Overstrand to Walcott Strategy Study

Cliff Processes

Part II: Technical Support Information

Report EX 4692
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HR Wallingford

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Summary

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This report addresses the geological conditions and the geomorphological processes active between Overstrand and Walcott. The cliffs along this coast are developed in a variable sequence of weak glacigenic deposits. Seawalls currently protect the cliffs at Overstrand, Trimingham, Mundesley, and Bacton, while timber palisades and groynes provide protection for much of the intervening cliffline.

Existing information on geology and geomorphology of this section of coast was collated and analysed in the context of a strategic coastal defence study. The following principal aspects are addressed:

- Material composition of the North Norfolk cliffs
- Sediment yield from the cliffs
- Cliff types in terms of slope stability and recession
- Prediction of future cliff behaviour
- Suggested cliff management programme

A field assessment of the cliff conditions between Overstrand and Walcott has led to the identification of three broad types of cliff recession that are applicable for modelling the 'Do Nothing' scenario following defence failure. For each cliff type, field assessments of characteristic slope angles have provided a broad indication of the limiting angles prior to failure and post failure. These angles are intended to form the input data for the numerical modelling of cliff recession (see the accompanying report on cliff modelling). Furthermore, estimated sediment yields from the unprotected cliff areas have been used in the assessment of longshore sediment transport (see the accompanying report on littoral sediment processes).

Contents

Tables

Figures

Appendices

Drawings

1. INTRODUCTION

This report addresses the geological conditions and the geomorphological processes active between Overstrand and Walcott. Existing information on geology and geomorphology of this section of coast was collated and analysed in the context of a coastal strategy study.

The following principal aspects are addressed:

- Material composition of the North Norfolk cliffs
- Sediment yield from the cliffs
- Cliff types in terms of slope stability and recession
- Prediction of future cliff behaviour and evolution in a 'Do Nothing' scenario
- Suggested cliff management programme

A field assessment of the cliff conditions between Overstrand and Mundesley has been conducted, and this has identified three broad types of recession model that are applicable for modelling the 'Do Nothing' scenario following defence failure. Furthermore, 26 distinct cliff behavioural units (CBUs) have been identified across the area on the basis of the surface form, geology, and the known or inferred landslide processes. The field assessments have also produced characteristic slope angles, which give a broad indication of the limiting angles prior to failure and post failure within each cliff unit. These slope angles are intended to form the input data to the cliffSCAPE modelling undertaken by the University of Bristol.

2. CLIFF CHARACTERISATION

2.1 Materials

The north Norfolk cliffs are developed in a highly variable sequence of Anglian-age deposits and earlier Pleistocene deposits, overlying an eroded Chalk platform. The Anglian-age deposits include a complex suite of interbedded tills - the Cromer Tills - and associated meltwater deposits, while the Pleistocene deposits consist of the Cromer Forest Bed Series. The main features of these deposits are:

1. **The Anglian deposits** – These materials were deposited by an ice sheet that covered the region during the Anglian glaciation, around 400,000 years ago. It is believed that there were three ice advances into the North Norfolk basin, each depositing a distinct till unit. During each period of ice retreat, sands and laminated clays were laid down in shallow water, pro-glacial lakes.

   The detailed stratigraphy has been the focus of much research over the last 125 years, concentrating of the classic exposures at Trimingham and West-East Runton; two of the more widely known nomenclatures are presented below.

Banham (1968)	Reid (1882)
Brick Kiln Dale Gravels Gimingham Sands Third Till Mundesley Sands	Contorted Drift
Second Till Intermediate Beds First Till	Cromer Till

   The three tills are laterally uniform well-sorted sandy deposits and are separated by layers of meltwater sands and gravels and lacustrine clays and silts.

   Hart (1987) has offered an alternative interpretation of the stratigraphy at West Runton:

Runton Sands and Gravels Laminated diamicton Woodhill Sands	Laminated diamicton unit

   The '*laminated diamicton unit*' is the name now given to all the glacial deposits.

The laminated diamicton, *sensu stricto*, has a minimum thickness of 15m. The unit is clay-rich and contains locally derived pebbles (e.g. flints and chalk, together with erratics). At West Runton, it corresponds with the '*contorted drift*' sequence of the third till and associated meltwater deposits.

The diamicton is highly deformed (i.e. contorted) comprising laminations and deformed blocks of clay, sand and gravel, and large rafts (*schollen*) of Beeston chalk (Figure 2.1). The deformations are believed to be the result of shearing, extension, and flow of the highly saturated materials beneath the ice sheet (Figure 2.2).

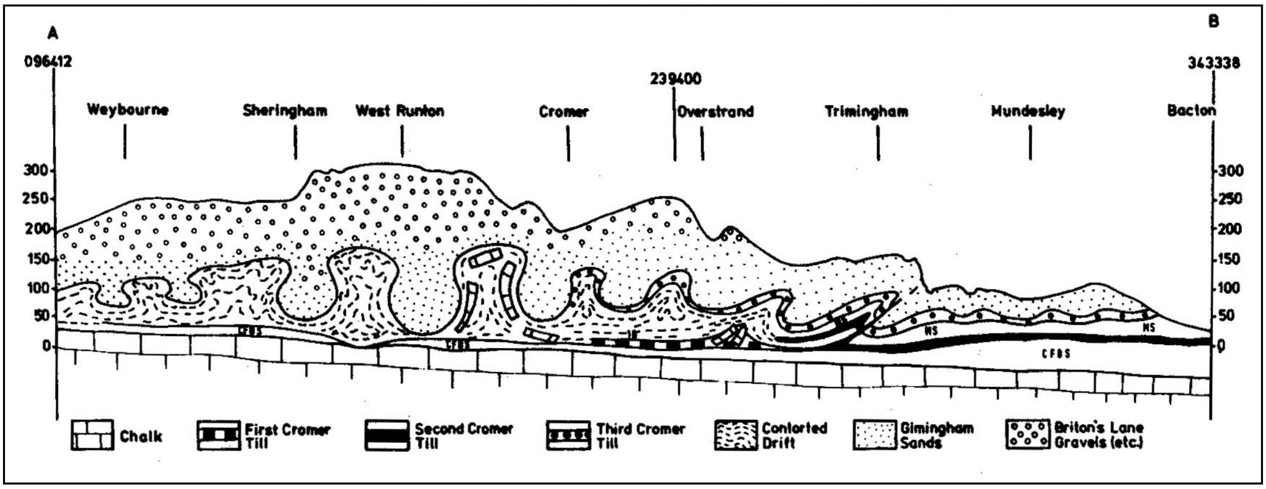

Figure 2.1 Cliff section along the north Norfolk coast (Banham 1975)

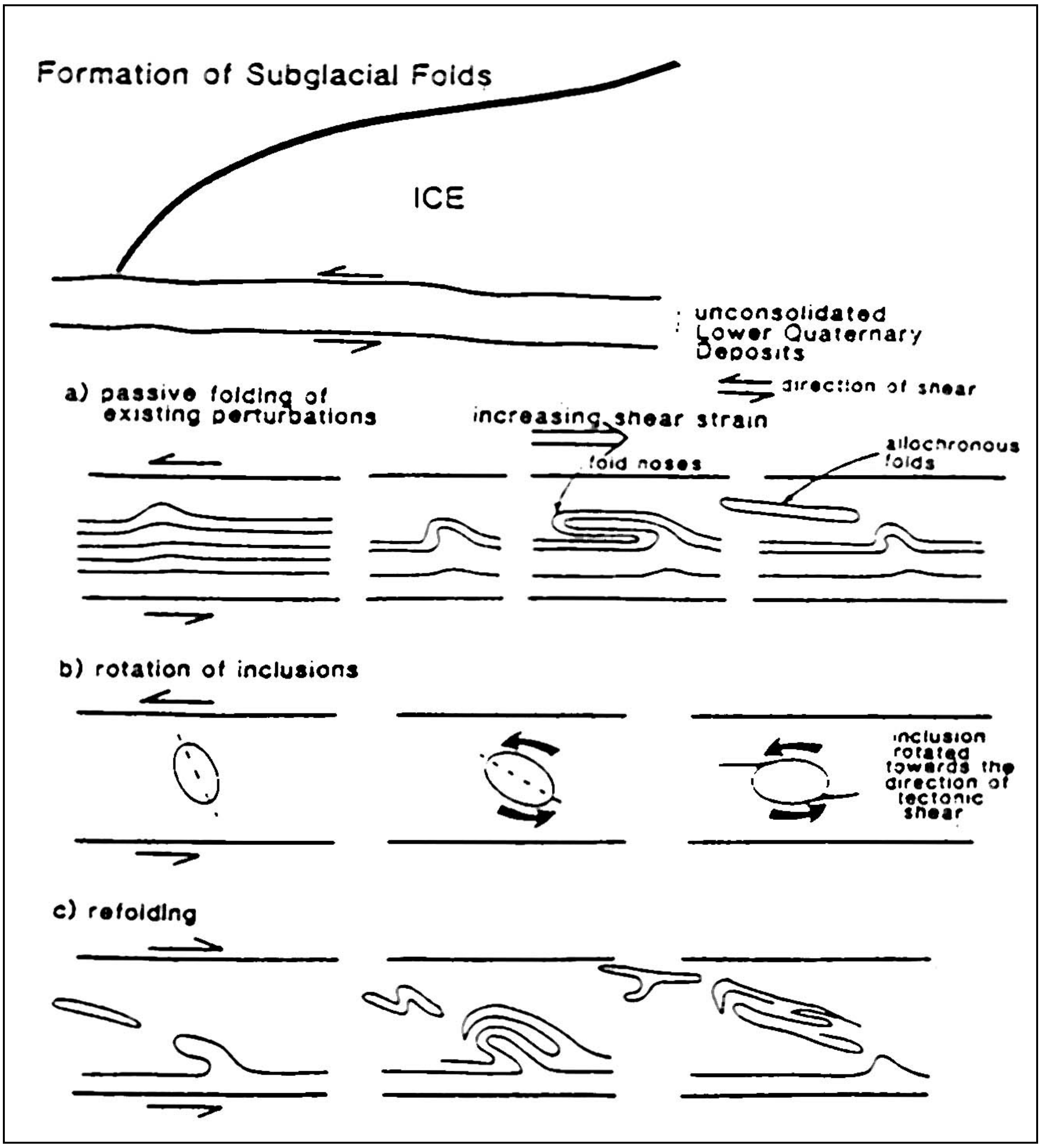

Figure 2.2 A summary of the mechanisms of sub-glacial deformation (Hart 1987)

Overburden loading by the Gimingham Sands and Briton's Lane Gravels caused diapirism of the underlying water saturated tills, leading to compensatory sinking of the sand units between the diapirs.

Perched water tables occur within the glacigenic sediments.

2. **The Cromer Forest Bed Series** – These deposits often appear at the base of the cliffs, although they may be obscured by landslide debris. They comprise grey shelly sands and shallow-water deposits and are the product of a succession of pre-Anglian glaciation, Pleistocene climatic events.

3. **The Chalk platform** – This declines in elevation from +2.7m at Sheringham to -2.1m at Cromer Pier and 5.5m below beach level at Overstrand. A piezometric surface that rises from around sea level to an elevation of +5mOD behind the cliffline probably occurs within the Chalk/Cromer Forest Bed Series. This surface probably fluctuates slightly with the tides.

The cliffline is noted for the rapid facies changes within the glacial materials. Thus, it is difficult to be precise about what materials can be expected at a particular section and what materials are likely to be encountered behind the cliffline.

Recorded sequences from Happisburgh, Trimingham, Sidestrand, and West Runton are presented below (each is in descending order of age).

Happisburgh Cliffs (10km to the south-east of Mundesley) (West 1977)

Material type	Layer Thickness	Description
Valley Gravels and Sands	5m	
Gimingham Sands	4m	
Third Cromer Till	11m	
Mundesley Sands	9m	Cross-bedded
Second Cromer Till	3m	
Intermediate Beds	6m	Turbidite units grading from sand to clay
First Cromer Till	4m	Small diapirs intrude into the Intermediate Beds
Cromer Forest Bed Series	1m+	

Trimingham Cliffs, see Figure 2.3 (Gibbard and Zalasiewicz 1988)

Head		
Sidestrand lacustrine unit		Infilled hollows on the till surface.
Upper diamicton unit	Outwash sand D Upper diamicton Outwash sand C	Probably corresponds with the Third Cromer Till, plus Gimingham Sands and Mundesley Sands
Trimingham unit	Upper clay Fine sand Marl Homogeneous clay Lower or rhythmitic clay	Probably corresponds with the Intermediate Beds. These are glacial lake deposits ('Lake Trimingham'), up to 45m thick. The sequence comprises varved clays, homogeneous clays, lake marls, aeolian sands.
Lower diamicton unit	Lower diamicton Outwash sand A	Probably corresponds with the First Cromer Till. The till includes deformed blocks of chalk 1-2m long
Pre-glacial deposits		

Sidestrand Cliffs (Gibbard and Zalasiewicz 1988)

k) Tidal sediments; pale sands with grey silty clay laminae	2m
j) Ferruginous gravels	
i) Freshwater silty mud	
h) Cross-bedded sand with gravel strings and thin bands of silty clay	
g) Red and yellow sands	5m
f) Grey sand with grey silty clay laminae	0.3m
e) Ferruginous gravel	0.2m
d) Coarse stratified sand with thin grey silt laminae	1m
c) Gravel with marine shells	1.2m
b) Sand	1.5m
a) Massive flint pebble lag resting on Chalk.	0.6m

Note: In contrast with the ‘normal’ sequence, the Sidestrand deposits have been interpreted as disturbed pre-glacial deposits and up-thrust Chalk.

West Runton Cliffs 5km north-west of Overstrand

Laminated diamicton unit	Runton sands and gravels	Probably corresponds with the Third Cromer Till, plus Gimingham Sands and Briton’s Lane Gravels
	Laminated diamicton	
Woodhill sands		Probably corresponds with the Intermediate Beds.
Pre-glacial deposits	Cromer Forest Bed Formation	

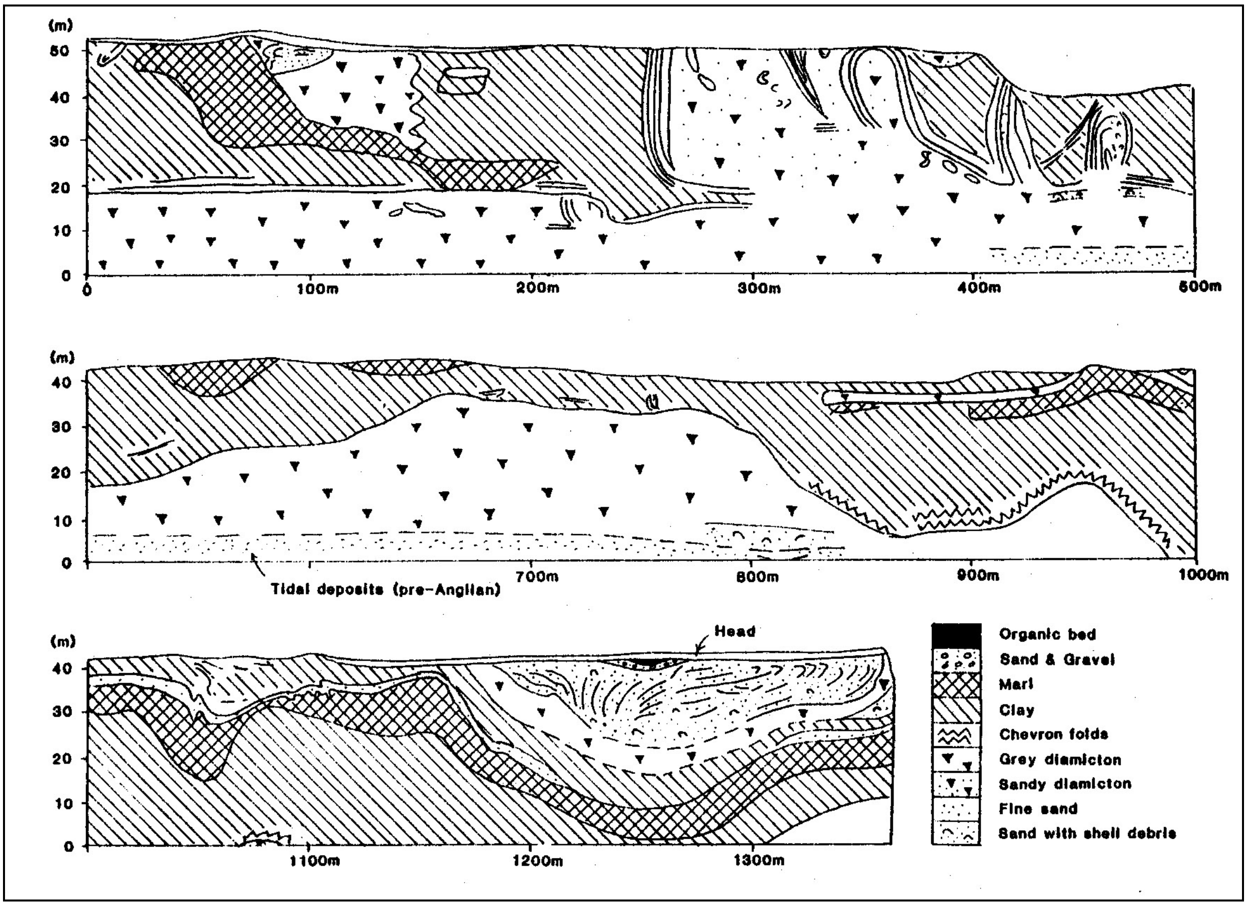

Figure 2.3 Coastal exposure at Trimingham, 1985 (Gibbard and Zalseiwicz 1998)

2.2 Sediment yield

An estimate of sediment yield from the North Norfolk cliffs has been presented by the BGS (1996) and is summarised in Table 3.1.

Table 2.1 A summary of the potential sediment yield from the Overstrand-Mundesley Cliffs (BGS 1996)

Location	Grid Ref., E N, E N	Mud %	Sand %	Gravel %	Yield** m^3	Cliff Unit (see Table 4.1)
Ostend N3C8 to N3B1	636480 332570 636854 332307	70.3	29.2	0.5	6,989	Unit 21
Bacton N3C7 to N3C8	635151 333493 636480 332570	64.7	35.3	0	5315	Unit 20
Bacton N3C6 to N3C7	634461 334024 635151 333493	36.9	63.1	0	4353	Unit 20
Bacton N3C5 to N3C6	633431 334805 634461 334024	24.0	66.0	10.0	9695	Unit 20
Bacton N3C4 to N3C5	633151 335080 633431 334805	33.2	64.7	2.1	18480	Units 18 & 19
Mundesley N3C4 to N3C3	633151 335080 631997 336089	35.6	63.77	0.7	20,912	Units 16 & 17
Mundesley N3C2 to N3C3	631700 336460 631997 336089	27.5	72.5	0	12,933	Unit 16
Mundesley N3C1 to N3C2	631220 336900 631700 336460	32.5	67.4	0.1	19,564	Unit 15
Trimingham N3D6 to N3C1	630420 337480 631220 336900	34.2	65.5	0.3	34,454	Units 13 & 14
Trimingham N3D5 to N3D6	628899 338399 630420 337480	30.3	65.6	4.1	47,134	Units 11 & 12
Trimingham N3D5 to N3D4	627870 339024 628899 338399	36.6	55.5	7.9	72,236	Unit 10

Note: * N3E5 etc. refer to EA Marker Numbers.
** Sediment yield per metre of cliff recession.

Table 2.1 A summary of the potential sediment yield from the Overstrand-Mundesley Cliffs (BGS 1996) (continued)

Location	Grid Ref., E N, E N	Mud %	Sand %	Gravel %	Yield** m^3	Cliff Unit (see Table 4.1)
Trimingham N3D3 to N3D4	627260 339361 627870 339024	62.5	37.5	0	27,876	Units 8 & 9
Sidestrand N3D2 to N3D3	626310 339910 627260 339361	82.8	17.1	0.1	24,155	Units 6B, 7, & 8
Overstrand N3D1 to N3D2	625890 340180 626310 339910	43.6	55.4	1.0	27,577	Units 5 & 6A
Overstrand N3E6 to N3D1	624751 341064 625890 340180	69.0	30.0	1.0	21,330	Units 2 – 5
Overstrand N3E5 to N3E6	624440 341170 624751 341064	40.2	59.5	0.3	50,748	Unit 1
Cromer N3E5 to N3E4	623380 341485 622641 341972	21.6	78.4	0	48,677	Unit 22

Note: * N3E5 etc. refer to EA Marker Numbers.
** Sediment yield per metre of cliff recession.

2.3 Cliff types

A range of landslide processes, reflecting the variable geology has shaped the cliffline into a series of steep to near-vertical cliffs and Undercliffs (i.e. cliffs comprising a lower seacliff separated from a pronounced rear cliff that marks the landward limit of instability). Coastal defences, including seawalls fronted by a sand/shingle beach retained by groynes, currently protect the cliffline at Overstrand and Mundesley; timber palisades and groynes provide protection for much of the intervening cliffline.

In places, the cliffs have been stabilised by a variety of landslide remedial measures, including drainage and retaining structures. In front of the Bacton gas terminal site the cliffs have been stabilised by a variety of landslide remedial measures, including re-grading and slope drainage. Coastal defences, including seawalls fronted by a sand beach retained by groynes, protect a low cliffline between Bacton Green and Walcott.

26 separate cliff behavioural units have been identified based on the surface form, geology, and the known or inferred landslide processes. The boundaries of these units are shown in Appendix 3 (drawings supplied separately as scale maps); however, without detailed field mapping, the extent of the units is provisional. A summary of the principal characteristics of each unit is presented in Table 4.1.

The condition of the cliff units was described in terms of the following categories:

- **Actively retreating** – On-going cliff recession, through a combination of regular cliff failures (often falls, mudslides and mudflows) and rare large landslide events. Of interest, a large landslide has occurred recently in cliff unit 7 (Sidestrand E, 626760E 349716N), involving the runout of debris some 75m or more across the foreshore.

- **Actively unstable** – On-going slope instability and loss of cliff top land despite the presence of coastal defences. Failures are generally small-scale mudslides and debris slides, although large events can and do occur.

- **Marginally stable** – Localised small-scale instability, largely confined to the cliff face, although some loss of cliff top land may occur. Problems of this nature are often associated with the build up of pore pressures along blocked or failed drainage lines.

- **Relatively stable** – Cliffs show very few signs of instability other than minor small slips or creep.

Construction of seawalls has generally reduced the rate of recession and the likelihood of slope instability problems. However, prevention of marine erosion has not eliminated the potential for slope failure, because of the importance of internal factors in promoting instability. Whilst slope degradation behind defences generally involves relatively small and minor events, large-scale dramatic events do occur and can result in considerable loss of land, as occurred at Clifton Way, Overstrand between 1990-1995. The slope toe had been protected by wooden breastwork defences. The use of such timber palisades appears to have reduced the recession rate rather than prevented erosion, because of the importance of internal factors in promoting instability. Water flow through the palisades allows the washing out of the sediment that accumulates at the toe of the cliffs behind the palisades. The cliffs are still attacked at the base sufficiently frequently to remain steep and unvegetated, and the geological exposures remain visible.

In general, there appears to a number of distinctive recession models:

- **Type A** – Cliffs prone to repeated high-angled debris slides and lobate mudslides within distinct, narrow gully channels. These cliffs are affected by regular, small-scale recession events, with cliff top losses of probably in the order 1-5m/failure event.

- **Type B** – Cliffs prone to large, episodic landslide events, usually deep-seated rotational slides or compound style failures. Significant cliff top losses can occur during landslide events, probably up to 25-30m in width.

- **Type C** – Cliffs prone to large, episodic landslide events, usually major elongate mudslides and multiple rotational failures. These cliffs appear to be associated with the laminated lake clays of the Intermediate Beds. At Clifton Way, for example, 85-110m of cliff top was lost due to mudslide activity between 1990 and 1995 (Frew and Guest 1997).

These three models describe the active recession on the unprotected (and part-protected) coast and the 'Do Nothing' scenario for those sections defended by seawalls or rock revetments.

For all three models, recession appears to involve a repeated cycle of the following three stages:

Stage 1 – basal undercutting of the intact cliff foot by wave action. This leads to steepening of the cliff profile and a reduction in slope stability;

Stage 2 – cliff failure, involving either small-scale shallow slides (e.g. mudslides or mudflows), rare, large deep-seated landslides (e.g. rotational or compound slides) or a combination of both;

Stage 3 – removal of debris from the foreshore by wave action, leading to the onset of basal undercutting.

Field assessments of characteristic slope angles provides a broad indication of the limiting angles prior to failure (i.e. approaching the end of Stage 1, above) and post failure (i.e. Stage 2) within each cliff unit. These angles are presented in Table 4.1.

Hutchinson (1976) describes how the lithology and structure (i.e. deformations in the laminated diamicton) control landsliding on the Cromer-Overstrand cliffs of the glacigenic sediments. In general, deep-seated landslides tend to be confined to cliffs higher than 50m, developed in the intensely deformed diamicton. There is a tendency for large, deep-seated landslides to exhibit a period of gradual pre-failure movements (varying from a few days to a few weeks) before final, sudden failure occurs.

A catalogue of some of the larger historical landslide events recorded on the Cromer-Overstrand cliffs is presented in Appendix A.

Table 2.2 A summary of the main features of the cliff units between Cromer and Walcott

Unit	Defences	Condition	Slope Angles		Estimated Variance		Cliff Width (crest to toe) (m)	Estimated Cliff Height (m)	Recession Model*
			"Stage 1" headlands	"Stage 2" Landslide embayments	"Stage 1" headlands	"Stage 2" Landslide embayments			
24. Cromer Undercliff	Groynes	Actively unstable	30-35	30	0.9	1.0	70-80	25-35	A
23. Lighthouse Hill	Groynes	Actively unstable	25-30	20-22	2.3	1.0	120-170	40-50	B
22. Overstrand (Golf Course)	Groynes	Actively unstable	27-30	22-25	1.4	1.0	70-80	30-40	B
1. Overstrand W (Golf Course)	Timber palisades and groynes	Actively unstable	30-35	22-23	4.1	1.3	30-40	20	A/B
2A. Overstrand (W)	Timber palisades and groynes	Marginally stable - Actively unstable	40	37	2.9	1.7	25-30	15-20	A
2B. Overstrand (Slipway)	Seawall and groynes	Marginally stable	30	37**	2.4	1.7**	25-30	15	A
3. Overstrand (C)	Seawall and groynes	Marginally stable - Actively unstable	30	25	2.2	1.2	30-50	15-20	B
4. Clifton Way	Seawall (part) or timber palisades, groynes; rock revetment at Clifton Way slide	Actively unstable	30	15-20	2.3	3.5	150 (max)	35	B/C
5. Overstrand (E)	Timber palisades	Actively retreating	40-45	25	4	1.2	60-90	25	B

Note: * Recession models are described in the text.
** No landslide embayments noted in these sections; however, angles estimated based on behaviour of neighbouring sections.

Table 2.2 A summary of the main features of the cliff units between Cromer and Walcott (continued)

Unit	Defences	Condition	Slope Angles		Estimated Variance		Cliff Width (crest to toe) (m)	Estimated Cliff Height (m)	Recession Model*
			“Stage 1” headlands	**“Stage 2” Landslide embayments**	**“Stage 1” headlands**	**“Stage 2” Landslide embayments**			
6A. Sidestrand (W)	Timber palisades	Actively retreating	40	33-35	3.2	1.5	70-100	20-25	A
6B. Sidestrand Hall	No defences	Actively retreating	40	32-35	3.3	1.6	75-110	20-30	A
7. Sidestrand (E)	No defences	Actively retreating	35-40	19-20	3.5	0.7	70-150	25	B
8. Trimingham (W)	No defences	Actively retreating	40	35	3	1.5	70-110	25	A
9. Trimingham (C)	No defences	Actively retreating	35	20	1.6	0.9	50-100	30-40	B
10. Trimingham (E)	Concrete seawall, timber palisades and groynes	Actively unstable	25	20	1.2	0.8	100-160	60	B
11. Beacon Hill	Timber palisades and groynes	Actively unstable	35-40	30	2.5	1.2	60-100	55-60	A
12. Marl Point	Timber palisades and groynes	Marginally stable – Actively unstable	30	25	0.9	1	50-100	45-50	B
13. Cliftonville	Timber palisades and groynes	Marginally stable – Actively unstable	40-45	35-37	2.5	1.5	20-40	17	A

Note: * Recession models are described in the text.

Table 2.2 A summary of the main features of the cliff units between Cromer and Walcott (continued)

Unit	Defences	Condition	Slope Angles		Estimated Variance		Cliff Width (crest to toe) (m)	Estimated Cliff Height (m)	Recession Model*
			“Stage 1” headlands	“Stage 2” Landslide embayments	“Stage 1” headlands	“Stage 2” Landslide embayments			
14. Mundesley (W)	Concrete blocks (within steel railing frames) and groynes	Marginally stable – Actively unstable	40	35	1.2	0.8	20-30	18	A
15. Mundesley (C)	Seawalls and groynes	Relatively stable	36-37	33**	0.9	1**	10-15	7	A
16. Mundesley (E) to Bacton Terminal (W)	Timber palisades and groynes	Actively unstable	38-40	30-32	3.7	2.5	30-50	20	A
17. Bacton Terminal (W) to Bacton Terminal (C)	Timber palisades and groynes	Actively unstable	47-52	45	4.9	1.0	20-25	15-20	A
18. Bacton Terminal (C) to Bacton Terminal (E)	Timber palisades and groynes: regraded and drained slopes	Relatively stable	28-30	38**	0.9	1.0**	20-25	15-20	A
19. Bacton Terminal (E) to Bacton Green	Timber palisades and groynes; sheet pile wall at the cliff foot	Marginally stable	33-35	30	0.9	1.0	15-20	10-15	A
20. Bacton Green to Walcott	Concrete seawall and groynes. Seawall obscures low cliff face	Stable***	No slope angles could be measured in this section as the seawall completely obscures what was probably a 5m high low cliff.				Not seen	5	A
21. Walcott to Ostend	Timber palisades and groynes	Actively unstable	46-50	29-35	7.1	2.5	10	10-20	A

Note: * Recession models are described in the text.
** No landslide embayments noted in these sections; however, angles estimated based on behaviour of neighbouring sections.
*** The seawall extends to the top of the cliffline.

3. CLIFF BEHAVIOUR AND MANAGEMENT

3.1 Future cliff behaviour

Failure of the coastal defences and slope stabilisation works would lead to a renewal of cliff recession and coastal landslide activity, with significant property and environmental/amenity losses. In order to develop a framework for assessing the potential for renewed recession of the protected cliffs it is useful to consider the behaviour of the unprotected cliffs elsewhere on the north Norfolk coast.

A number of points can be made:

- Despite the variability of the glacigenic sediments, the cliffs have retreated at relatively uniform long-term rates. Cambers (1976) reports a long-term recession rate of 0.65-0.75m/year, based on comparison of cliff positions on Ordnance Survey maps of 1880 and 1967. Figures 3.1 and 3.2 summarise the pattern of historical recession along the cliffline, which highlights a maximum recession of 175m between Overstrand and Trimingham for the period 1885 – 1985.

Time Period	Recession Rate (m/year)
1880-1905	0.72
1905-1946	0.65
1946-1967	0.75

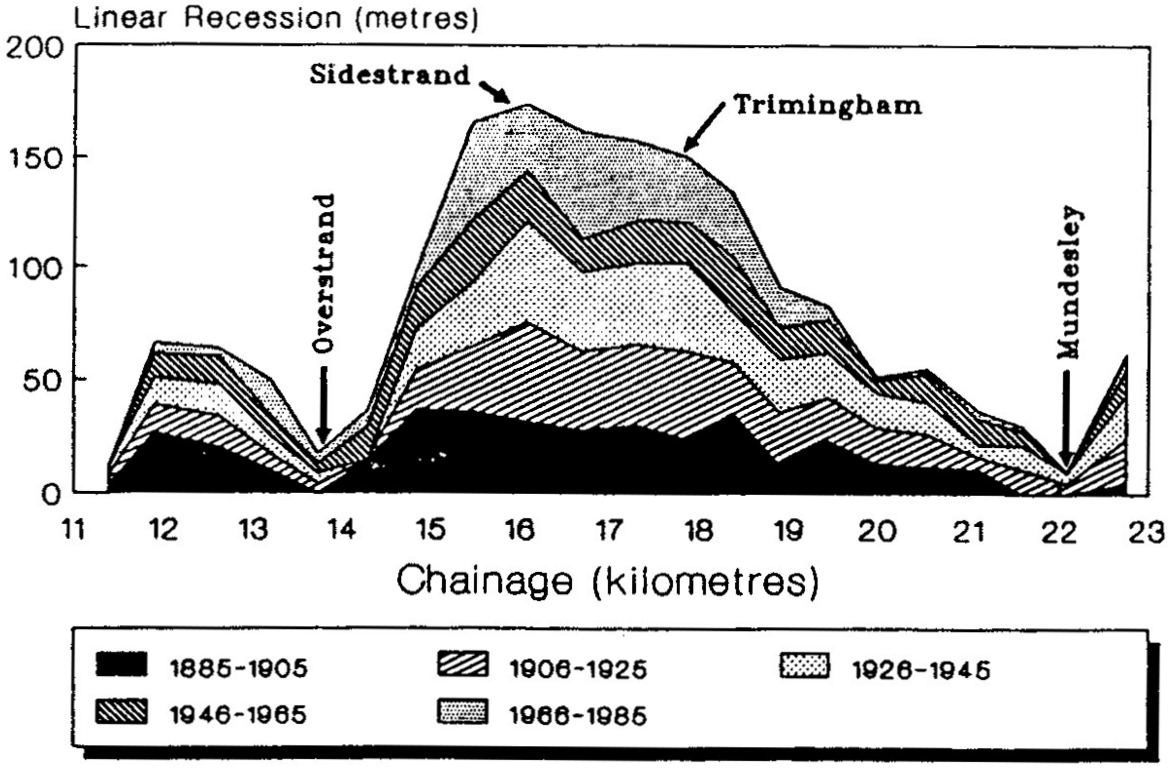

Figure 3.1 A summary of the cumulative recession along the North Norfolk cliffs (Clayton and Coventry 1986)

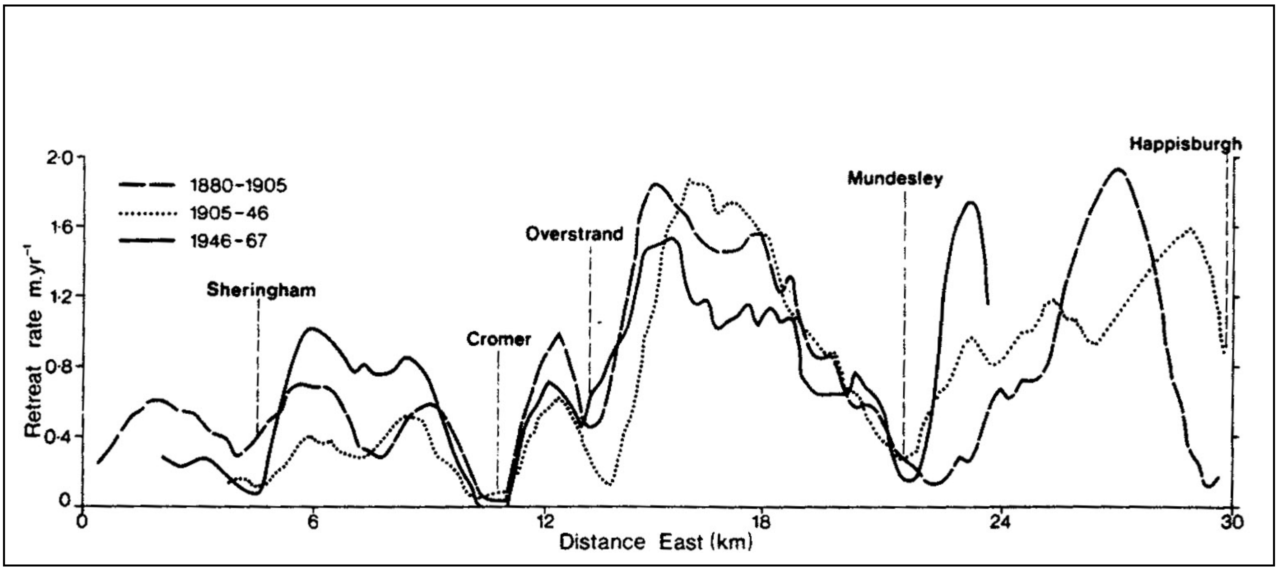

Figure 3.2 Variation in cliff recession rates along the North Norfolk coast (Cambers 1976)

- Cliff recession is driven by wave attack at the cliff foot, removing landslide debris from the cliff foot and undercutting the exposed *in-situ* materials. The importance of wave action was demonstrated by Cambers (1976), who related the recession rate to the frequency that the high tide mark reached the cliff foot:

Site	Retreat Rate m/year (1971-72)	Number of times the cliff base was reached by the high-tide mark (1971-72)
Weybourne	0.029	26
West Runton	0.466	122
Overstrand	1.450	385

- Lowering of the foreshore (a sand/shingle beach overlying a chalk bedrock platform) exerts a significant control on the rate of cliff recession. The horizontal recession of the cliff line, R, has been related to the vertical erosion of the platform, z, by simple relations such as

  $dz = dR \tan \beta$,

  where β is the gradient of the shore platform.

  Rates of platform lowering can be surprisingly high, especially on coastlines developed in glacial tills or clays, in the order of 0.1-10mm/year. This can become an important consideration in the long-term performance of coastal defence structures. The water depths in front of the structure can increase significantly over its design life, affecting the overtopping performance and standard of protection as well as increasing the risk of undermining.

  Shore platform erosion may continue irrespective of the cliff recession process. Thus, when defences fail or are removed, waves can arrive at the cliff foot more frequently than would be the case on a ‘natural’ (i.e. unprotected) cliff-beach system. This offers a possible explanation for the dramatic, short-term recession rates recorded at Happisburgh. Following the removal of the defences (timber palisades) at this location, the cliffs retreated 50m in a 3-year period from 1996-1999. However, as the cliff-beach system gradually develops a new equilibrium form, the recession rate will decline after a number of years.

- Recession rates can be highly variable over the short-term. In the following table, results from Cambers (1976) demonstrate how recession rates between West Runton and East Runton varied from 0 to over 3m in any single year :

Site	1971 Retreat (m)	1972 Retreat (m)	1973 Retreat (m)
1	0	0.1	0
2	0	0	0
3	0	0.3	0
4	0	0	0
5	0	0	3.0
6	0	0.1	0.6
7	0	0	0

- The dominant recession mechanism is landsliding, as indicated below (from Cambers 1976). This highlights the importance of episodic cliff top failure events rather than continuous year-by-year loss in causing cliff retreat.

Site	Landslides %	Mudflows %	Wind Erosion %	Water Erosion %
Weybourne	100	0	0	0
Sherringham	72	0	28	0
Overstrand	73	7	0	20
Mundesley	86	0	5	9

Hutchinson (1976) describes how landsliding on the Cromer-Overstrand cliffs is controlled by the lithology and structure (i.e. deformations in the laminated diamicton) of the glacigenic sediments. In general, deep-seated landslides tend to be confined to cliffs higher than 50m, developed in the intensely deformed diamicton. There is a tendency for large, deep-seated landslides to exhibit a period of gradual pre-failure movements (varying from a few days to a few weeks) before final, sudden failure occurs.

A catalogue of some of the larger historical landslide events recorded on the Cromer-Overstrand cliffs is presented in Appendix A. A number of the largest events are listed below.

Date	Recession Event Size
1927	100 yards long, 10-20 yards wide.
1931	50 yards long, 25-27 yards wide.
1947	300 yards long, 10 yards wide.
1958	70 yards long, 30 yards wide.
1962	80 yards long, 7 yards wide.
1962	160 yards long, 15 yards wide.
1973	100m long, 6-8m wide.

The cliffs are very sensitive to the impact of large storm events. For example, the cliffs at Bacton were cut back by as much as 100’ (c30m) during the 1953 storm surge (Grove 1953). Cambers (1976) notes how a smaller surge in November 1971 led to significant landsliding, with 11% of the total cliff volume lost in 1971 occurring in that one day. During the following months, however, the recession rate was lower than average because the landslide debris remained on the foreshore and protected the cliff foot.

3.2 Do Nothing scenarios

The implications of this type of cliff behaviour for the future management of the North Norfolk cliffs are best summarised by the following two points:

1. The clifflines are highly vulnerable to the failure or removal of the coastal defences. Such loss of the defences would result in a rapid onset of wave attack at the cliff foot.

2. The cliff face behind and adjacent to the breach would transform from what is effectively a stable slope to an actively unstable near-vertical cliff within a relatively short period (estimated to be less than 5 years). The area affected by instability would rapidly spread along the cliffline.

For those areas where the Type A recession model is applicable (i.e. Cliff units 1 and 2 in Overstrand; units 13-16 at Mundesley), the renewal of cliff top recession behind and adjacent to a breach would probably involve:

- A dramatic initial surge of cliff top retreat, possibly involving the loss of up to 50m within the first 5 years after defence failure/removal.

- The establishment of a relatively uniform long-term average annual recession rate with episodic events separated by periods of very slow or no retreat. As the cliffs are low (<50m high), the individual landslides are likely to be small-scale failures, possibly involving around 2-5m cliff top loss in a single event.

- Dramatic, overnight losses associated with the impact of low probability storm surge events. It is possible that over 30m of retreat could occur in a single event.

For Types B and C recession model areas, the potential for large, episodic loss of cliff top land needs to be superimposed on the Type A recession trend. Such events are likely to be of the order of 25-30m for the Type B sites (i.e. Cliff unit 3 at Overstrand). In contrast, the 1990-1995 losses at Clifton Way suggest that over 100m might be lost over a relatively short period at Type C sites (i.e. Cliff unit 4 at Overstrand).

The predicted climate changes and rise in sea level will probably lead to changes in the frequency and, possibly, the magnitude of landslide events. This will result in increased recession rates.

A simple *historical projection* model provides an indication of the possible changes (National Research Council 1987; Leatherman 1990):

$$\text{Future recession rate} = \frac{\text{Historical recession rate}}{\text{Historical sea level rise}} \times \text{Future sea level rise}$$

The model is very simple and assumes that sea level rise is the dominant influence on recession. Analysis of North Shields tidal gauge data from 1901 to 1996 (Woodworth et al 1999) has demonstrated that sea levels on the east coast have risen by up to 1.7mm/year during the last century. Furthermore, this trend was shown to be accelerating by 0.4 to 0.5mm/year. If the sea level rises over the next 60 years at an average rate of 6mm/year (in accordance with MAFF recommended allowances), the historical projection method suggests an increase by a factor of 3.5 in average annual recession rate. This suggests a long-term average recession rate of

2.6m/year (0.75m x 3.5). This figure probably represents an upper bound rate, with the current recession rate on the nearby, unprotected cliffs (0.75m/year) providing a lower bound figure.

As noted earlier, the cliff recession process, caused by occasional relatively large landslides, is episodic rather than continuous. For this reason it is better to express the long-term recession rate as up to 26m every 10 years rather than 2.6m/year. Figure 3.3 presents a hypothetical sequence of recession events that might follow failure/removal of the defences.

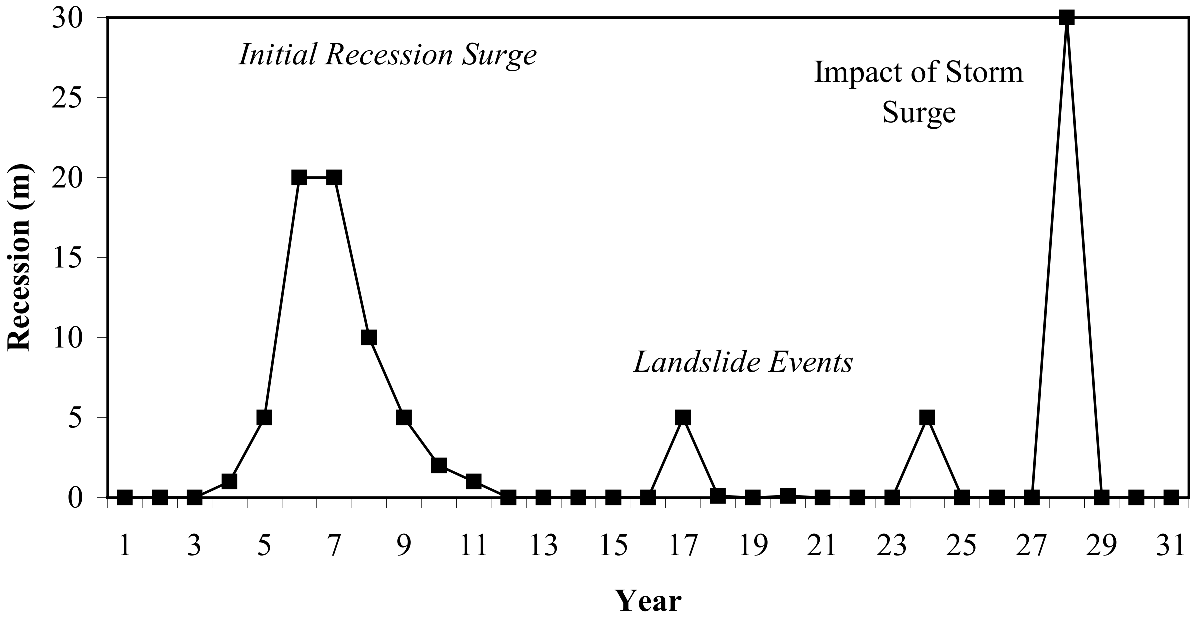

Figure 3.3 A hypothetical recession sequence, following seawall failure at year 0

3.3 Cliff management

It is suggested that a cliff management programme is developed and implemented to ensure that the stability of the protected cliffs is maintained to an acceptable level, including:

- Systematic inspections, recording, and regular monitoring using manual survey techniques. Visual inspection can be valuable in identifying future problem sites and keeping them under review until a more formal measurement and recording strategy becomes necessary. Standardised recording sheets should be used. A photographic record should be kept of the cliff position at specific points.

- Investigation, maintenance, treatment, and repair of small-scale slips when they occur to prevent development or propagation of major, deep-seated failures.

- Implementation of emergency works and preventative measures on the slopes as and when required.

- Regular drainage inspections and repairs.

Elsewhere, management of the unprotected cliffs is necessary to ensure public safety. Cliff recession rates should be monitored on a regular basis (e.g. annual measurements at a network of erosion posts). A narrow setback area at the seaward edge of the cliff top could be created and maintained, where public access is restricted.

4. CONCLUSION

The coastal cliffs between Cromer, Overstrand, Mundesley, and Walcott are developed in a variable sequence of weak glacigenic deposits, including a distorted diamicton unit, sand/gravel meltwater layers, and lacustrine clays. Seawalls (a rock revetment at Clifton Way, Overstrand) currently protect the cliffs at Overstrand, Trimingham, Mundesley, and Bacton, while timber palisades and groynes provide protection for much of the intervening cliffline. These defences appear to have reduced the recession rate rather than prevented erosion, because of importance of internal factors in promoting instability. Whilst slope degradation behind defences generally involves relatively small and minor events, large-scale events do occur.

The cliffs in front of part of the Bacton Terminal site have been regraded and drained to improve the stability. At present they appear to be affected by only small-scale slope failures and are not retreating. Concrete seawalls have been built in front of what was probably a low cliff (<5m high) between Bacton Green and Walcott. If the defences fail (either as a result of shoreline processes or because of a major landslide event) marine erosion of the cliff foot will re-commence and, in time, the cliff top will begin to retreat.

A field assessment of the cliff conditions has led to the identification of three broad types of recession model that are applicable for modelling the 'Do Nothing' scenario following defence failure. These models are:

- **Type A** – Cliffs prone to repeated high-angled debris slides and lobate mudslides within distinct, narrow gully channels. These cliffs are affected by regular, small-scale recession events, with cliff top losses of probably in the order 1-5m/failure event.

- **Type B** – Cliffs prone to large, episodic landslide events, usually deep-seated rotational slides or compound style failures. Significant cliff top losses can occur during landslide events, probably up to 25-30m in width.

- **Type C** – Cliffs prone to large, episodic landslide events, usually major elongate mudslides and multiple rotational failures.

Table 4.1 below presents a judgement of the recession models that are expected to be applicable for the different clifflines along the frontages of interest.

Surface form, geology, and landslide processes have provided the basis for estimating the potential recession models that will apply under the 'Do Nothing' scenario. However, it should be stressed that the cliffline is noted for the rapid facies changes within the glacial materials. Thus, it is difficult to be precise about what materials can be expected at a particular section and what materials are likely to be encountered behind the cliffline. The present day conditions may not prove to be a reliable indicator of future behaviour.

Table 4.1 A summary of the potential cliff recession models

Strategy Area	Unit	Slope Angles		Potential Recession Model
		'Stage 1' headlands	**'Stage 2' Landslide embayments**	
Cromer to Overstrand	24. Cromer Undercliff	30-35	30	**A**
	23. Lighthouse Hill	25-30	20-22	**B**
	22. Overstrand Golf Course	27-30	22-25	**B**
Overstrand	1. Overstrand (W) (Golf Course)	30-35	22-23	**A/B**
	2A. Overstrand (W)	40	37	**A**
	2B. Overstrand (Slipway)	30	37**	**A**
	3. Overstrand (C)	30	25	**B**
	4. Clifton Way	30	15-20	**C**
	5. Overstrand (E)	40-45	25	**B**
Sidestrand and Trimingham	6A. Sidestrand (W)	40	33-35	**A**
	6B. Sidestrand Hall	40	32-35	**A**
	7. Sidestrand (E)	35-40	19-20	**B**
	8. Trimingham (W)	40	35	**A**
	9. Trimingham (C)	35	20	**B**
	10. Trimingham (E)	25	20	**B**
	11. Beacon Hill	35-40	30	**A**
Mundesley	12. Marl Point	30	25	**B**
	13. Cliftonville	40-45	35-37	**A**
	14. Mundesley (W)	40	35	**A**
	15. Mundesley (C)	36-37	33**	**A**
	16. Mundesley (E)	38-40	30-32	**A**
Bacton and Walcott to Ostend	17. Bacton (W)	47-52	45	**A**
	18. Bacton (C)	28-30	38**	**A**
	19. Bacton (E)	33-35	30	**A**
	20. Bacton – Walcott	Low cliffs covered by seawall		
	21. Ostend	46-50	29-35	**A**

Note: ** No landslide embayments noted in these sections; however, angles estimated based on behaviour of neighbouring sections.

For all three models, recession appears to involve a repeated cycle of the following stages:

Stage 1 – basal undercutting of the intact cliff foot by wave action. This leads to steepening of the cliff profile and a reduction in slope stability;

Stage 2 – cliff failure, involving either small-scale shallow slides (e.g. mudslides or mudflows), rare, large deep-seated landslides (e.g. rotational or compound slides) or a combination of both;

Stage 3 – removal of debris from the foreshore by wave action, leading to the onset of basal undercutting.

Field assessments of characteristic slope angles has provided a broad indication of the limiting angles prior to failure (i.e. approaching the end of Stage 1, above) and post failure (i.e. Stage 2) within each cliff unit. These angles and the associated variance are included in Table 4.1 and are intended to form the input data for the numerical modelling of cliff recession (see the accompanying report on cliff modelling)

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Appendices

Appendix A

Catalogue of Landslide Events on the Cromer – Overstrand Coast 1611-1973
(Hutchinson 1976)

Table A.1 Catalogue of Landslide Events on the Cromer-Overstrand Coast 1611-1973 (Hutchinson 1976)

Year	Description
1611	Many large portions of land washed away
1799	'During the winter 1799, the cliffs near the light-house made several remarkably large shoots, one of which brought with it at least half an acre of ground, and extended a considerable way into the sea at low water mark'.
1825	Jan 25th. 'On Saturday morning last a large mass of earth was detached from a part of the hills near Cromer, called Lighthouse Hills, which at that place are about 250 feet in height. It fell with great force on the beach, extending itself beyond the low water mark about 300 yards from the cliff; it is calculated that it now covers upwards of 12 acres, and that it must contain not less than half a million cubic yards, equal to as many cart loads. As the fall of this enormous body was awfully sudden and unexpected, it is fortunate no person was near it…..'
1825	Feb 5th 'The extraordinary high tide which visited the coast of Norfolk on the 5th of February last, swept away considerable portions of the cliffs throughout their course on the eastern side of the country… The tremendous effects produced by the sea elevated many feet above the highest level recorded, and agitated by the remarkable wetness of the soil. So completely were the high grounds along the eastern coast previously saturated by the land springs, that daily avalanches, or 'shoots' as they were previously termed, had occurred during the winter. Many of these shoots consisted of enormous masses of clay, mud and sand, from 100 to 200 feet in thickness, which overspread the beach with their debris and prevented all passage below, except at extreme low water; and formed an inaccessible barrier, in some cases several hundred yards in depth, for some miles along the shore, between Cromer and Mundesley'.
1832	Aug 19th. A great fall from Lighthouse Hill which caused apprehension for the safety of the lighthouse itself. Trinity House determined on erecting a new one inland. The fall extended to low water mark and covered several acres of the beach. The fall brought the cliff edge to within 8 paces from the lighthouse. The slide extended about 450 feet along the coast and involved a piece of the cliff top about 100 feet wide.
1835	A large landslide is reported.
1837	Feb 18th On the 17th to 18th an extraordinary high tide, accompanied by a furious north-easterly gale, washed away a Bath House and other buildings built on Cromer beach. On the morning of Feb. 18th the cliff being undermined fell in, bringing with it one house.
1843	A large landslide, taking 6 acres of the Lighthouse Hill.
1845	Three celts were found after a cliff fall near Cromer.
1866	Dec 6th. During the night of the 5th to 6th, the old (Foulness) lighthouse toppled down the cliff and was immediately buried by a great fall from the cliff which followed it.
c1879	An extensive, recent landslide was seen at Foulness in August 1879, which according to residents 'extended to 3 acres of land'. Its debris buried the beach at high tide.
1881	A large landslide, 300 feet long, in the Lighthouse Hills, is reported which took upwards of an acre of land.
1881	Spring. A landslip is reported near Overstrand which happened 'so suddenly that a ploughman and a pair of horses, which at the time were at work on the soil near the summit of the cliff, made a narrow escape from being precipitated on the beach below. The horses, upon feeling the tremor of the ground beneath their feet, shied and plunged, but fortunately in an inland direction, and they and their driver were saved'.
1882	A landslide (360 yards by 150 yards) on Target Hill in which a pony was buried.
1898	Jan. 'After a heavy north-east gale in 1898, a large piece of the cliff forming part of the golf links subsided'.
1898	Jan. 'after another gale and hightide, two large falls occurred about 200 yards in width and 150 feet in height, the quantity of earth falling on the beach being estimated at from 3000 to 4000 tons, forming at the present time a small promontory on the beach'.
1898	June. A landslide 200 yards in length is reported.
1899-1902	It is reported that important slips took place in 1899, 1901 and 1902 between Runton and Sidestrand, up to 10 to 160 yards in length by 18 to 70 yards deep.

Year	Description
1908	October. A large landslide, taking part of the golf links, is reported.
1911	A large landslide, taking part of the golf links, is reported.
1927	Aug 28th. A landslide, involving a piece of the cliff top 100 yards long and 10 to 20 yards wide and estimated at more than 20,000 tons took place in the early hours before dawn on Sunday morning. The debris covered an area 100 yards by 120 yards and was about 20 feet thick. The landslide was located west of the lighthouse, east of Marl Bluff.
1928	Aug 28th. A landslide, involving a piece of the cliff top 100 yards west of Cromer, is reported to have taken place before dawn.
1931	July 11th. A large landslide of about 100,000 tons is reported to have taken place at 5.20 am on Saturday morning in the cliffs nearly opposite the lighthouse, at the western end of Lighthouse Hills. It was thought to be the largest for more than 30 years on this stretch of coast. The debris narrowly missed a boring rig working on the beach and formed a tongue out into the sea. The area of cliff top lost measured more than 150 feet in length and up to between 75 and 80 feet in width (in from the cliff edge).
1937	Feb 5th. A large landslide, of about 100,000 tons is reported near Lighthouse Hill. The cliff edge was left intact as the slide involved only the lower three-quarters of the cliff, thus completing a fall which started at the same place about 5 years earlier (the 1931 slide). The debris spread 150 yards across the beach.
1947	Oct 22nd. A large landslide, of about 40,000 tons, is reported to have taken place in the early hours of Saturday morning several hundred yards east of the Lighthouse. A slide of cliff top about 300 yards long and 10 yards wide is said to have taken place.
1950	Dec 22nd. A landslide of several thousand tons took place at the east end of Cromer promenade, at Doctor's Steps. Although the final fall occurred on December 22nd, considerable movements had preceded this, 15 feet of sinking being reported on December 18th.
1951	A small fall opposite Cromer Coastguard Station.
1952	Jan. A fall of about 200 tons of cliff, opposite Cromer Coastguard Station.
1952	Feb 24th. A second fall of about 200 tons, opposite Cromer Coastguard Station.
1957	Feb 28th. A small landslide reported towards the east end of Overstrand Promenade, affecting the lower third of the grassed slope.
1958	April 24th. A large landslide occurred ¼ mile to the east of the lighthouse, involving a strip of golf course about 70 yards long and up to 30 yards wide.
1961	March. A landslide between Lighthouse Hill and Overstrand.
1962	April 21st-23rd. A fall of several hundred tons, is reported from the same place as the 1958 slip. A strip of golf course about 80 yards long and up to 7 yards wide was involved.
1962	May 17th. A large landslide occurred at the same place as the April 1962 fall, involving a strip of golf course about 160 yards long and up to 15 yards wide. The slide started around the beginning of May and by 16th May a 'plateau' of the above dimensions had sunk about 12 feet, while remaining virtually horizontal, and was sinking at a rate of about half and inch per hour.
1962	June to September. A shallow translational slide took place almost adjoining the May 1962 slide on its western slide.
1963	Between 27th May and 22nd July. About 8,000 tons of the upper cliff on the west side of the cavity of the May 1962 slide fell onto the rear of the associated slide masses.
1963	November 28th. A landslide of about 4,000 tons occurred at Overstrand, damaging a sea front shelter. Believed to be due to underground springs.
1964	December c9th. A cliff fall of many hundreds of tons, involving a slice of the golf course, 40 yards long.
1965/66	A large slide, approaching 100m in width, took place immediately east of groyne F. The debris extended about 90m out to sea from the line of the original cliff foot. Little or none of the cliff top was involved.
1972	December 24th. A slide on the 125 foot high cliff near Overstrand. A strip of cliff top 15 feet wide was involved.
1973	December 15th or 16th. A large slide near the Cromer-Overstrand boundary. A slice of the golf course about 100m long and 6-8m wide, with a volume of 0.5 million cubic yards. The debris extended up to 82m out across the beach from the cliff foot and was about 130m wide and a maximum of about 10m thick.

Appendix B

Photographs of cliffs in various Cliff Behavioural Units

Plate 1 Cliff behavioural unit 16 – view east

Plate 2 Cliff behavioural unit 16 – small-scale sand flow

Plate 3 Cliff behavioural unit 17 – view west

Plate 4 Cliff behavioural unit 18 – view east; note the regraded slopes

Plate 5 Cliff behavioural unit 18 – view east; note the localised small failures of the regraded slope

Plate 6 Cliff behavioural unit 19 – view east; note the recent sheet pile wall at the cliff toe

Plate 7 Cliff behavioural unit 20 – Bacton Green, view east; note the seawall in front of a low cliff

Plate 8 Cliff behavioural unit 20 – Keswick, view east; note the seawall in front of a low cliff

Plate 9 **Cliff behavioural unit 21 – Ostend, view east; note the recent small cliff failure**

Plate 10 Cliff behavioural unit 21 – Ostend, view east

Drawing

RS / 008 Plan view of Cliff Behavioural Units