Muston Sands to Reighton Sands: Prediction of 50-Year Cliff Recession Distances

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1 Introduction

This short report has been prepared in response to the request from Natural England for advice relating to the following coastal cliff site:

- the proposed extension to the Flamborough Head SSSI.

The specific casework question to be addressed relates to the expected 50-year cliff recession distance between Muston Sands and Reighton Sands, Filey Bay. These predictions are required to underpin the site notification.

The assessment has used the same methodology as that used to estimate the 50-year recession distance for other clifflines between Flamborough Head and South Bay, Scarborough. This methodology has been reported in:

Lee M (2012) Flamborough Head, Filey Brigg to South Bay: Prediction of 50-Year Cliff Recession Distances. March 2012.

The following definitions are used in this Report:

Cliff Recession is the landward retreat of the cliff profile (from cliff foot - cliff top) in response to the cliff erosion process.

Cliff Behaviour Unit (Cliff Unit); the fundamental units for cliff investigation and management, reflecting the interrelationships between process and form over time. Cliff Units comprise three interrelated systems: cliff tops, cliffs and the foreshore (Figure 1).

Cliff Recession Categories; a broad classification of recession rates, based on the work of Cosgrove et al., (1997):

Class Range (m/year)	**Category**
0-0.1	Negligible
0.1-0.5	Moderate
0.5-1.0	Intense
1.0-1.5	Severe
>1.5	Very severe

Cliff Top; the junction of the cliff face and the un-displaced material adjacent to the cliff face.

Undercliff; an intermediate series of cliff faces and landslide benches between the rear cliff and the sea cliff.

Sea cliff; the most seaward cliff face within a landslide complex.

Rear cliff; the most landward cliff face within a landslide complex (i.e. the cliff top).

Relative sea level rise (RSLR) is the increase in the level of the sea relative to the land, taking account of both eustatic and tectonic/isostatic changes. RSLR can be associated with eustatic (global) sea-level rise or land subsidence, or a combination of both.

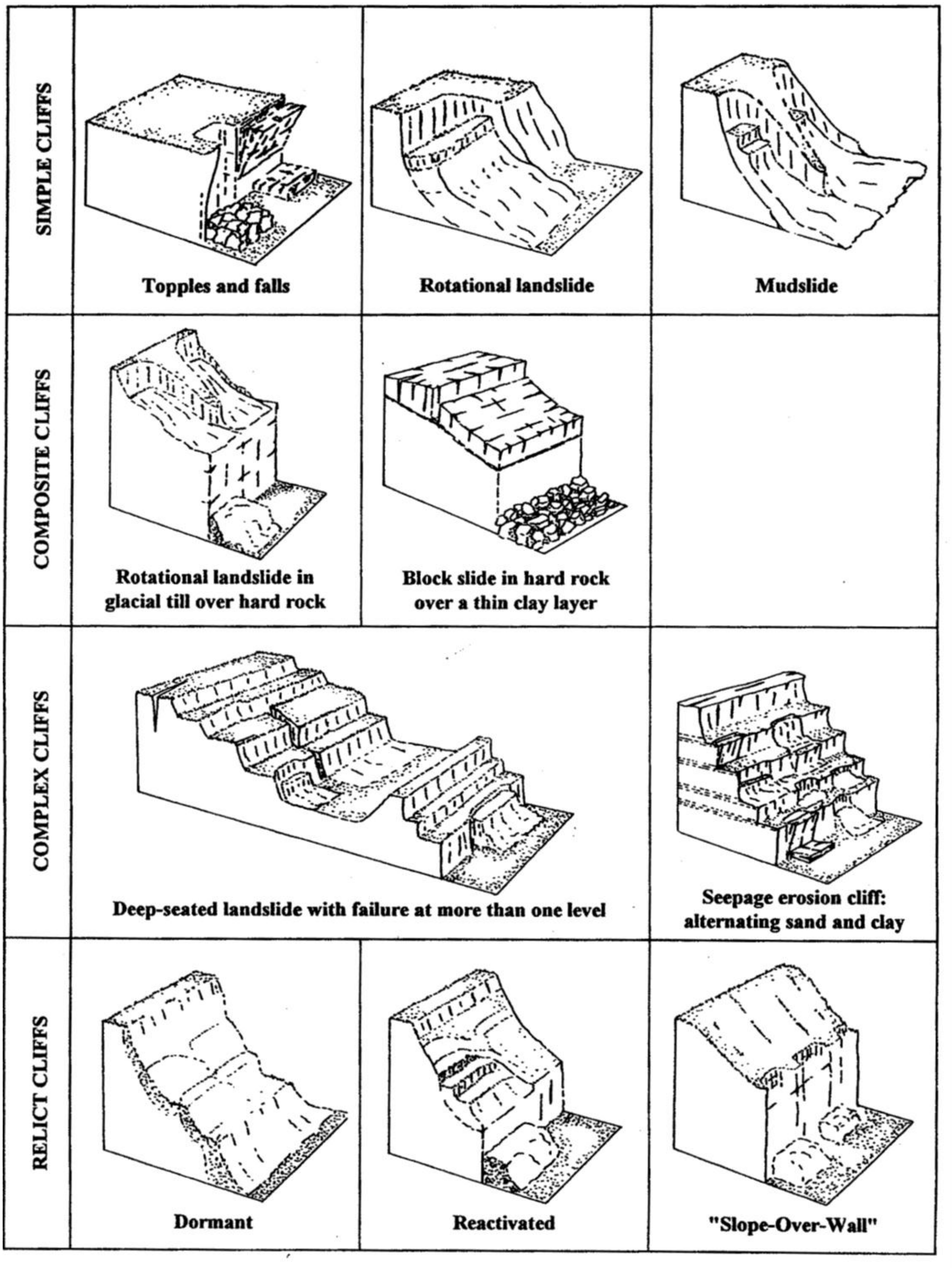

Figure 1 Cliff Types (from Lee and Clark, 2002)

2 Background: Recession Prediction Methods

Prediction of cliff recession rates over a period of accelerating relative sea-level rise (RSLR) remains a significant challenge. A variety of approaches are available, including (see Lee and Clark, 2002):

- *extrapolation of past trends*; this approach is based on the assumption that the historical recession rate provides a reliable indication of the future rate. Problems arise if the rate of RSLR in the future is expected to be different from the rise over historical period.
- *the Bruun rule*; RSLR is assumed to result in the parallel retreat of the cliff profile, albeit with a corresponding rise in elevation of the cliff foot. This geometric relationship forms the basis of an empirical model (the Bruun rule) for deriving the shoreline response to sea level rise (Bruun 1962).
- *historical projection*; this approach assumes that future changes in recession rate are directly proportional to the change in rate in RSLR. It involves multiplying the past rate by an adjustment factor derived from the ratio of future to past rates of RSLR (Leatherman, 1990).
- *probabilistic methods*; a variety of models have been developed, ranging from quasi-empirical judgement-based models (e.g. Lee, 2005) to more complex process-response simulation models (e.g. Lee et al., 2001; Lee et al., 2002; Dickson et al., 2007).

The problem with all these models has been validation of the results. Many predictions have been made for cliffline changes over the next 50-100 years. However, the future has not arrived yet and, hence, the results cannot be tested against what actually happens.

Lee (2011) attempted to provide some insight into the validity of model predictions by using the early 1990s as a start point for an analysis of Holderness cliff recession that took account of the RSLR advice from MAFF (1991). The results indicate that the method that gives the best prediction for the period 1990-2004 would have been simple extrapolation of past recession rates. The historical projection approach and the Bruun Rule over-estimate the actual recession for this period by over 400% and 20%, respectively.

Part of the problem is that the rate of RSLR did not accelerate in the way that had been predicted (MAFF 1991 suggested an allowance of 5mm/year). There has been a consistent global rise of around 1.7mm/year throughout the last century, with a high degree of fluctuation from decade to decade (the highest rates are probably around 2-2.5mm/year; e.g. Holgate 2007). Some 10-year periods show above average rise, others show lower rates of rise or RSL fall. The 2 decades since 1990 appear to fit this pattern, with no evidence of the significant acceleration in global sea levels that had been predicted. Holderness cliff recession rates have risen over the last 60 years, from around 1.2m/years in the early 1950s to around 1.5m/year by the year 2000. However, in the same way that there has been no significant acceleration in the rate of global sea level rise since 1990 there has been no rapid increase in the recession rate (Lee 2011).

It is quite possible that the acceleration in RSLR has been simply delayed and that it will be a driving factor in controlling cliff recession over the next 50-years. This, however, remains a considerable uncertainty and it seems unlikely that a single method can be used to predict recession rates with any degree of confidence. The better solution seems to be to provide predictions for contrasting scenarios:

1. Scenario 1 no acceleration of RSLR; this can be modelled by simple extrapolation of past trends;
2. Scenario 2 acceleration of RSLR at the predicted rates; assuming that future changes in recession rate are directly proportional to the change in rate in RSLR, this can be modelled with the historical projection approach:

   Predicted Recession Rate = Historical Recession Rate x Predicted RSLR/Historical RSLR

Recent analysis of tidal gauge data has demonstrated that over the last century sea-level has risen on the north east coast by up to 2.5mm/year (based on North Shields data, 1886-2008; Figure 2). If the sea level rises over the next 100 years at an average rate of 5mm/year, the above historical projection method suggests a factor of 2 increase in average annual recession rate.

Predicted Recession Rate = Historical Recession Rate x Predicted RSLR/Historical RSLR

= Historical Recession Rate x (5/2.5)

These 2 approaches will be used in this assessment. The extrapolation method is likely to result in a lower bound estimate, whereas the historical projection approach is likely to be very conservative. The reality may lie somewhere between.

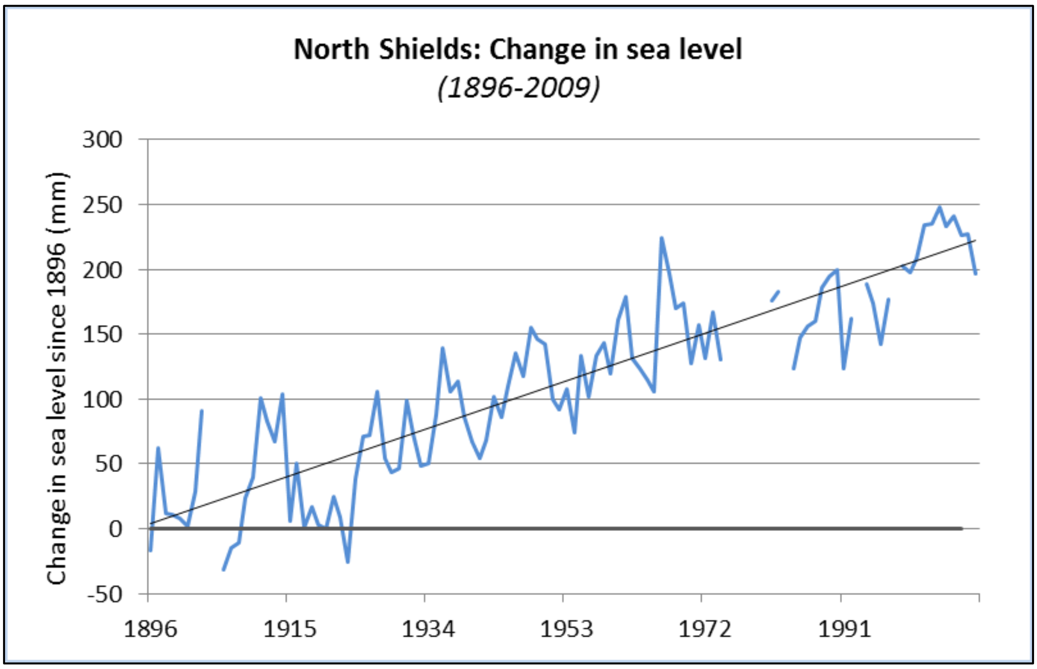

Figure 2 North Shields: changes in RSL (1896-2008) Source: Department of Energy and Climate Change
http://www.decc.gov.uk/assets/decc/Statistics/climate_change/1719-summary-report-on-sea-level-rise.pdf

Since the 2012 cliff recession report was compiled the results of the National Coastal Erosion Risk Mapping (NCERM) project have been made available through the Environment Agency's "What's in Your Backyard" website (http://www.environment-agency.gov.uk/homeandleisure/37793.aspx). The project provides coastal erosion projections for 20, 50 and 100-year time periods, taking into account the impact of climate change and relative sea-level rise. No details are available about the methodology used to make these projections, although an earlier paper by Moore et al. (2010) provides a useful introduction. An important distinction was made between complex and "non-complex" cliffs (Figure 1):

- non-complex cliffs; historical recession rates were incremented by 1% per year (for the UKCP09 high emission scenario) up to year 100.
- complex cliffs; the historical frequency of events that involve loss of cliff top land was modelled to increase linearly over the next 100 years (the magnitude of these events was assumed to stay the same as in the past).

The NCERM projections for the Filey Bay cliffs are presented in Table 1 and are compared with simple extrapolation and historical projection approaches in Section 5.

Table 1 NCERM projected cliff recession distances for the Filey Bay clifflines

Cliff Unit	Location Reference	20 years	50 years	100 years
Muston Cliffs	13890	0-6m	10-20m	20-40m
	13950	4-8m	10-20m	20-40m
	13960	4-8m	10-20m	20-40m
	13970	4-8m	10-20m	20-40m
	13980	4-8m	10-20m	20-40m
Primrose Valley Cliffs	13990	4-8m	10-20m	20-40m
	14020	4-8m	10-20m	20-40m
Flat Cliffs*	14030	5.7-11.3m	21.7-61.6m	43.4-61.6m
	14040	5.7-11.3m	21.7-61.6m	43.4-61.6m
Hunmanby Cliffs	14060	4-8m	10-20m	20-40m
	14070	4-8m	10-20m	20-40m
	14080	4-8m	10-20m	20-40m
	14100	4-8m	10-20m	20-40m
	14130	3.4-7.7m	10-20m	20-40m
	14150	10.6-19.4m	26.5-48.5m	53-97m
	14160	4-8m	10-20m	20-40m
	14170	4-8m	10-20m	20-40m
Reighton Cliffs	14180	4-8m	10-20m	20-40m

Note: * Estimates presented in the Flat Cliffs stability assessment and management plan (Halcrow, 2012)

3 Cliff Units: the Filey Bay Cliffs

The cliffline is unprotected and has developed in Late Devensian age (around 18k BP) glacial tills (the Filey Formation) that were emplaced across much of the landscape. These tills include stiff, silty sandy clays, sands and gravels and laminated stiff silty clays. Boreholes at Flat Cliffs revealed that the glacial sediments have a maximum recorded thickness of at least 35 m (-12.4m OD), but could exceed this given that the underlying Upper Jurassic Kimmeridge Clay was not encountered (Halcrow, 2012).

Five main cliff units have been identified (Table 2):

1. Muston Cliffs; part-vegetated simple cliffs developed in Filey Formation glacial tills. These cliffs are actively eroding through a series of relatively small rotational failures and lobate mudslides.
2. Primrose Valley Cliffs; part-vegetated simple cliffs developed in Filey Formation glacial tills. These cliffs are actively eroding through a series of relatively small rotational failures and lobate mudslides.
3. Flat Cliffs; a pre-existing landslide complex (an “undercliff”) developed in glacial till, comprising relatively deep-seated rotational and non-rotational landslides and shallower mudslides.
4. Hunmanby Cliffs; part-vegetated simple cliffs developed in glacial tills. These cliffs are actively eroding through a series of relatively large rotational failures.
5. Reighton Cliffs; part-vegetated landslide complex developed in glacial tills. These cliffs are actively eroding through a series of relatively large rotational failures.

Table 2 Cliff Units: Filey Bay

Cliff Unit	Description
	**MUSTON CLIFFS** (Filey to Primrose Valley) ***Bedrock;*** not observed (possibly Kimmeridge Clay below foreshore level) ***Superficial Deposits***; Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)**; Locally active to Partly active **Cliff Instability;** Part-vegetated mudslides and rotational failures in glacial till **Recession rates (SMP2);** 0.25m/year
	**PRIMROSE VALLEY CLIFF** (Primrose Valley to Flat Cliffs) ***Bedrock;*** not observed (possibly Kimmeridge Clay below foreshore level) ***Superficial Deposits***; Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Locally active **Cliff Instability;** Part-vegetated mudslides and rotational failures in glacial till **Recession rates (SMP2);** 0.25m/year

Cliff Unit	Description
	**FLAT CLIFFS CLIFF** (Flat Cliffs to Butcher Haven) ***Bedrock;*** not observed (Kimmeridge Clay below foreshore level; -20m OD) ***Superficial Deposits***; Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Locally active **Cliff Instability;** Pre-existing landslide complex: relatively deep-seated rotational and non-rotational landslides and shallower mudslides **Recession rates (Filey Bay Strategy Study);** 0.16m/year (cliff top)
	**HUNMANBY CLIFF** (Butcher Haven to Reighton Sands) ***Bedrock;*** not observed (possibly Kimmeridge Clay below foreshore level) ***Superficial Deposits***; Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Totally active to Locally Active **Cliff Instability;** Active rotational failures and mudslides developed in glacial till **Recession rates (SMP2);** 0.25m/year

Cliff Unit	Description
	**REIGHTON CLIFF** (Reighton Sands to Boat Cliff) ***Bedrock;*** not observed (possibly Speeton Clay below foreshore level) ***Superficial Deposits***; Filey Formation glacial tills. **Cliff Activity (NECAG Slope Condition)** Partly Active **Cliff Instability;** Relatively deep-seated rotational and non-rotational landslides developed in glacial till **Recession rates (Filey Bay Strategy Study);** 0.17m/year

4 Historical Cliff Recession Rates

Information on long-term historical recession of Filey Bay is limited to the generalised statements made in Futurecoast (Halcrow 2002) and in the SMP2 document. This information is summarised in Table 3.

Table 3 Estimated cliff recession rates: Muston Sands to Reighton Sands (from: Futurecoast and the SMP2)

Cliff Unit	Futurecoast			SMP2*
	Recession Potential	**Activity**	**Average Annual Recession Rate (m/year)**	**Average Annual Recession Rate (m/year)**
Muston Cliffs	Medium	Active	0.5 - 1	0.25
Primrose Valley Cliffs	Medium	Active	0.5 - 1	0.25
Flat Cliffs	Medium	Marginally stable	0.5 - 1	0.25
Hunmanby Cliffs	Medium	Active	0.5 - 1	0.25
Reighton Cliffs	Medium	Marginally stable	0.5 - 1	0.25

Note: * The 2nd generation Shoreline Management Plan for River Tyne to Flamborough Head (Royal Haskoning, 2007)

The recession estimates presented in Futurecoast are generally higher than those reported in the SMP2 documents. However, it is understood that the Futurecoast rates are high-level predictions based on cliff types and materials. The SMP2 rates are likely to have been supported by some historical map analysis.

In the Filey Strategy study (Halcrow 2002), long-term recession rates were determined at a limited number of points by historical map analysis. Of relevance to the current study are:

- Profile 117, Flat Cliffs (1853-2000); cliff top recession rate 0.16m/year (see Photo 1);
- Profile 118, Reighton Cliffs (1893-2000); cliff top recession rate 0.17m/year.

Since 2008, Scarborough Borough Council (as part of NECAG) has monitored cliff recession rates at a series of Ground Control Points between Staithes and Filey Bay. These control points are typically at 300m centres along selected clifflines. Data collection involves a bi-annual survey, measuring the distance from the control point to the cliff edge along a fixed bearing. A total of 16 points lie between Muston and Reighton Cliffs. The various monitoring reports produced since 2008 are available from the North East Coastal Observatory website: http://www.northeastcoastalobservatory.org.uk/.

The cliff monitoring results are summarised in Table 4. The only cliff where significant cliff top recession (>0.2m/year; moderate to intense recession) has been recorded is Muston Cliff (Ground Control Points 5 and 7). The fact that many sites have shown no recession merely indicates the episodic nature of cliff retreat, rather than that the cliffs in question are stable; the monitoring period (2008-2013) has simply been too short.

An assessment of cliff recession at Flat Cliffs was undertaken by Halcrow (2012) as part of the Scarborough Borough Council stability assessment and management study. This assessment used both historical maps (Table 5) and aerial photography (Table 6) to determine long, medium and short-term changes at 5 profile sites within this cliff unit. Cliff top rates indicate recession at the landward margin of the landslide complex, whereas cliff toe rates indicate seacliff recession (Photo 1). Cliff top recession has been minimal over this period; this would suggest that the rear cliff of the landslide complex has not retreated over the last c. 160 years. Long-medium term cliff toe recession has been around 0.11 and 0.24m/yr (i.e. moderate recession).

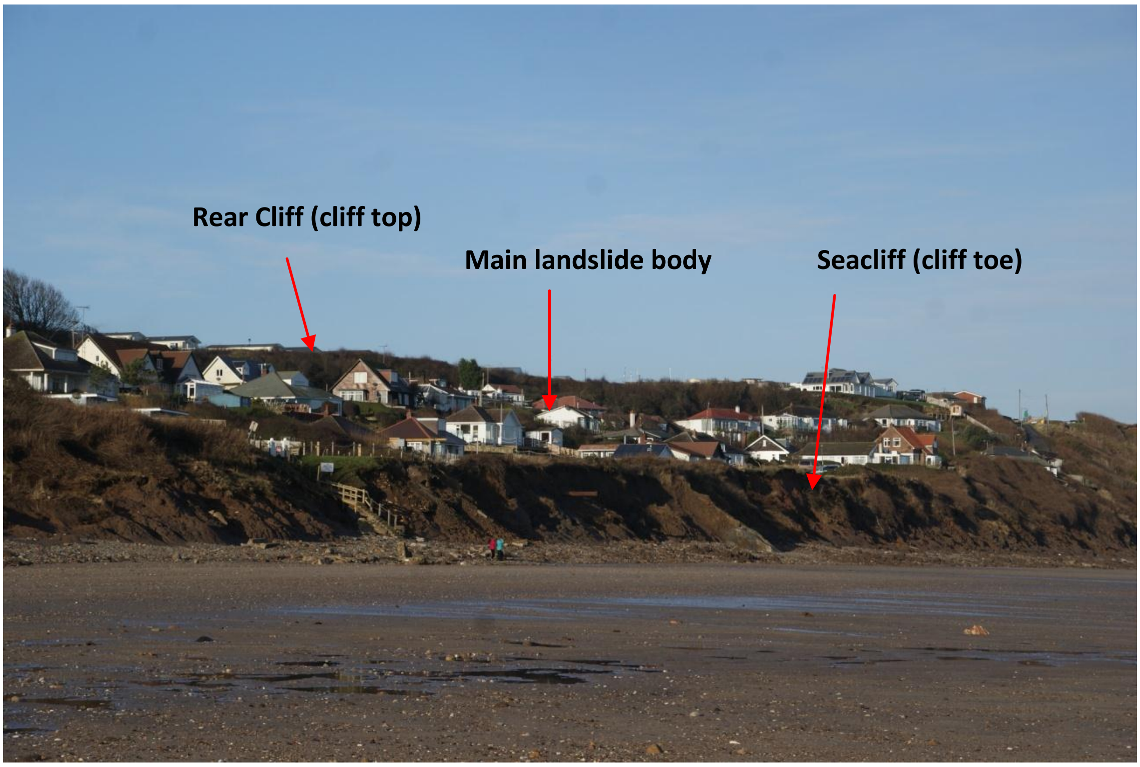

Photo 1 Flat Cliffs: the main landslide complex components

Table 4 North East Coastal Group cliff recession measurements: Scarborough to Filey (from Halcrow, 2013)

Ground Control Point	Cliff Unit	Distance to Cliff Top (m)		2008-2013 Recession*(m)	Recession Rate m/year
		2008 Baseline	April 2013 Survey		
5	Muston Cliffs	7.1	1	6.1	1.22
6		6.7	7.1	-0.4	0
7		6.7	5.1	1.6	0.32
8	Primrose Valley Cliffs	10.2	10.4	-0.2	0
9		8.3	8.4	-0.1	0
10		7.5	7.3	0.2	0.04
11	Flat Cliffs	6.6	6.5	0.1	0.02
12		7.7	7.8	-0.1	0
12A**		13.9	13.9	0	0
13		4.2	No data		
14	Hunmanby Cliffs	8	7	1	0.2
15		5.2	4.8	0.4	0.08
16		7.7	7.8	-0.1	0
17		10.7	10.9	-0.2	0
18	Reighton Cliffs	7.2	7.1	0.1	0.02
19		6.6	6.4	0.2	0.04

Note: * minus values indicate apparent cliff advance i.e. these are error values
** Baseline for Control Point 12A is March 2011

Table 5 Flat Cliffs: estimated cliff recession rates from historical maps (from Halcrow, 2012)

Profile No.	Cliff Top Retreat m/year			Cliff Foot Retreat m/year		
	Long-term (1854-2010)	Medium-term (1929-2010)	Short-term (1970s-2010)	Long-term (1854-2010)	Medium-term (1929-2010)	Short-term (1970s-2010)
25	0.22	0.32	0.77	0.12	0.24	0.2
26	0.03	0.17	0.28	0.11	0.17	0.06*
27	0	0.04*	0.05*	0.15	0.13	0.08*
28	0.05	0.1*	0.18	0.11	0.12	0.07*
29	0.04	0.13	0.13*	0.13	0.19	0.06*

Note: * indicates that the retreat rates are less than the accuracy of the historical sources (root mean square error, RMSE). RMSE for the long-term map comparison is 0.04m; medium-term RMSE = 0.12; short-term RMSE = 0.16m.

Table 6 Flat Cliffs: estimated cliff recession rates from aerial photographs (from Halcrow, 2012)

Profile No.	Cliff Top Retreat m/year			Cliff Foot Retreat m/year		
	Long-term (1940-2010)	Medium-term (1967-2010)	Short-term (1982-2010)	Long-term (1940-2010)	Medium-term (1967-2010)	Short-term (1982-2010)
25	0.01*	0.01*	0.01*	0.11	0	0.12*
26	0.03*	0.04*	0.08*	0.13	0	0.06*
27	0.35	0.21	0.22	0	0	0.14
28	0.19	0	0	0	0	0.08*
29	0.19	0	0.21	0.05	0	0.13

Note: * indicates that the retreat rates are less than the accuracy of the historical sources (root mean square error, RMSE). RMSE for the long-term photograph comparison is 0.03m; medium-term RMSE = 0.09; short-term RMSE = 0.08m.

Table 7 Estimated baseline cliff recession rates

Cliff Unit	Cliff Type and Materials	Assumed Baseline Recession Rate m/year	Source
Muston Cliffs	Simple cliff: Glacial till	0.25	SMP2
Primrose Valley Cliffs	Simple cliff: Glacial till	0.25	SMP2
Flat Cliffs	Landslide complex: Glacial till	0.2	Flat Cliffs study
Hunmanby Cliffs	Simple cliff: Glacial till	0.25	SMP2
Reighton Cliffs	Landslide complex: Glacial till	0.17	Filey Bay Strategy

Given the limited data available on long-term recession rates, it remains something of a challenge to define a baseline recession rate for each cliff unit that can be used as the basis for future predictions. The expected long-term recession rates presented in Table 7 have been based on the information discussed above, plus the author’s experience of recession rates elsewhere on the North Yorkshire-Humberside coast.

5 50-Year Cliff Recession Predictions

As discussed in Section 2, lower and upper bound estimates of the recession distance at each of the cliff units have been generated using simple models:

- lower bound estimate; this has involved simply extrapolating the assumed baseline rate over 50-years:

  50-Year Distance = Baseline Rate x 50

- upper bound estimate; this is based on the use of the "historical projection" method, and involves multiplying the baseline rate by an adjustment factor calculated from the ratio of the historical and future rates of relative sea-level rise (RSLR):

  50-Year Distance = Baseline Rate x (Future RSLR/Historical RSLR)
  = Baseline Rate x (5mm/2.5mm)

The results are presented in Table 8. Even for the very conservative "Historical Projection" approach, the predicted recession distances are not great, between 20m and 25m.

Table 8 Predicted 50-Year Recession Distances

Cliff Unit	Cliff Type	Assumed Baseline Recession Rate m/year	Lower Bound Estimate: 50-year Extrapolation (m)	Upper Bound Estimate: 50 year Retreat: Historical Projection (m)	NCERM Prediction (m)
Muston Cliffs	Simple cliff: Glacial till	0.25	12.5	25	10-20m
Primrose Valley Cliffs	Simple cliff: Glacial till	0.25	12.5	25	10-20m
Flat Cliffs	Landslide complex: Glacial till	0.16	10	20	21.7-61.6m*
Hunmanby Cliffs	Simple cliff: Glacial till	0.25	12.5	25	10-20m
Reighton Cliffs	Landslide complex: Glacial till	0.17	8.5 (Rounded up to 10m)	17 (Rounded up to 20m)	10-20m

Note: * Recession distance quoted in the Flat Cliffs stability assessment and management plan (Halcrow, 2012).

These predictions are broadly consistent with the NCERM predictions (shown in the right-hand Column of Table 8), with the exception of the landslide complex at Flat Cliff. Here, the 50-year NCERM projection is estimated to be between 21.7m and 61.6m, depending on the UKCP09 emissions scenario. This estimate has been derived by modelling the impact of climate change and RSLR as causing an increase in the frequency of landslide events that affect the rear cliff of the landslide complex (see Appendix A). Whilst the estimate of 61.6m cliff top might appear extremely conservative (especially when compared with negligible long-term cliff top recession rates), this value has been included in Scarborough Borough Council's Flat Cliff stability assessment and management report (Halcrow 2012, Page 26). If this scenario was realised, then much of the existing community and part of the cliff top caravan site would be lost within the next 50 years.

The cliff top recession predictions are presented in Figures 3 and 4, which show the extent of each cliff unit and the upper and lower bound estimates of cliff top loss over 50-years, along with the NCERM projections. How these estimates should be used to define the inland boundary of the SSSIs is a decision for Natural England. By way of guidance, the upper bound estimates are probably very conservative for most cliffs. If this recession distance is chosen, then there can be reasonable confidence that the estimates are unlikely to be exceeded. The higher NCERM values for Flat Cliff are likely to be extremely conservative.

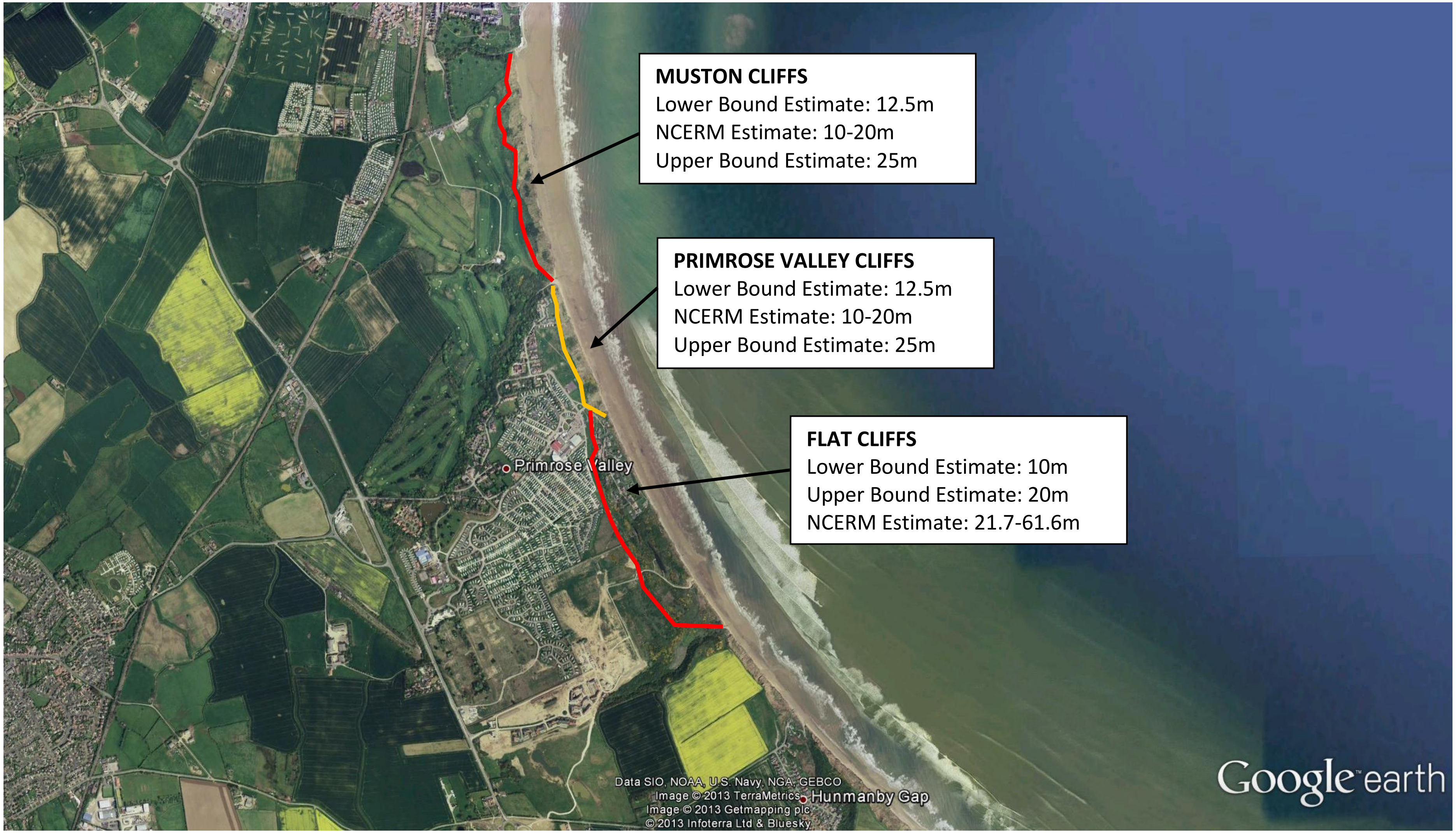

Figure 3 Proposed extension to the Flamborough Head SSSI. Muston Sands to Reighton Sands: predicted 50-year recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

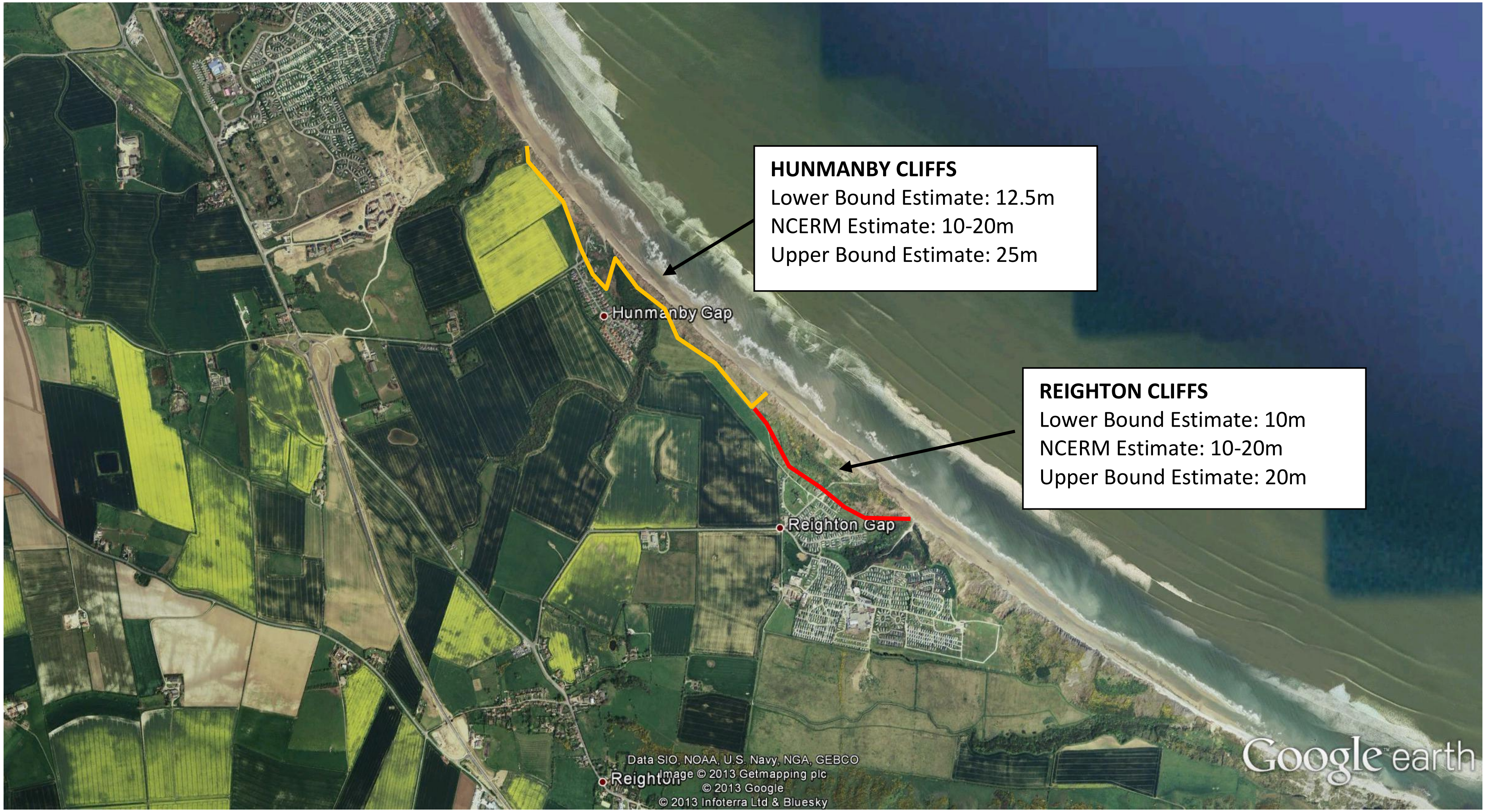

Figure 4 Proposed extension to the Flamborough Head SSSI. Muston Sands to Reighton Sands: predicted 50-yrear recession rates of site boundaries (Image source: Google Earth). The coloured lines show the approximate cliff unit boundaries.

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Appendix A: Flat Cliffs

Flat Cliffs have been occupied since the 1920s and now comprises around 50 residential properties, many with permanent occupancy. These properties lie within a pre-existing landslide complex (an "undercliff") that was first identified in 2001 (Halcrow, 2002). The stability of the site has been investigated by Scarborough Borough Council to develop a better understanding of the hazards and risk posed by landsliding to the residents and assets (Halcrow 2012).

Halcrow's studies (Halcrow 2002, 2012) indicate that the landslide extends around 1km alongshore and is up to 100m wide, comprising a series of linear benches from a steep rear cliff to a sea cliff at the back of the beach. It is not known when the landslide first occurred, but it is clear from damage to infrastructure and buildings that slow to very slow ground movement has been ongoing for, at least, the last 10-20 years. Monitoring results from inclinometers installed in boreholes drilled in 2001 and 2011 have been inconclusive and, as a result, the position of the landslide shear surface remains uncertain. However, geomorphological mapping and the pattern of damage indicates that the landslide complex probably contains relatively deep-seated rotational and non-rotational landslides and shallower mudslides.

Halcrow (2012) developed a geomechanical model to evaluate the stability of the landslide complex. This revealed that the Northern section is actively unstable (Factor of Safety <1[1]). In contrast, the Central and Southern sections are more stable (Factors of Safety >1.8). The model was used to demonstrate that ongoing erosion of the unprotected sea cliff will lead to the progressive destabilisation of the landslide and accelerated ground movements within the existing complex. Halcrow (2012) state that "*in the long-term, occupation of Flat Cliffs is unlikely to be sustainable due to the risk of cliff instability and coastal erosion*". Ultimately a point could be reached when the complex has become sufficiently destabilised to cause a new landslide to occur affecting the ground inland of the current rear cliff i.e. the complex will expand inland.

It has long been recognised that the future behaviour of "undercliff-style" landslide complexes is extremely difficult to predict (e.g. Lee and Clark 2002). This is because two types of activity can be envisaged:

- Type 1; ongoing sea cliff retreat and ground movement within the landslide complex (i.e. "*business as usual*");
- Type 2; the potential for a new landslide and rapid rear cliff retreat (i.e. "*dramatic change*").

Past recession rates can provide an indication of future Type 1 behaviour. However, both the timing and magnitude of a new landslide (Type 2 behaviour) are usually extremely uncertain.

The National Coastal Erosion Risk Mapping Project (NCERM) developed a methodology for predicting recession rates at complex cliff sites. The approach only considers the Type 2 activity i.e. episodic landslide events involving rear cliff retreat. This has been described by Moore et al. (2010) as involving the following steps:

- defining a characteristic magnitude and frequency for landslide events that cause rear cliff retreat. For Flat Cliffs, 10m recession events are defined as occurring, on average, once every 10 years (Moore et al., 2010). Thus, a 10m size event has an annual probability (P) of occurrence of 0.1.

[1] The stress imposed by gravity is resisted by the strength of the materials forming the slope. The quantitative comparison of these opposing forces gives rise to a ratio known as the 'Factor of Safety' (*F*):

$$\text{Factor of Safety (F)} = \frac{\text{Resisting forces}}{\text{Destabilising forces}} = \frac{\text{Shear strength}}{\text{Shear stress}}$$

The Factor of Safety of a slope at the point of failure (i.e. movement) is assumed to be 1.0. The higher the Factor of Safety, the larger the *margin of stability*.

- adjusting the magnitude/frequency to take account of the effects of future climate change (as indicated by UPCP09). For Flat Cliffs, it is predicted that the frequency of 10m size events will increase from the present estimate of 1 in 10 years to 1 in 2 years by 2109 (annual probability increases from 0.1 to 0.5 over this period). This increase in annual probability is applied linearly between 2009 and 2109.

The recession over a particular time period appears to be calculated as follows:

Total Recession (Year 1 to n) = ∑ (P x Event Size), Years 1 to n

The first event in the sequence is assumed to occur in Year 1.

Halcrow (2012) present the NCERM predictions for Flat Cliff:

Climate Change Projection (UKCP09)	**20 Years**	**50 Years**	**100 Years**
Low	5.7m	21.7m	43.4m
Medium	11m	27.5m	55m
High	11.3m	61.6m	61.6m