Actual, at time of construction.
Projected, assuming pre-defence rate continues.
Observed, after defence construction.

Figure 4

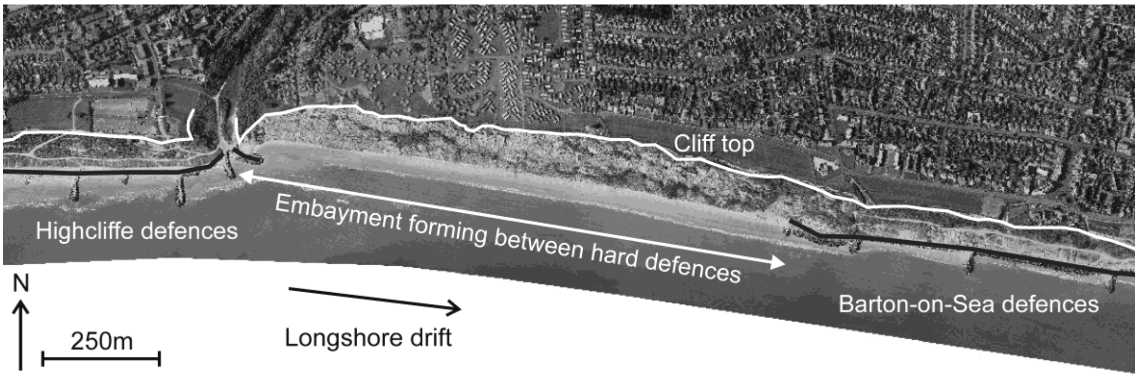

Cliff top
Highcliffe defences
Embayment forming between hard defences
Barton-on-Sea defences
N
250m
Longshore drift

Figure 5.

Figure captions

Figure 1. Idealised development of set-back on a soft cliffed coast adjacent to hard defences.

Figure 2. Location and summary of the three study regions and eight study sites, including aerial photographs (based on Brown et al. 2012a, 2012b; Coastal Concern Action Group 2008, East Riding of Yorkshire Council 2004, HR Wallingford 1991 and Wright 1998. Aerial photographs courtesy of the Channel Coastal Observatory, East Riding of Yorkshire Council and North Norfolk District Council). Arrow indicates drift direction. Dashed white line indicates cliff top in date indicated on each photograph representing the nearest available record of cliff top position relative to when the defences were constructed. Solid white line indicates cliff top in 2005. Black lines indicates defences. (A) Barmston, (B) Hornsea, (C) Mappleton, (D) Withernsea, (E) Highcliffe, (F) Barton-on-Sea, (G) Becton, (H) Happisburgh. Due to multiple defence extensions, Hornsea and Withernsea were measured over two time periods (known as case 1 and case 2). Map outlines Crown Copyright 2016. An Ordnance Survey/EDINA supplied service.

Figure 3. Measuring cliff retreat. In this example at Barton-on-Sea, the area of land loss was measured over 10 m transects, and then averaged over a 50 m length of cliff (adapted from Brown et al. 2012b).

Figure 4. Idealised categories of down-drift erosion with respect to retreat rates.

Figure 5. An embayment forming between hard protection works at Highcliffe, Christchurch Bay, southern England. Image (taken 2008) courtesy of the Channel Coastal Observatory (www.channelcoast.org).

Table 1. Examples of down-drift erosion world-wide

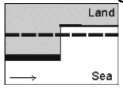
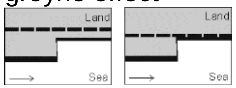
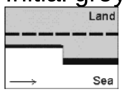
Location	Defence	Consequence	Type of land affected	Reference
Madras, India	Breakwater constructed in 1875	Severe down-drift erosion resulting in groyne construction. Erosion extended 5km down-drift. Shoreline advanced up-drift	Open coast during port development	Komar 1976, 1983
Summerille, on the tidal Potomac River, Virginia, USA	Bulkheads and groynes	Increased erosion down-drift threatened to outflank defences, leading to a spur added at 90° to trap sediment	Farmland and property	Anderson et al. 1983
Ofir-Apúlia, northern Portugal	Groynes and a revetment	Increased erosion rates down-drift	Loss of holiday facilities	Granja and Carvalho 1991, 1995
North Point Marina on the Illinois shoreline of Lake Michigan, USA	150m rip-rap	Down-drift coast set back 65m in 8 months	Parking facilities	Terpstra and Chrzastowski 1992
Skagen harbour, Denmark	Harbour jetties, 500m long	Increased down-drift erosion rates, with the deficit moving down-drift at 0.5km/year, slowing to 0.2-0.3km/yr	Hinterland around harbour	Bruun 1995
Lagos, Nigeria	Breakwater	Down-drift beach retreated 1.3km. Beach nourishment required. Up-drift beach prograded by over 1.3km	Beach and residential buildings	Bruun 1995

Fire Island, New York, USA	Stabilisation of the Moriches Inlet	Increase in retreat rates, but cause disputed	Beach front properties bringing a litigation claim due to accelerated land loss	Galgano and Leatherman 1999
Mappleton, Holderness, eastern England	450m of rock groynes	Down-drift retreat increased from 2m/yr to 4.7m/yr	Farm located 1.2km down-drift brought an unsuccessful litigation case	Lands Tribunal 1999; Maddrell and Gowan 2001
Sandringham, Melbourne, Australia	Rock groynes	Adjacent stable cliff started to erode, leading to the building of a second groyne in 2006, with a third proposed	Open space / residential	Stephenson 2007

Table 2. Summary of the ten case studies presented in Brown (2008) and Brown et al. (2012a, b) on the Holderness, Christchurch Bay and Norfolk coastlines.

Rate of down drift erosion after defence construction relative to initial rate	Study site	Measurement period of post-defence retreat rate	Time defended (years)	Cross-shore excess retreat (m)	Down-drift longshore extent	Up-drift set-back?	Longshore growth constrained by hard headland?
Increased erosion and cross-shore excess retreat	Hornsea (B - case 1)	1905-2005	99	88±42	Not distinguishable	Yes, multiple times	No
	Withernsea (D - case 1)	1870-2005	130	88±49	Not distinguishable	Yes, multiple times	No
	Barton-on-Sea (F)	1963-2005	38	42±29	Greater than 300m	Yes	Yes
	Becton (G)	1963-2005	34	33±29	Up to 650m	Yes	No
	Mappleton (C)	1989-2005	14	25±12	3,900m - 4,400m	No	No
	Withernsea (D - case 2)	1978-2005	37	20±13	Up to 700m	Yes	No
	Barmston (A)	1978-2005	≥ 27	15±13	Up to 650m	Yes	Yes
Retreat rates maintained or decreased	Highcliffe (E)	1963-2005	38	17±29	Up to 1,250m	No	Yes
	Hornsea (B - case 2)	1968-2005	28	10±21	Not distinguishable	Yes	Yes
Retreat rates accelerated after defence removal	Happisburgh (H)	Defences removed from 1991-2005	33 (prior to defence removal)	N/A, but embayment 100m deep	900m	N/A	Yes

Table 3. Coastal configurations on the adjacent cliffline as a result of defence building. On inset diagrams: Thick line indicates defended cliffline; thin line indicate the present cliffline; dashed line indicates cliffline position without defence construction or removal; and the arrow indicates direction of longshore transport.

Type of cliffline movement	Definition	Examples (including non-cliffed sites)
Terminal groyne effect 	Where defences stop or dramatically reduce longshore drift, inducing a sediment deficit down-drift, causing an increase in retreat rate.	Hornsea, UK case 1 (this study) Withernsea, UK cases 1 and 2 (this study) Barton-on-Sea, UK (this study) Becton, UK (this study) Mappleton, UK (this study) Barmston, UK (this study) Ofir-Apúlia, Portugal (Granja and Carvalho 1991, 1995) North Point Marina, US (Terpstra and Chrzastowski 1992) Sandringham, Australia (Stephenson 2007) Summerille, US (Anderson 1983) Skagen harbour, Denmark (Bruun 1995) Fire Island, US (Galgano and Leatherman, 1999) Sea Palling, UK (Dolphin et al. 2012) Sylt, Germany (Dette and Gärtner 1987) Edisto Beach, US (Kana et al. 2004) Madras, India (Komar 1983)
Perceived terminal groyne effect 	Where defences stop or reduce longshore drift and down-drift retreat rates do not accelerate (independent of beach nourishment).	Highcliffe, UK (this study) Hornsea, UK case 2 (this study) Tunstall, UK (Brown 2008) Easington, UK (Brown 2008) Lake Michigan, US (Shabica et al. 2004) Breach Inlet / Sullivans Island, US (Kana et al. 2004)
Initial groyne effect 	Where defences did not trap sufficient sediment up-drift so retreat continued or decreased.	Hornsea, UK cases 1 and 2 (this study) Withernsea, UK cases 1 and 2 (this study) Barton-on-Sea, UK (this study) Becton, UK (this study) Barmston, UK (this study)

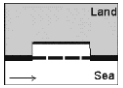
		Happisburgh / Doggett’s Lane, UK (Brown 2008) Ulrome, UK (Brown 2008) Overstrand, UK (Brown 2008) Vale de Lobo, Portugal (Cruz de Oliverira et al. 2008) Stillwell Hall, Marina, US (Stamski 2005) Pedrinhas, Portugal (Granja and Carvalho, 1991, 1995) Espinho-Furadouro, Portugal (Granja and Carvalho, 1995)
Abandoned groyne effect 	Where defences which stop or dramatically reduce erosion, inducing a sediment deficit are later abandoned between adjacent maintained defences causing a set-back and an increase in retreat rate.	Happisburgh, UK (this study)

Table 5. Options available when the coast becomes set back.

Number	Option	Description	Case study
1	Extend defences	Common where set-backs continue to grow, they have the potential of outflanking defences making them ineffective at their extremities. The extension may purely be a continuation of the previous defences, but alternative methods of protection, such as a series of shortening groynes placed longshore, semi-permeable groynes or terminal structures could be introduced as an intermediate measure.	Hornsea (case 1), Withernsea (case 1), Highcliffe, Barton-on-Sea, Becton
2	Maintain defences, reinforcing the extremities	Common in many localities, where reinforcement can take place via armouring on the beach to protect sea walls, particularly where beach levels have decreased with respect to their pre-defence levels.	Hornsea, Withernsea, Highcliffe, Barton-on-Sea
3a 3b	Partly abandon defences or totally abandon defences	Partial defence abandonment is regarded as a newer approach within shoreline management, and there is an increasing shift towards this option, together with total abandonment of defences, where it is cost efficient to do so.	Happisburgh
4	Employing soft measures, including beach nourishment	More frequently results during or just after the construction of defences, to reduce the likelihood of a set-back developing until it reaches a new equilibrium. It can also be used as an emergency measure if excess retreat unexpectedly develops (e.g Sea Palling, Norfolk, UK — Hamer et al. 1998)	Highcliffe