Cell 1 Regional Coastal Monitoring Programme

Analysis of 1940s and 2015 Aerial Photography & Detailed Assessment of Filey Bay to Cayton Bay

Final Report

March 2016

Contents

Appendices

List of Figures

List of Tables

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Abbreviations and Acronyms

Acronym / Abbreviation	Definition
AONB	Area of Outstanding Natural Beauty
DGM	Digital Ground Model
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLWS	Mean Low Water Neap
MLWS	Mean Low Water Spring
m	metres
ODN	Ordnance Datum Newlyn

Glossary of Terms

Term	Definition
Beach nourishment	Artificial process of replenishing a beach with material from another source.
Berm crest	Ridge of sand or gravel deposited by wave action on the shore just above the normal high water mark.
Breaker zone	Area in the sea where the waves break.
Coastal squeeze	The reduction in habitat area which can arise if the natural landward migration of a habitat under sea level rise is prevented by the fixing of the high water mark, e.g. a sea wall.
Downdrift	Direction of alongshore movement of beach materials.
Ebb-tide	The falling tide, part of the tidal cycle between high water and the next low water.
Fetch	Length of water over which a given wind has blown that determines the size of the waves produced.
Flood-tide	Rising tide, part of the tidal cycle between low water and the next high water.
Foreshore	Zone between the high water and low water marks, also known as the intertidal zone.
Geomorphology	The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc.
Groyne	Shore protection structure built perpendicular to the shore; designed to trap sediment.
Mean High Water (MHW)	The average of all high waters observed over a sufficiently long period.
Mean Low Water (MLW)	The average of all low waters observed over a sufficiently long period.
Mean Sea Level (MSL)	Average height of the sea surface over a 19-year period.
Offshore zone	Extends from the low water mark to a water depth of about 15 m and is permanently covered with water.
Storm surge	A rise in the sea surface on an open coast, resulting from a storm.
Swell	Waves that have travelled out of the area in which they were generated.
Tidal prism	The volume of water within the estuary between the level of high and low tide, typically taken for mean spring tides.
Tide	Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the moon and sun acting on the rotating earth.
Topography	Configuration of a surface including its relief and the position of its natural and man-made features.
Transgression	The landward movement of the shoreline in response to a rise in relative sea level.
Updrift	Direction opposite to the predominant movement of longshore transport.
Wave direction	Direction from which a wave approaches.
Wave refraction	Process by which the direction of approach of a wave changes as it moves into shallow water.

Preamble

The Cell 1 Regional Coastal Monitoring Programme covers approximately 300km of the north east coastline, from the Scottish Border (just south of St. Abb's Head) to Flamborough Head in East Yorkshire. This coastline is often referred to as 'Coastal Sediment Cell 1' in England and Wales (Figure 1). Within this frontage the coastal landforms vary considerably, comprising low-lying tidal flats with fringing salt marshes, hard rock cliffs that are mantled with glacial sediment to varying thicknesses, softer rock cliffs and extensive landslide complexes.

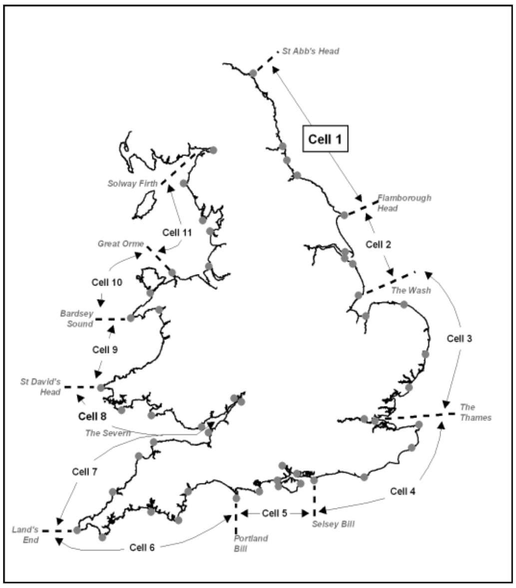


Figure 1 Sediment Cells in England and Wales

The work commenced with a three-year monitoring programme in September 2008 that was managed by Scarborough Borough Council on behalf of the North East Coastal Group. This initial phase has been followed by a five-year programme of work, which started in October 2011. The work is funded by the Environment Agency, working in partnership with the following organisations:

Northumberland County Council
North Tyneside Council
South Tyneside Council
Northumberland Coast Area of Outstanding Natural Beauty
Sunderland City Council
Durham County Council
Redcar & Cleveland Borough Council
Hartlepool Borough Council
Whitby · Scarborough · Filey Borough of Scarborough – A great place to live, work & play
East Riding of Yorkshire Council
Environment Agency
Natural England
The National Trust

1. Introduction

The Cell 1 Regional Coastal Monitoring Programme covers approximately 300km of the northeast coastline from the Scottish Border to the southern boundary of Scarborough Borough Council, approximately 10km northwest of Flamborough Head. This report forms a component of the Cell 1 coastal monitoring programme being undertaken by CH2M (formerly Halcrow) since 2013 for a consortium of local authorities coordinated by Scarborough Borough Council.

The report is a follow-up to the assessments of the baseline survey carried out by Infoterra in 2010 (Halcrow 2010) and the repeat survey flown by the Environment Agency between autumn 2012 and spring 2013 (Halcrow 2013a). The current report has three objectives:

- to use 2015 aerial survey data to more accurately document short-term change in cliffs and dunes on the Cell 1 coast since the surveys of 2010 and 2012/13
- to present a new georeferenced historical aerial imagery dataset from the 1940s covering the Cell 1 coast and to undertake an analysis of longer-term coastal change over the last c. 70 years
- to present a more detailed analysis of the coast between Filey Bay and Cayton Bay using georeferenced aerial imagery from the 1940s, 1960s and 1990s in support of an updated coastal strategy for these locations.

All surveys of the Cell 1 coast undertaken since 2010 cover the coastline of the whole of Cell 1, extending from at least MLW (MLWS in areas of particular interest) to at least 500m inland. Data has been collected from the intertidal zone, coastal cliffs and landslides, and dune complexes. Surveys have comprised synchronous capture of LiDAR and vertical aerial photography to produce map-accurate orthorectified photography, digital elevation models (DEMs) and hillshade and slope angle maps. Oblique aerial photography was also collected to revealed details of the cliff face.

The orthorectified photography (‘orthophotos’) have a positional accuracy of ±0.1m. The accuracy of the archive data for the Cell 1 coast is considerably lower.

A total of 252 shore normal transects have been used to measure recession rates at specific cliff and dune locations. This database is used to present average rates of change for cliff behaviour units (CBUs) and dune sections to give representative data for each area.

2. Data sources and accuracy

The coastline of Cell 1 has been the subject of several aerial surveys since 1999. However, until the cell-wide monitoring programme was developed in 2008, work was the responsibility of different coastal groups, resulting in surveys being uncoordinated and data being stored in different formats. Consequently, the 2010 survey provides the first consistent baseline dataset covering the whole Cell 1 coastline. Halcrow (2010) undertook a qualitative assessment of this 2010 baseline against the archive historical data from 1999 to 2003 and demonstrated only localised changes in the cliffs and low recession rates. Errors in the imagery combined with the limited amount of coastal change often made it impossible to accurately define erosion rates.

Halcrow (2013a) updated this assessment to include the 2012/13 survey data and assessment of short-term coastal change. In an attempt to more accurately define erosion rates along the Cell 1 coast, a mosaic of historical imagery from the 1940s has been acquired and georeferenced for this study. Archive data from 1968 and 1996 have also been assembled and brought into the GIS for the coastal frontage of Filey Bay to Cayton Bay to provide additional information on short-term rates of change here. The present report therefore provides an update to the rates of short-term coastal change between 2010 and 2015, uses a new set of georectified image mosaics from the 1940s to quantify longer-term rates of change, and provides addional details on historical change along the coastal frontage of Filey Bay to Cayton Bay.

The image archive for the Cell 1 coast is summarised in Table 2.1. The 1999 dataset has not been used in the current assessment because the file format is not compatible with ArcView GIS.

Table 2.1: Details of vertical aerial imagery currently available

Year Flown	Format	Resolution	Coverage	GIS compatibility	Accuracy (RMSE)
Images from various years in the 1940s. 1945 taken as representative date.	'Semi-orthorectified' images (.tif)	20 cm	Whole of Cell 1	Yes	c. 1.4m where there is good ground control. Worse elsewhere
1968	'Semi-orthorectified' images (.tif)	28cm	Filey Bay – Cayton Bay	Yes	c. 1.8m
1996	'Semi-orthorectified' images (.tif)	29cm	Filey Bay – Cayton Bay	Yes	c. 1.9m
1999	Orthorectified images (.CRV)	25 cm	Whole of Cell 1	Only if exported from Cities Revealed Viewer	unknown
2003 (June to August)	Orthorectified images (.SID)	12.5 cm	Just SBC frontage	Yes	3m*
2008	Orthorectified images (.SID)	12.5 cm	NECAG frontage	Yes	2.16m*
2010 (13 May to 12 June)	Orthorectified images (.ECW)	10 cm	Whole of Cell 1	Yes	0.09m
Sept-Oct 2012 and April-May 2013	Orthorectified images (.ECW)	10 cm	Whole of Cell 1	Yes	<0.1m
April –June 2015	Orthorectified images (.ECW)	10 cm	Whole of Cell 1	Yes	<0.1m

* The accuracy of the data are unknown and quoted figures are assumptions or approximate measures.

The accuracy of the data collected prior to the 2010 baseline survey is variable. Imagery from the 1940s epoch has been georeferenced using digital photogrammetry, supported by control points that can be seen in contemporary Ordnance Survey MasterMap data and the 2015 LiDAR and photography. The photogrammetric technique relies on image overlaps of at least 40% on adjacent imagery and produced a seamless mosaic of imagery. The accuracy of the georeferencing has been assessed by comparing the position of fixed points, such as buildings and roads, in the historical imagery and the Ordnance Survey MasterMap data. This has shown RMS errors for each tile of data are generally very good at ±1m. However, the actual error varies across the image mosaic and will be significantly greater than ±1m at locations distant from control points. An estimate of the actual error in each 1940s mosaic tile has been made with reference to the changes in cliff top position measured between the 1940s and 2015. It is assumed that advances in the cliff top are error, and therefore the amount of advance measured gives an indication of the likely error at the coastline. Measurements of cliff retreat that are less than the average measured cliff advance for the photo mosaic tile cannot be relied on. The location of each mosaic tile of 1940s data, the calculated RMSE and the estimated true error are shown in Table 2.2.

In practical terms, this means that at sections of the coast that were well-developed with buildings and coastal structures in the 1940s, the RMSE may be ±1m, but in other areas that are less-developed and therefore do not have fixed points that be recognised in the 1940s and present day, error may be significantly greater.

Error statistics for the data from 1968 and 1996 covering the coastal frontage of Filey Bay to Cayton Bay are shown in Table 2.3.

Table 2.2: RMSE data for 1940s imagery data covering Cell 1

Mosaic tile	Coverage	RMSE	Estimated error
1	CBU 0 to 13 – Filey Bay South to Scarborough North Bay (Central)	±1.39m	±7.65m
2	CBU 15 to 41 – Scarborough North Bay (North) to Runswick Bay	±1.92m	±5.15m
3	CBU 41 to 54 – Sandsend to Redcar	±1.19m	±4.90m
4	CBU 55 to 61 – NW Hartlepool Headland to Seaham Harbour North	±1.51m	±6.72m
5	CBU 62 to 78 – Seaham Hall to Seaton Sluice	±1.18m	±2.76m
6	CBU 78 to 83 – St Mary's Island to Creswell	±1.60m	±0.39m
7	CBU 87 to 91 – North Boulmer to Howick Haven	±1.27m	±0.24m
8	CBU 93 to 96 – Beadnell to Bear's Head	±1.09m	±1.55m
AVERAGE	CBU 0 to 96 – Filey Bay South to Bear's Head	±1.39m	±3.10m

Table 2.3: RMSE data for historical imagery data covering Filey Bay and Cayton Bay

Date	RMSE (±m)	Estimated error (±m)
1968	±1.82m	±5.08m
1996	±1.91m	±3.63m

The 2003 dataset comprises a series of scanned wet film prints that have been individually georeferenced. This means each print has a unique RMSE and error of fit is particularly significant in areas of high relief, such as coastal cliffs. Further complications arise because of the overlap of photographs, meaning a given section of coastline may be imaged by up to four different prints where features do not necessarily overlap. Consequently it is difficult to determine which print has the most accurate positioning, particularly where fixed objects are not present for direct comparison. A series of spot checks have been made along the frontage by comparing the position of fixed objects in the 2012/13 and 2003 imagery, which suggests RMSE at the cliff top is around 3m. This has been taken as representative for the whole dataset, but it is likely that local errors will be greater. Checks showed differences in position of the cliff toe between different overlapping prints vary by as much as 10m, as a result of image distortion caused by different camera view angles. For this reason, there is very low confidence in the accuracy of cliff toe positions and no attempt to map the cliff toe or quantify toe erosion has been made using the 2003 data.

The 2008 dataset comprises a series of georeferenced mosaics. Positional errors are unknown, but have been estimated from a comparison of 100 fixed points that are visible in both the 2008 and 2010 imagery. The results suggest that in areas of limited relief error is between 0 to 4m, with an average error of around 2m. However, this error increases where relief is sharp, such as at cliffs, and in areas away from inland control points, such as on shore platforms or on area of open country with no field boundaries. In such areas, positional errors of 10 to 50m were encountered. It was therefore decided that the 2008 imagery was of insufficient accuracy to provide meaningful information on the position of the cliff.

3. Methodology

3.1 Assessment of change

The cliff top and dune front were digitised at a consistent scale of 1:1,000. For data collected since 2010, mapping has been undertaken using LiDAR in addition to the aerial photography, which helps to precisely define the cliff edge. In the Scarborough Borough Council and Redcar and Cleveland Council Borough Council frontages, both the cliff toe and the cliff top were digitised to document annual toe erosion and episodic headscarp recession events that occur in the landslides present on this coast. In the other areas, where simple cliffs predominate, only the cliff top was measured. On dune frontages, the toe of the dune, which is taken to be represented by the limit of vegetation, was mapped.

Cliff recession or change in the dunes was measured using a series of shore-normal transects with a nominal 500m spacing. Transects were distributed to ensure at least three were present in each of the cliff (or dune) behaviour units mapped previously (Halcrow 2010). The distance between the landward ends of each transect and the intersection with the mapped feature line in each year was measured. The difference between the two lengths represented the amount change at that point (Figure 3.1). The rate of change can then calculated with reference to the time, in years, between the two datasets being assessed.

In the case of the data collected since 2010, where the time between epochs of data is small, change have been calculated based on the number of months between images and then converted into an annual rate.

To provide a more statistically robust dataset, average rates were calculated for each CBU.

3.2 Management of error

Despite careful digitising of the cliff top it is inevitable that error remains in the data set. This principally results from interpretation errors when digitising the cliff line and errors in the rectification of the imagery. A key component of any analysis of coastal change is to calculate the error and ensure error is quoted when any rate of change is presented. This ensures that only ‘real’ change, above the calculated error, is presented and the true magnitude of error can be considered.

Error inherent in source data

The error-of-fit of orthorectified aerial photographs is described by the root mean square error (RMSE), which compares the position of features in the photography with the ‘true’ position of features, derived from accurate ground survey or Ordnance Survey mapping. The RMS error of the photography commissioned for the Cell 1 regional monitoring programme in 2010 and 2012/13 is ±0.1m (Table 2). This means that feature on the photograph are, on average, within 10cm of their real position.

When comparing two or more photographs to assess amounts of rates of coastal change, it is necessary to consider the combined effects of error in the two epochs. This combined error is calculated by summing the RMS errors of the two sets of imagery and dividing by the time period in years between the sets of imagery. For precision, the time between the two sets of imagery has been expressed in months:

$$Error\ in\ annual\ rate\ of\ recession = \frac{Error\ in\ photograph\ 1 + error\ in\ photograph\ 2}{Number\ of\ months\ between\ photographs} \times 12$$

The 2012/13 was affected by poor weather, which, together with tidal and daylight constraints meant it was not completed in autumn 2012 as planned, and additional flights were required in spring 2013. The resulting RMSE on the calculated rates of change is ±0.084m/yr for the period 2010 to autumn 2012 and ±0.063m/yr for the period 2010 to spring

2013. For simplicity, a single error figure of ±0.1m/yr is quoted to cover the measured change between 2010 and 2012/13.

The RMS error of the 2015 data is ±0.1m/yr, providing the same image accuracy as the 2010 and 2012/13 data. However, the 2015 imagery is affected by occasional distortion of the cliff line at certain parts of coastline that results from the aerial photography processing methodology struggling to projecting imagery where there are large changes in relief. LiDAR survey data from 2015 was therefore be used in conjunction with the 2015 aerial survey to precisely map the coastline. The RMSE for the LiDAR varies across the survey area, but is on average ±0.03m. An RMSE ±0.1m is therefore used for all 2015 mapping. See Appendix G for source maps.

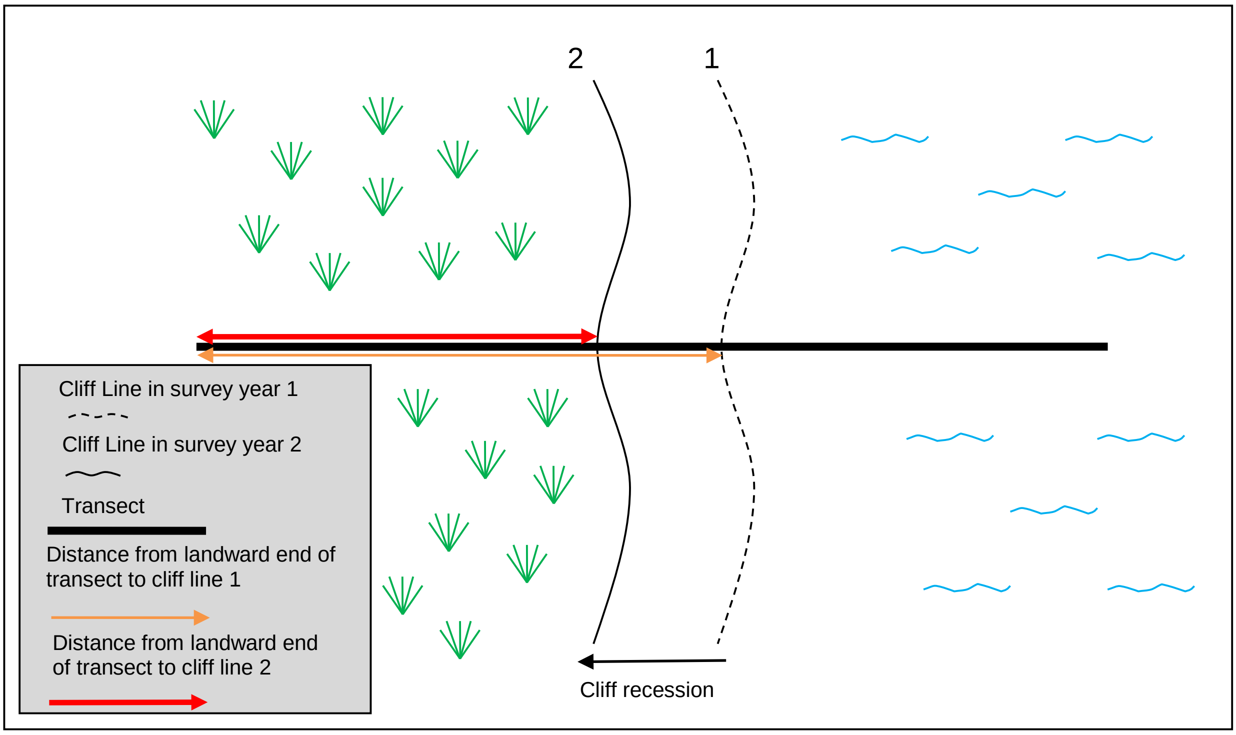


Figure 3.1: Cliff recession measurement. Cliff recession is difference is distance between landward end of profile and coastline in survey years 1 and 2. Rate of change is this distance divided by the time between the two surveys. For dunes, the coastline may show a net advance over the monitoring period to give an accretion rate.

Table 3.1 gives a summary of all RMS errors for combined epochs. Calculated erosion rates that are greater than these values can therefore be quoted with confidence.

Table 3.1: RMSE data for combined epochs covering Cell 1

Combined Epoch	RMSE
2010 to 2012/13	±0.10m/yr *
1945 to 2015	±0.02m/yr ^
1945 to 1968 (Filey-Cayton only)	±0.45m/yr ^
1968 to 1996 (Filey-Cayton only)	±0.13m/yr ^
1996 to 2015 (Filey-Cayton only)	±0.11m/yr ^
2003 to 2015	±0.26m/yr *
2008 to 2015	±0.32m/yr *
2010 to 2015	±0.04m/yr *
2012/13 to 2015	±0.08m/yr *

* The accuracy of some of the constituent datasets are unknown and quoted figures are assumptions.
^Combined epoch RMSE calculated using estimated error in 1945 imagery and reported RMSE in 1968 imagery

Additional historical aerial imagery are available for the Filey Bay and Cayton Bay areas of the Scarborough Borough Council frontage. The calculated RMSEs and estimated actual errors of these data are provided in Table 3.3.

Interpretation error

Derivation of the 'coastline' is undertaken by interpretation of the aerial photos and associated digital elevation model. In most cases, where the coastline is formed by a sharp cliff edge, this process is straightforward, but the presence of shadow, vegetation or subtle breaks of slope, associated with certain soft rock cliffs, means that careful interpretation at a consistent scale is required to minimise error. In this study, a consistent scale of 1:1000 was used for all interpretation. In areas of ambiguity, both sets of photography were compared to ensure that the same feature was interpreted as the 'coastline' to be assessed.

Methodological error

The use of transects is a recognised practice for measuring coastline recession (Lee and Clark, 2002). However, transects must be oriented normal to the coastline to get a true measure of recession. All transects have been oriented normal to the general trend of the coastline. However, local changes in orientation of the cliff line may cause the transect to be oblique to the coastline, leading to local error (Figure 3.2). This error has been mitigated by careful location of transects and calculation of average rates of change for CBUs.

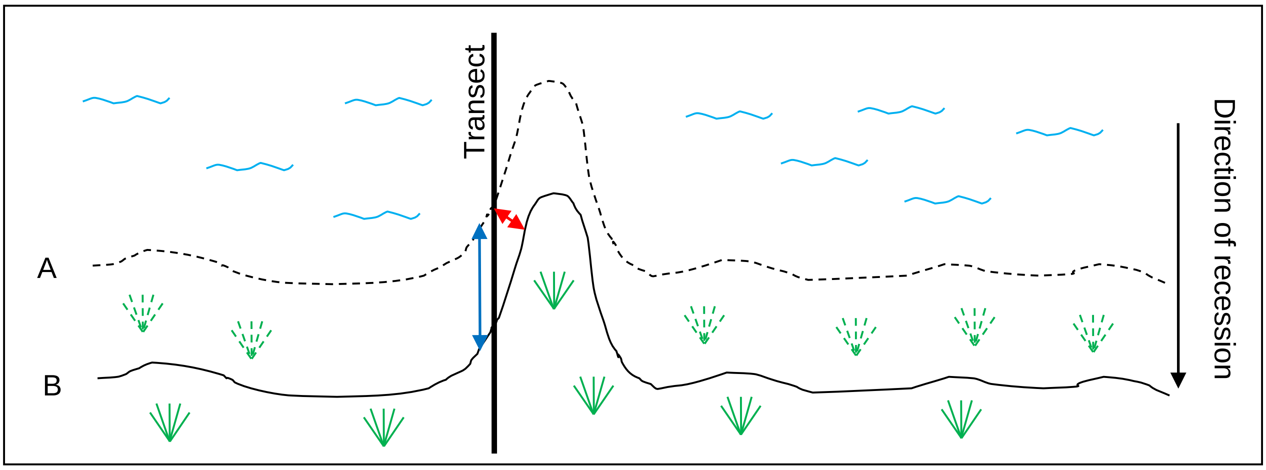


Figure 3.2: Effects of transect being oblique to the local orientation of the coastline. Note how the actual recession of the coast (red arrow) is much less than that indicated in the measured transect (blue arrow).

Mitigation of error

In summary, errors in the method have been managed by:

- Careful location of transects
- Digitising the coast line at a consistent scale, using the DEM and photo to ensure accurate feature interpretation
- Grouping transects into cliff behaviour units and quoting average rates of change that mitigate the effects of localised error as well as individual rates of change that may provide evidence for localised episodic events
- Quoting all measured change and calculated rates of change with an appropriate error statistic.

When undertaking this erosion assessment, it was recognised that a calculated advance of a cliff top is impossible and any indication of this in the dataset must result from error. However, it is possible for the cliff base to advance, in response to deposition of a debris lobe. Figure 3.3 provides and illustration of this principal.

3.3 Measurement Change in the Dune Front

In addition to measurement of the cliff top and cliff toe position, the position of the dune front was also mapped in certain areas. The position of the dune front is harder to define than the cliff edge and was normally taken as the most seaward extent of continuous dune vegetation when viewed at a scale of 1:1,000. The methodology is subject to the same sources of error as for mapping cliff top and cliff toes. Due to the high mobility of dune sand, and the ability of dunes to rapidly accrete or erode in response to episodic storms, larger changes in the dunes are expected than for cliffs.

In total, 94 dune transects were used to measure change in the position of the dune front. The majority of these fell within the Northumberland Council area due to the nature and length of the coastline there. Dune transects were spaced a nominal 500m to 1km apart, depending on the extent of the dune system. The transects were grouped into 14 ‘dune units’, analogous to the CBUs, to mitigate unrepresentative results and errors at individual profiles, and to provide summary results.

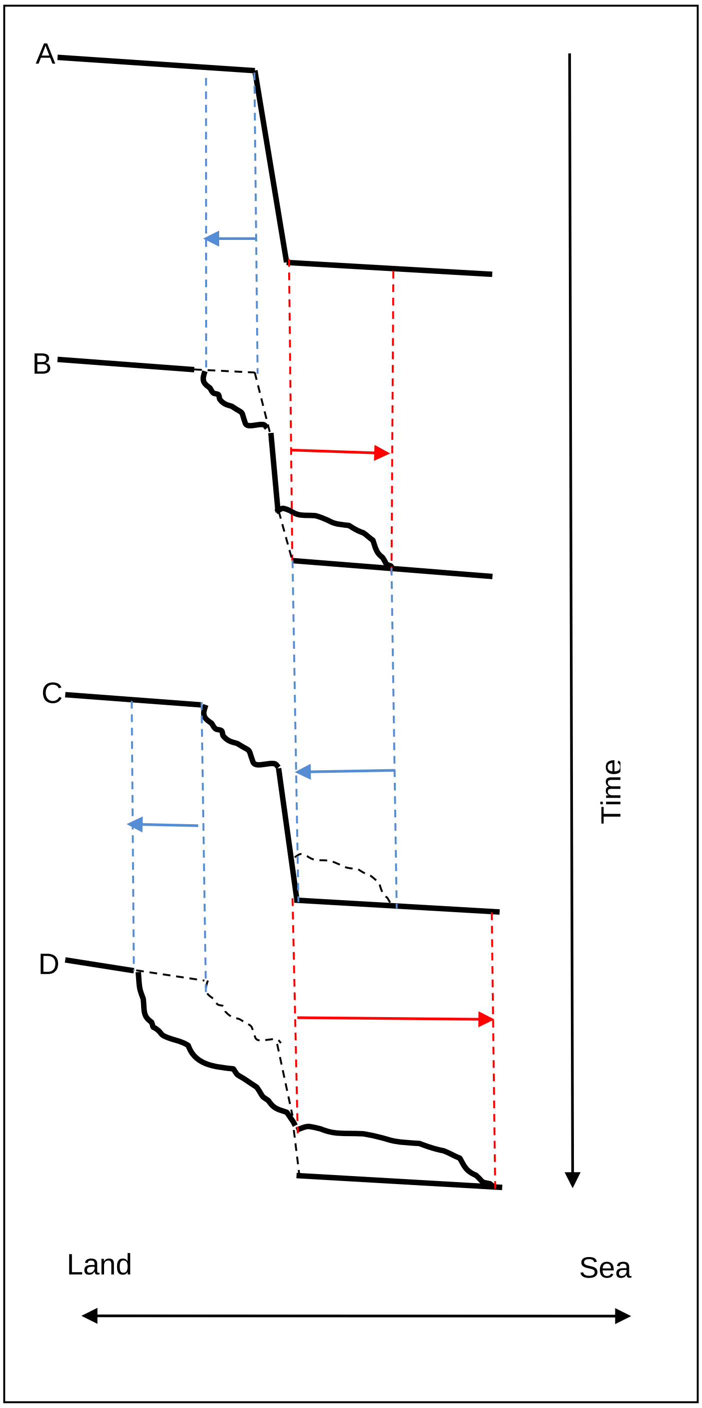


Figure 3.3: Schematic illustration of possible changes in the cliff profile.

A to B – cliff top failure and deposition of a debris lobe leads to recession of the cliff top and advance of the cliff toe

B to C – erosion of the debris lobe leads to recession of the cliff toe

C to D - cliff top failure and deposition of a debris lobe leads to recession of the cliff top and advance of the cliff toe

4 Results and Discussion

4.1 Cliff top and cliff toe recession by CBU

Average recession rates for all epochs have been calculated for each CBU and are shown Tables 4.1 to 4.8. Negative values indicate cliff retreat and positive values indicate advance, which must be error. “No Data” indicates locations where no cliff position could be mapped with confidence. Location maps for each CBU are provided in Appendix A. Summary statistics for each CBU are provided in Appendix B and the data for each profile are given in Appendix C. It should be noted that the figures quoted are averages for CBUs and therefore it is possible for rates of change to be less than the quoted error margins (which are based on the expected error at individual transects) due to the inclusion of:

- Transects within a CBU where no change has occurred (affects both the cliff top and cliff toe).
- The offsetting effect where some individual transects within a CBU have experienced recession and others have experienced advance (affects just the cliff toe).

Medium-term change (2003 or 2008 to 2015)
Data captured in 2003 only covers the Scarborough Borough Council area, therefore change between 2003 and 2015 could only be evaluated within this area. Cliff top and cliff toe change between 2003 and 2015 (Table 4.1 to 4.8) is very limited. This reflects the limited time between the surveys, the low accuracy of the 2003 imagery and associated high RMS errors. Even accounting for the long period between surveys, the error means rates of change greater than 0.26m/yr are likely to represent real change (Table 3.1).

Measured changes between 2008 and 2015 at the cliff top (Table 4.1 to 4.8) are greater and more reliable, but coverage is limited because the 2008 survey does not extend north of the River Tyne. Cliff top erosion rates of up to 1.0±0.32m/yr are relatively common. However there are also two CBUs with average erosion rates of greater than 2.6±0.32 m/yr at Runswick Bay (CBU 42) and at Salterfen Rocks (North Side) (CBU63). These sites have been visited during routine site inspections and are known to have episodic activity, and therefore the data may not be representative of the wider coast. At Salterfen Rocks (North Side) the cliff top appears to advance (an impossibility, see Section 3.2) between 2008 and 2010, before experiencing retreat again in the 2012/13 and 2015 survey. This indicates that whilst cliff top recession is occurring at these locations, it is not at the scale suggested by the very short-term data.

The following can be concluded from the erosion data between 2008-2015:

- The average rate of cliff top recession of CBUs in the Scarborough Borough Council frontage is 0.41±0.32m/yr. A particularly high recession rate is indicated in CBU 42 at Runswick Bay, however, this is not supported by site observations and is likely to be error in the data. Relatively high recession at 1.1±0.32m/yr is shown in CBU 0 at Filey Bay South, which is supported by site observations.
- No cliff top recession greater than the RMS error is detected in the Redcar and Cleveland Borough Council.
- No cliff top recession greater than the RMS error is detected in the Hartlepool Borough Council area during this period.
- No cliff top recession greater than the RMS error is detected in the Durham County Council area.
- The average rate of cliff top recession in CBUs in the Sunderland City Council area is 0.99±0.32m/yr. This is comparatively high, and whilst some real change is likely to have occurred in CBUs where the cliffs are composed of soft sediment, it is unlikely to be on

the scale suggested by the data due to issues with georectification of the aerial imagery used. The maximum recorded recession occurred in CBU 63 at Salterfen Rocks (North) at 2.70±0.32m/yr.

- No cliff top recession greater than the RMS error is detected in the South Tyneside Council area.

Overall the 2008 aerial photography datasets indicate erosion greater than the RMSE at around 10% of the cliffed frontage between Flamborough Head and the River Tyne, with change less than the calculated error at other locations.

Short-term change (2012/13 to 2015)
The two most recent aerial surveys have a very high degree of accuracy, with an RMSE of ±0.08m/yr on rates of change measured between 2012/13 and 2015. Imagery covers the whole coast of the Cell 1 Regional Monitoring Programme. The data show that across all the CBUs, the average cliff top recession rate is 0.48m±0.08m. The improved accuracy of the recent data allows statistically significant erosion to be measured in around 25% of CBUs. The maximum erosion over this period was 1.99±0.08m/yr in CBU 1 at transect 44, Filey Bay south of Hummanby Gap to Speeton Hills. The 2015 imagery indicates fresh mudsliding at this location and debris runout at the cliff toe (Figure 4.1).

The measured rate of change at the cliff toe is more limited. Around 50% of the CBUs along the Scarborough Borough Council frontage experienced toe erosion that could be measured, 25% experienced advance, potentially related to debris runout, and the remainder showed no measurable change. The average rate of recession across all CBUs that were experiencing average recession at the toe was 0.67±0.08m/yr. The maximum erosion rate was 3.3±0.08m/yr in CBU 54 transect 150 at Saltburn to Redcar. Aerial imagery shows a reduction in the extent of vegetation at the toe along this CBU. The average rate of advance of the toe, resulting from run-out of debris lobes is 0.33±0.08m/yr-1, with a maximum of 1.35±0.08/yr at CBU 23 at Robin Hood's Bay (South). In most instances, the greatest rates of change have occurred where debris run-out lobes from cliff failures have advanced the cliff toe, or where pre-existing debris lobes have been eroded. Change at CBU 23 may be in part due to local georectification error.

The following can be concluded about erosion rates measured between 2012/13 and 2015:

- In the Scarborough Borough Council area, average cliff toe advance, related to debris runout, was 0.33±0.08m/yr. Average cliff toe retreat was 0.67±0.08m/yr. The average cliff top retreat for all CBUs was 0.51±0.08m/yr. One of the highest rates of cliff top recession in the whole of Cell 1 was experienced at CBU 1 (Filey Bay South, between Hummanby Gap and Speeton Hills), where a rate of 1.99±0.08m/yr was recorded. Visual assessment of the 2015 imagery shows this area has experienced recent landslide activity, with fresh mudslide scars visible on the cliff face and debris runout at the cliff toe, lending support to the conclusion.
- In the Redcar and Cleveland Borough Council area, average cliff toe advance was 0.27±0.08m/yr. Average cliff toe retreat was 0.93m±0.08m/yr, with a maximum of 1.44±0.08m/yr in CBU 54 between Saltburn and Redcar. The 2015 imagery indicates extensive toe retreat within this CBU, including vegetation loss and rockfall on the beach. The cliff top eroded on average by 0.19±0.08m/yr.
- In the Hartlepool Borough Council area no significant erosion was recorded within the CBU.
- On the Durham County Council frontage, the average cliff top retreat was 0.37±0.08m/yr. A comparatively high rate of recession was recorded in CBU 59 at Horden to Seaham, up

to 4.22±0.08m/yr at transect 172. The 2015 imagery shows extensive rockfall on the shore platform, indicating recent episodic cliff top retreat at this location (Figure 4.2).

- In the Sunderland City Council area, the cliff top retreated by an average of 0.42±0.08m/yr. The maximum rate of recession occurred between Seaham Hall and Salterfen Rocks in CBU 62 at 0.51±0.08m/yr.
- In the South Tyneside Council area, average cliff top recession was 0.23±0.08m/yr.
- In the North Tyneside Council area, no cliff top recession was detectable at most transects. Rates recorded at Whitley Bay Promontory in CBU 74 are not reliable given the low photo quality at this location.
- In the Northumberland County Council area, average cliff top recession was 0.16±0.08m/yr, reflecting the hard rock cliffs of this coast. Newbiggin Point in CBU 80 recorded maximum recession of 0.47±0.08m/yr.

Cliff recession is an episodic process, with failure occurring when various thresholds of stability have been exceed. This means short-term statistics, such as those presented above, will tend to show relatively high rates of change because the effect of infrequent cliff failures are recorded, which may not be representative of longer time periods. Furthermore, the intervening period between the surveys of 2012/13 and 2015 included the December 2013 storm surge, which is known to have caused significant erosion to parts of the northeast coast, suggests that the erosion rates may be atypically high (Halcrow, 2013b).

Table 4.1: Average recession (and toe advance) rates for CBUs in Scarborough Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
0	2	Composite Cliff	Filey Bay South	-0.56	0.24	-0.40	-1.10	-0.47	-0.20
1	8	Simple Landslide	Filey Bay - South of Hummanby Gap to Speeton Hills	-0.36	-0.17	-0.34	-0.02	-0.29	-0.66
2	3	Complex Cliff	Filey Bay - Flat Cliffs	None Detected	-0.21	-0.07	No Data	None Detected	No Data
3	6	Simple Landslide	Filey Bay - North of Flat Cliffs to Filey Town	-0.44	-0.41	0.17	None Detected	-0.58	-0.07
4	4	Simple Landslide	Filey Town to Filey Brigg S	0.27	-0.16	0.10	None Detected	-0.26	None Detected
5	12	Composite Cliff	Filey Brigg N to Cayton Bay	No Data	0.54	0.43	None Detected	-0.35	None Detected
6	2	Simple Landslide	Cayton Bay (SE)	No Data	0.38	-4.14	None Detected	-0.02	-0.11
7	2	Complex Cliff	Cayton Bay (NW)	No Data	-0.09	0.08	None Detected	No Data	No Data
8	2	Simple Landslide	Osgodby Point to White Nab	No Data	-0.40	-1.41	No Data	None Detected	None Detected
9	2	Composite Cliff	White Nab to Black Rocks (S. of Scarborough)	No Data	0.40	-0.31	None Detected	None Detected	-1.31
10	3	Relict Cliff	Scarborough South Bay	No Data	No Data	No Data	No Data	-0.12	No Data
12	5	Relict Cliff	Scarborough Castle Cliff and North Bay (South)	No Data	No Data	No Data	-0.81	-0.13	None Detected
13	1	Relict Cliff	Scarborough North Bay (Central)	No Data	No Data	No Data	No Data	-0.57	None Detected

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
15	2	Composite Cliff	Scarborough North Bay (North)	No Data	0.02	0.53	None Detected	None Detected	-0.16
16	5	Simple Landslide	Scalby Ness	No Data	0.27	-0.94	None Detected	-0.15	None Detected
17	1	Composite Cliff	Scalby Ness to Cliff Top House	No Data	-0.63	-0.20	No Data	None Detected	-0.82
22	4	Complex Cliff	Redhouse Farm (E. Of Cloughton) to Ravenscar	No Data	-0.51	-0.89	-0.50	None Detected	-0.60
23	1	Composite Cliff	Robin Hood's Bay (South)	No Data	-0.44	1.35	None Detected	-0.03	-0.40
24	4	Simple Landslide	Robin Hood's Bay (Central)	No Data	-0.13	-0.11	None Detected	-0.28	None Detected
25	2	Simple Landslide	Robin Hood's Bay (Stoupe Beck to Boggle Hole)	No Data	0.34	-0.25	-0.18	None Detected	None Detected
27	1	Relict Cliff	Robin Hood's Bay (Village South)	No Data	-0.98	-0.35	No Data	None Detected	-0.75
29	3	Simple Cliff	Robin Hood's Bay Village to White Stone Hole	No Data	-0.39	-0.22	-0.18	-0.04	None Detected
32	4	Composite Cliff	Lighthouse s. of Whitby to Whitby (inc. Saltwick Nab)	No Data	0.41	-0.35	-0.34	-0.21	-0.54
34	1	Relict Cliff	Whitby Harbour	No Data	-0.46	No Data	No Data	-0.61	None Detected
35	1	Simple Cliff	Whitby West Cliff (Harbour End)	No Data	0.11	-0.63	None Detected	-0.29	None Detected
36	2	Relict Cliff	Whitby West Cliff	No Data	No Data	No Data	None Detected	-0.56	None Detected
37	2	Simple Landslide	Upgang Beach	No Data	0.12	0.15	None Detected	-1.27	None Detected
38	1	Simple Landslide	South of East Row	No Data	No Data	No Data	-0.39	None Detected	-0.79
41	15	Composite Cliff	Sandsend to Runswick Bay (Hob Holes)	No Data	0.05	0.06	None Detected	-0.11	None Detected
42	3	Complex Cliff	Runswick Bay (Hob Holes) to Runswick Village	No Data	0.14	-0.07	-2.64	-0.09	None Detected
43	13	Composite Cliff	Runswick Bay Village to Staithes	-0.30	-0.61	0.13	-0.47	-0.28	None Detected

Table 4.2: Average recession (and toe advance) rates for CBUs in Redcar and Cleveland Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
46	2	Composite Cliff	Cowbar Nab (North Side)	No Data	-0.09	0.23	-0.46	-0.78	None Detected
47	3	Composite Cliff	East of Boulby	0.72	-0.68	0.84	None Detected	-0.03	-0.18
48	6	Complex Cliff	West of Boulby	No Data	0.32	-0.14	None Detected	-0.27	None Detected
49	4	Composite Cliff	East of Skinningrove (Hummersea Scar)	No Data	-0.57	0.03	None Detected	-0.41	-0.29
51	8	Composite Cliff	Skinningrove breakwater to Saltburn	No Data	0.30	-1.20	-0.14	-0.17	-0.10
52	2	Simple Landslide	Saltburn (East)	No Data	0.10	0.01	-0.84	-0.18	-0.06
54	9	Simple Landslide	Saltburn to Redcar	No Data	-0.09	-1.44	None Detected	-0.09	-0.32

Table 4.3: Average recession (and toe advance) rates for CBUs in Hartlepool Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
55	2	Simple Cliff	NW of Hartlepool Headland	No Data	No Data	No Data	None Detected	-0.68	-0.01

Table 4.4: Average recession (and toe advance) rates for CBUs in Durham County Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
56	1	Simple Landslide	Crimdon Park	No Data	No Data	No Data	None Detected	-0.69	None Detected
57	4	Composite Cliff	Blackhall Rocks	No Data	No Data	No Data	None Detected	None Detected	None Detected
58	3	Simple Landslide	Blackhall Colliery	No Data	No Data	No Data	None Detected	-0.10	None Detected
59	15	Composite Cliff	Horden to Seaham	No Data	No Data	No Data	-0.29	-0.10	-0.46
60	2	Simple Cliff	Seaham (South of Harbour)	No Data	No Data	No Data	None Detected	-0.21	None Detected
61	3	Simple Cliff	Seaham (North of Harbour)	No Data	No Data	No Data	-0.12	-0.14	-0.28

Table 4.5: Average recession (and toe advance rates) for CBUs in Sunderland City Council area. (NB CBU 62 partly in Durham County Council area).

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
62	7	Simple Landslide	Seaham Hall to Salterfen Rocks	No Data	No Data	No Data	-0.26	-0.27	-0.51
63	1	Simple Cliff	Salterfen Rocks (North Side)	No Data	No Data	No Data	-2.70	-2.81	-0.33
64	2	Relict Cliff	Grangetown to Hendon Frontage (Sunderland)	No Data	No Data	No Data	None Detected	-0.29	None Detected

Table 4.6: Average recession (and toe advance) rates for CBUs in South Tyneside Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
66	2	Simple Landslide	Whitburn South	No Data	No Data	No Data	None Detected	-0.70	None Detected
67	11	Simple Cliff	Whitburn to South Shields	No Data	No Data	No Data	-0.05	-0.42	-0.23

Table 4.7: Average recession (and toe advance) rates for CBUs in North Tyneside Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
72	3	Simple Cliff	Tynemouth Longsands	No Data	No Data	No Data	No Data	-0.24	None Detected
74	1	Simple Cliff	Whitley Bay Promontory	No Data	No Data	No Data	No Data	None Detected	-0.53
75	1	Relict Cliff	Whitley Bay	No Data	No Data	No Data	No Data	-0.14	None Detected
76	2	Simple Landslide	Whitley Bay North	No Data	No Data	No Data	No Data	-0.08	None Detected
77	1	Relict Cliff	Whitley Bay to St Mary's Island	No Data	No Data	No Data	No Data	-0.17	None Detected

Table 4.8: Average recession (and toe advance) rates for CBUs in Northumberland County Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Advance/ Retreat Cliff Toe (m/yr)	Short Term Advance/Retreat Cliff Toe (m/yr)		Medium Term Retreat Cliff Top (m/yr)	Short Term Retreat Cliff Top (m/yr)	
				2003-2015 ±0.26m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr	2008-2015 ±0.32m/yr	2010-2012/13 ±0.10m/yr	2012/13-2015 ±0.08m/yr
78	4	Simple Cliff	St Mary's Island to Seaton Sluice	No Data	No Data	No Data	No Data	-0.25	None Detected
79	4	Simple Cliff	Newbiggin (South of Spittal Point)	No Data	No Data	No Data	No Data	-0.55	-0.08
80	2	Simple Cliff	Newbiggin Point	No Data	No Data	No Data	No Data	-0.06	-0.47
81	1	Simple Cliff	Newbiggin (Beacon Point)	No Data	No Data	No Data	No Data	-0.67	None Detected
82	2	Simple Cliff	Snab Nab (Lynemouth)	No Data	No Data	No Data	No Data	-0.09	-0.05
83	1	Simple Cliff	Creswell	No Data	No Data	No Data	No Data	-0.69	-0.17
87	3	Simple Cliff	North of Boulmer	No Data	No Data	No Data	No Data	-0.23	-0.19
88	1	Simple Landslide	Sugar Sands (Between Boulmer and Howick)	No Data	No Data	No Data	No Data	None Detected	None Detected
91	1	Simple Cliff	Howick Haven	No Data	No Data	No Data	No Data	-0.09	No Data
92	0	Simple Cliff	Beadnell	No Data	No Data	No Data	No Data	No Data	No Data
96	5	Simple Cliff	Saltpan Rocks to Bear's Head	No Data	No Data	No Data	No Data	-0.34	None Detected
97	11	Simple Cliff	Berwick to Scottish Border	No Data	No Data	No Data	No Data	-0.32	-0.01

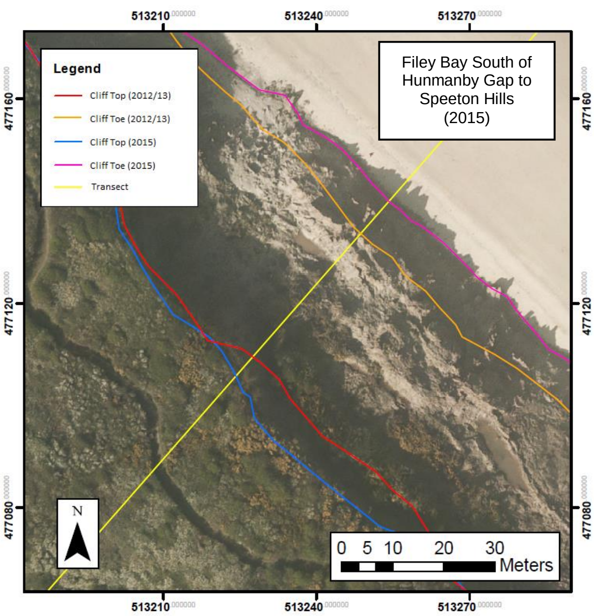


Figure 4.1: Change in cliff line position at Filey Bay South of Hunmanby Gap to Speeton Hills between 2012/13 and 2015.

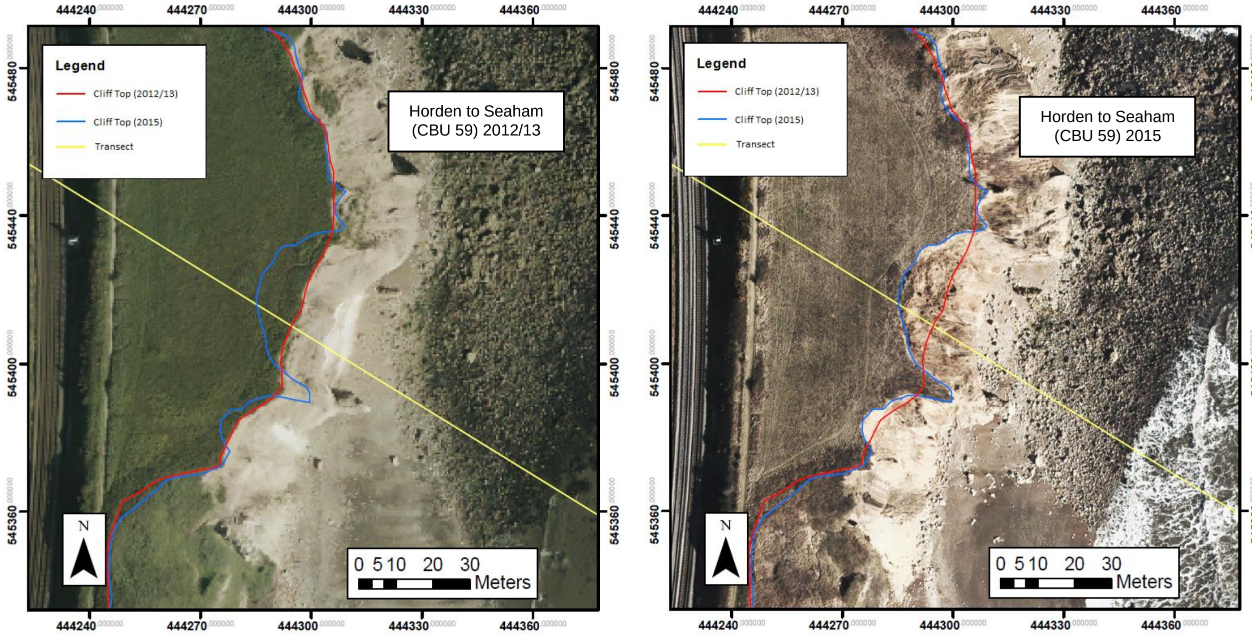


Figure 4.2: Change in cliff line position at Horden to Seaham between 2012/13 and 2015. Cliff positions in corresponding previous/later imagery overlain on each image

4.2 Assessment of Dunes

Results for changes in the position of the dune front are available for time periods 2008 to 2015 south of the River Tyne, and between 2010, 2012/13 and 2015 for the whole of the Cell 1 frontage. The location of the dunes assessed is provided in Appendix E. Table 4.8 presents the average advance and recession results for the 14 dune units assessed. Full results from the dune front analysis are provided in Appendix F.

These data show that the average long term rates of change between 2008 and 2015 were 3.1±0.5m/yr erosion and 7.5±0.1m/yr advance. Over the shorter-term period between 2012/13 and 2015 the same dunes showed an average of 2.13±0.08m/yr erosion and 3.26±0.08m/yr advance. Overall, Table 4.8 indicates advance is more common than recession over the two periods and most change is within 2m/yr. The full results show that change of >10m/yr is also not uncommon.

The northeast coast was affected by a storm surge on 5/6 December 2013 and stormy conditions continued through January 2014 (Halcrow, 2013b). Beach profiles and topographic surveys of the coast undertaken since the surge have documented the widespread impacts, including erosion and subsequent recovery of beaches and dunes, but the aerial survey records have not hitherto been used. The period between the 2010 and 2012/3 photography shows the rate of the change prior to the storm, while the period between the 2012/3 and 2015 aerial surveys covers the period following the storm and includes both erosional and recovery phases. The data show widespread high rates of accretion before the storm surge and erosion or lower rates of accretion since, south of the River Tees. Walk-over visual inspections following the storm surge reflect these observations (Halcrow, 2013b). In contrast, dunes north of the River Tees display widespread erosion prior to the surge and high rates of accretion subsequently. Dunes north of Alnmouth Bay show behaviour over the two time periods are similar overall, and the dunes have recovered quickly. These data indicate the very dynamic nature of dunes and their ability to rapidly respond to storm events.

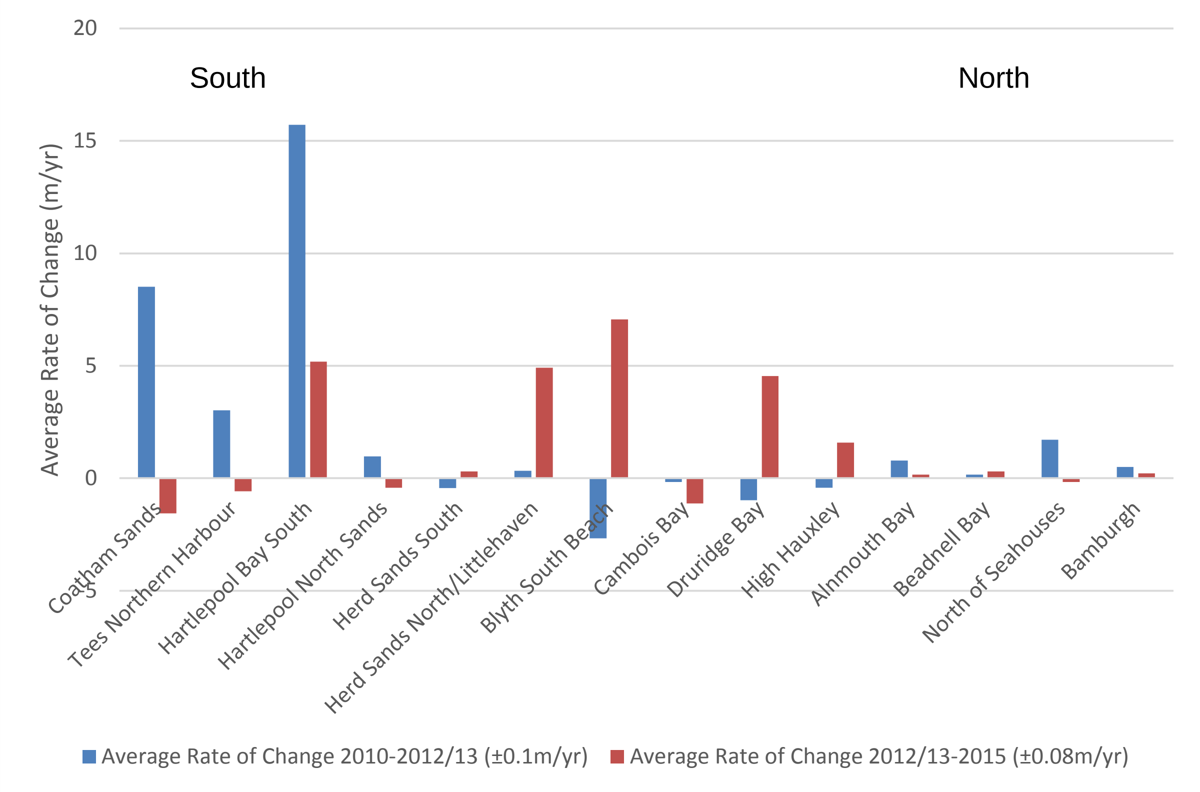


Figure 4.3: Patterns in change in dunes between 2010 and 2015 and impacts of the December 2013 surge.

High average rates of advance between 2012/3 and 2015 have occurred in dune unit 6 at Herd Sands Littlehaven, dune unit 7 at Blyth South Beach and dune unit 9 at Druridge Bay. These are due to localised changes in the dune front, with more vegetation being established in 2015. The most dynamic area assessed is transect 10 at Coatham Sands on the south side of the southern harbour breakwater at the mouth of the Tees, however since the most recent time period the dune front has stabilised.

These data indicate the very dynamic nature of dunes in the Cell 1 frontage. Caution is needed when interpreting these data, particularly extrapolating rates of change derived from short time periods. All rates of change are derived from a snap-shot impression of the dune front that is indicated by the vegetation limit. However, vegetation can be inundated by sand in a single storm event, giving the impression of erosion when in fact a large volume of sand has been deposited on the shoreline. A more accurate impression of dune activity will be derived from interpretation of longer-term datasets in the future, and comparison of these data with on-going monitoring of dunes using ground-based survey data collected as part of the wider Cell 1 regional monitoring project.

Table 4.9: Results of dune front position analysis. Positive numbers indicate dune accretion, negative number show erosion

Dune Unit	Number of Transects	Location	Short-Term Change			Medium-Term Change:
			Average Rate of Change 2008-2010 (±1.1m/yr)	Average Rate of Change 2010-2012/13 (±0.1m/yr)	Average Rate of Change 2012/13-2015 (±0.08m/yr)	Average Rate of Change 2010-2015 (±0.03m/yr)
1	10	Coatham Sands	-0.86	8.51	-1.56	2.78
2	4	Tees Northern Harbour	-1.60	3.02	-0.58	0.86
3	2	Hartlepool Bay South	-1.77	15.72	5.19	9.80
4	8	Hartlepool North Sands	-1.20	0.98	-0.42	0.40
5	2	Herd Sands South	-4.80	-0.43	0.30	-0.18
6	2	Herd Sands North/Littlehaven	-8.55	0.34	4.91	1.92
7	6	Blyth South Beach	No Data	-2.67	7.07	0.92
8	5	Cambois Bay	No Data	-0.16	-1.12	-0.74
9	11	Druridge Bay	No Data	-0.97	4.54	0.91
10	3	High Hauxley	No Data	-0.42	1.58	0.13
11	8	Alnmouth Bay	No Data	0.79	0.17	0.35
12	7	Beadnell Bay	No Data	0.17	0.31	0.05
13	3	North of Seahouses	No Data	1.72	-0.17	0.52
14	6	Bamburgh	No Data	0.51	0.22	-0.02

5 Assessment of Historical Data

In order to gain a better understanding of the long-term rates of coastal change, an historical aerial photography dataset from the 1940s has been acquired and georeferenced, allowing the cliff top to be digitised and rates of change to be calculated. Additional epochs form 1968 and 1996 were provided by Scarborough Borough Council for the coastal frontage of Filey Bay to Cayton Bay. Production of accurate georectified historical imagery relies on identification of features of known position that can be recognised in both the historical image and in contemporary surveys or Ordnance Survey mapping. Consequently the accuracy of the georectified image will be low if few fixed points can be identified, as often occurs on undeveloped coastlines.

An estimate of the actual error in each mosaic tile has been made with reference to the changes in cliff top position measured between the 1940s and 2015 (Table 3.2). It is assumed that advances in the cliff top are error, and therefore the amount of advance measured gives an indication of the likely error at the coastline. Measurements of cliff retreat that are less than the average measured cliff advance cannot be relied on.

The assessment for the 1940s epoch will therefore be based firstly on a qualitative description of change to document the location and nature of activity, and secondly by a quantitative assessment that derived rates of change which take account of the estimated error.

5.1 Qualitative Assessment of Change

Table 5.1 and 5.2 provide a qualitative description of change for the assessment of the 1940s imagery. Features indicative of recession and/or advance visible in the 1940s imagery are described and compared against 2015 imagery in order to evaluate change and give a qualitative indication of the rate of change.

In summary, the qualitative assessment shows widespread localised activity on the cliffs in the 1940s epoch, although overall there is no evidence to support significant cliff recession between the 1940s and 2015 imagery and landslide activity appears to have reduced over time. The areas showing the largest failures and most widespread landslide activity in the 1940s include CBU 25 and 29 at Robin Hood’s Bay, CBU 37 at Upgang Beach, CBU 59 at Horden to Seaham, CBU 62 and 63 from Seaham Hall to Salterfen Rocks and Newbiggin (South of Spittal Point) in CBU 79. These areas are largely stable in the present day.

Table 5.1: Assessment of 1940s epoch, qualitative descriptions of change for CBUs.

Local Authority Frontage	CBU	CBU Type	Location	Features visible in 1940s	Features visible in 2015
Scarborough Borough Council	**0**	Composite Cliff	Filey Bay South	Several fresh mudslides on cliff	No fresh features
	1	Simple Landslide	Filey Bay - South of Hummanby Gap to Speeton Hills	Landslide activity with debris runout and rockfall debris on shore platform	Extensive cliff top retreat is visible Cliff is more vegetated
	2	Complex Cliff	Filey Bay - Flat Cliffs	Developed area. No features indicating change.	Developed area. No features indicating change
	3	Simple Landslide	Filey Bay - North of Flat Cliffs to Filey Town	Mudslide activity widespread, including headscarp retreat and debris runout	No features indicating recent change visible. Mudslide scars vegetated.
	4	Simple Landslide	Filey Town to Filey Brigg S	Several fresh mudslides north of Filey Town.	Several fresh mudslides, including recent runout of debris

Local Authority Frontage	CBU	CBU Type	Location	Features visible in 1940s	Features visible in 2015
	5	Composite Cliff	Filey Brigg N to Cayton Bay	Rockfall on shore platform.	Rockfall debris on shore platform. No indication of recent rockfalls
	6	Simple Landslide	Cayton Bay (SE)	Localised areas of mudslide activity and recent debris runout.	Cliffs vegetated
	7	Complex Cliff	Cayton Bay (NW)	Very localised rockfall	No activity
	8	Simple Landslide	Osgodby Point to White Nab	Several localised mudslides on cliff	A few mudslides. Cliffs more vegetated
	9	Composite Cliff	White Nab to Black Rocks (S. of Scarborough)	Localised rockfall to shore	Rockfall debris on shore platform. No indication of recent rockfalls
	10	Relict Cliff	Scarborough South Bay	Area developed	No change
	12	Relict Cliff	Scarborough Castle Cliff and North Bay (South)	Area developed	No change
	13	Relict Cliff	Scarborough North Bay (Central)	Area developed	No change
	15	Composite Cliff	Scarborough North Bay (North)	No features visible.	Rockfall widespread. Very localised areas of fresh failures.
	16	Simple Landslide	Scalby Ness	Very localised areas of rockfall	Cliffs more vegetated
	17	Composite Cliff	Scalby Ness to Cliff Top House	Widespread evidence of past rockfall on shore platform.	Rockfall widespread along shore platform, some recent.
	22	Complex Cliff	Redhouse Farm (E. Of Cloughton) to Ravenscar	Widespread evidence of past rockfall on shore platform.	Cliffs more vegetated
	23	Composite Cliff	Robin Hood's Bay (South)	No features visible	No features visible
	24	Simple Landslide	Robin Hood's Bay (Central)	Localised rockfall near Stoupe Beck. Fresh mudslides and debris runout	Ongoing activity
	25	Simple Landslide	Robin Hood's Bay (Stoupe Beck to Boggle Hole)	Localised areas of mudslide activity and recent debris runout lobes	Cliff more vegetated but significant recession is suggested since 1940s
	27	Relict Cliff	Robin Hood's Bay (Village South)	Several fresh mudslides nearby cliff top development	Area developed and protected
	29	Simple Cliff	Robin Hood's Bay Village to White Stone Hole	Localised rockfall to shore nearer the Village	Rockfall more widespread nearer Village. Clear change in orientation of coastline in 180m section near Village where evidence of recession of cliff top and rockfall debris runout onto shore platform
	32	Composite Cliff	Lighthouse s. of Whitby to Whitby (inc. Saltwick Nab)	Rockfall widespread though not appear recent	No change
	34	Relict Cliff	Whitby Harbour	Area developed	No change
	35	Simple Cliff	Whitby West Cliff (Harbour End)	No features visible, part developed	No change
	36	Relict Cliff	Whitby West Cliff	No features visible, part developed	No change

Local Authority Frontage	CBU	CBU Type	Location	Features visible in 1940s	Features visible in 2015
	37	Simple Landslide	Upgang Beach	Several mudslide scars and debris lobes to shore	Significant cliff recession has occurred since 1940s. Cliff remain active
	38	Simple Landslide	South of East Row	Area developed	Area developed though evidence of earlier mudslide affecting orientation of fence line
	41	Composite Cliff	Sandsend to Runswick Bay (Hob Holes)	Localised rockfall to shore platform	No change
	42	Complex Cliff	Runswick Bay (Hob Holes) to Runswick Village	Several small fresh mudslides	No change in features. Localised recession of cliff top has occurred since 1940s
	43	Composite Cliff	Runswick Bay Village to Staithes	Very localised area of rockfall to shore	No change
Redcar and Cleveland Borough Council	**46**	Composite Cliff	Cowbar Nab (North Side)	No features indicating change visible	Significant cliff retreat since 1940s has impacted the road
	47	Composite Cliff	East of Boulby	No features indicating change visible	No change
	48	Complex Cliff	West of Boulby	Widespread historical rockfall debris on shore platform	No change
	49	Composite Cliff	East of Skinningrove (Hummersea Scar)	No features indicating change visible	No change
	51	Composite Cliff	Skinningrove breakwater to Saltburn	Occasional historical rockfall debris on shore platform	No change
	52	Simple Landslide	Saltburn (East)	No features indicating change visible	No change
	54	Simple Landslide	Saltburn to Redcar	Very localised areas of mudslides	Cliffs more vegetated
Hartlepool Borough Council	55	Simple Cliff	NW of Hartlepool Headland	No change visible	Rockfall debris on shore platform.
Durham County Council	**56**	Simple Landslide	Crimdon Park	No features indicating change visible	Cliffs appear more vegetated
	57	Composite Cliff	Blackhall Rocks	Very localised rockfall to shore platform, not appear recent	No change
	58	Simple Landslide	Blackhall Colliery	No features indicating change visible	No change
	59	Composite Cliff	Horden to Seaham	Very localised rockfall to shore	Rockfall more widespread. and significant erosion since 1940s evident
	60	Simple Cliff	Seaham (South of Harbour)	No features indicating change visible	Area developed and protected
	61	Simple Cliff	Seaham (North of Harbour)	Very localised rockfall to shore	Area developed and protected
Sunderland City Council	**62**	Simple Landslide	Seaham Hall to Salterfen Rocks	Shadow obscured cliff	Fresh mudslides in parts, and localised rockfall and debris runout to shore.
	63	Simple Cliff	Salterfen Rocks (North Side)	Localised rockfall to shore, may be historical	Localised fresh rockfalls

Local Authority Frontage	CBU	CBU Type	Location	Features visible in 1940s	Features visible in 2015
	64	Relict Cliff	Grangetown to Hendon Frontage (Sunderland)	Localised rockfall to shore, small mudslides from cliff top	Area developed and protected
South Tyneside Council	**66**	Simple Landslide	Whitburn South	Very localised recent debris at toe	Localised debris blocks on beach. Localised significant recession since 1940s
	67	Simple Cliff	Whitburn to South Shields	Rockfall widespread and significant in parts, localised recent failures.	Rockfall widespread and less vegetation indicating increased activity.
North Tyneside Council	**72**	Simple Cliff	Tynemouth Longsands	Very localised areas of mudslide debris/rockfall onto shore	Area developed, no change
	74	Simple Cliff	Whitley Bay Promontory	No features indicating change visible	Fresh rockfall to east of promontory
	75	Relict Cliff	Whitley Bay	No features indicating change visible	Area developed and protected
	76	Simple Landslide	Whitley Bay North	Localised small mudslides	Localised small mudslides
	77	Relict Cliff	Whitley Bay to St Mary's Island	No activity	Area developed and with cliff protection
Northumberland County Council	**78**	Simple Cliff	St Mary's Island to Seaton Sluice	Widespread recent rockfalls	Changes associated with removal of structures
	79	Simple Cliff	Newbiggin (South of Spittal Point)	Widespread rockfall debris	Widespread recent rockfall. Significant localised cliff retreat since 1940s
	80	Simple Cliff	Newbiggin Point	No features indicating activity	Very localised areas of recent rockfall. Some developments on cliff top. Significant localised cliff retreat since 1940s
	81	Simple Cliff	Newbiggin (Beacon Point)	No features indicating activity	Very localised rockfall has retreat cliff top
	82	Simple Cliff	Snab Nab (Lynemouth)	Localised rockfall to shore	No change
	83	Simple Cliff	Creswell	No features indicating change visible	No change
	87	Simple Cliff	North of Boulmer	Very localised rockfall and blocks on shore	No change
	88	Simple Landslide	Sugar Sands (Between Boulmer and Howick)	No features indicating change visible	Historical mudslide lobe has vegetated over
	91	Simple Cliff	Howick Haven	No features indicating change visible	No change
	92	Simple Cliff	Beadnell	No features indicating change visible	No change
	96	Simple Cliff	Saltpan Rocks to Bear's Head	Localised rockfall to shore	No change apart from fresh mudslides in upper parts of cliff
	97	Simple Cliff	Berwick to Scottish Border	No Data	No Data

Table 5.2: Assessment of 1940s epoch, qualitative descriptions of change for dune units.

Local Authority Frontage	Dune Unit	Location	Dune change 1945-2015
Redcar and Cleveland Borough Council	1	Coatham Sands	Significant increase in seaward extent, more vegetated
Hartlepool Borough Council	2	Tees Northern Harbour	Moderate decrease in seaward extent, vegetation less established
	3	Hartlepool Bay South	Significant increase in seaward extent, more vegetated
	4	Hartlepool North Sands	Minor increase in seaward extent, generally more vegetated
South Tyneside Council	5	Herd Sands South	Moderate decrease in seaward extent, less vegetated due to car park development
	6	Herd Sands North/Littlehaven	Minor increase in seaward extent, more vegetated
Northumberland County Council	7	Blyth South Beach	Minor increase in seaward extent to south of beach, more vegetated. Significant decrease in seaward extent to north of beach, vegetation less established
	8	Cambois Bay	Minor decrease in seaward extent, vegetation less established
	9	Druridge Bay	Significant decrease in seaward extent to north of bay, vegetation less established
	10	High Hauxley	Moderate decrease in seaward extent, vegetation less established
	11	Alnmouth Bay	Minor increase in seaward extent, generally more vegetated
	12	Beadnell Bay	Moderate decrease in seaward extent at south of beach, indication of recent burial of vegetation. Minor increase in seaward extent to north, though vegetation less established
	13	North of Seahouses	No significant change, vegetation less established
	14	Bamburgh	Moderate increase in seaward extent, more vegetated

5.2 Quantitative assessment

The cliff top and cliff toe have been mapped from the 1940s imagery and rates of change to 2015 have been calculated. The 1940s mosaics are comprised of photographs from all years during the period 1940 to 1949 and therefore a date of 1945 is taken for the whole epoch when calculating rates of change. The georectification errors in the 1940s imagery are locally high and therefore rates of change are only reported where they exceed the error. At other locations, change is too low to be accurately reported.

Additional aerial photography data from 1968 and 1996 are available for the Scarborough Borough Council frontage between Filey Bay and Cayton Bay. These data have been used to determine short-term rates of change for the periods 1945 to 1968, 1968 to 1996 and 1996 to 2015.

Average recession rates for all epochs have been calculated for each CBU and data for each local authority region are shown Tables 5.3 to 5.10. Negative values indicate cliff retreat and positive values indicate advance. “No Data” indicates where no cliff position could be mapped, ‘none detected’ indicates locations where the erosion rate is lower than the RMS error and cannot be reported with any confidence. Location maps for each CBU are provided in Appendix A. The data for each profile are given in Appendix C. It should be noted that the averaging process used to calculate rates of change for each CBU may result in a figure that is less than the margin of error.

The combined RMSE values for each of the image mosaics has been calculated using the estimated error for each tile of the 1940s data and RMS error of the 2015 data. Figures range from ±0.01 to ±0.11m/yr between 1945 and 2015 (Table 3.2). Rates of change less than the combined RMS errors of the image mosaics cannot be relied upon.

The data show that across all the CBUs the average cliff top recession rate between 1945 and 2015 is 0.06±0.05m/yr. Erosion greater than the RMSE was detected at around 25% of

CBUs, with others recording no, or insignificant erosion. The maximum erosion over this period was at Newbiggin (South of Spittal Point), where a rate of 1.05±0.01m/yr was measured at transect 220. The erosion rate for the whole CBU was also high at 0.63±0.01m/yr. Other areas indicating significant rates of erosion include CBU 63 at Salterfen Rocks (North Side) where erosion of 0.77m/yr±0.04m/yr was recorded and CBU 42 at Runswick Bay where erosion of 0.81m/yr±0.07m/yr was recorded.

Erosion in the cliff toe position has been measured for the Scarborough Borough Council frontage between Filey Bay South and Redcar, where large landslide complexes are widespread. Toe erosion was detected at around 50% of the CBUs, with an average rate of 0.25±0.08m/yr. The maximum erosion rate is 0.58±0.08m/yr in CBU 22 at Redhouse Farm.

Advances of the position of the toe are credible and may relate to runout of debris to the foreshore. The rate of toe advance detected is likely to be an underestimate because the data provides a snapshot of feature change. The toe 'advance' is due to debris runout, which was instantaneous, but toe erosion will have occurred over subsequent years as debris is reworked. Around 5% of the CBUs showed advance of the toe at an average rate of 0.19±0.05m/yr. Maximum toe advance is 0.18±0.08/yr in CBU 17 at Scalby Ness to Cliff Top House.

Taken as whole, the 1940s aerial photography datasets indicate measurable erosion (greater than the RMSE) of around 30% along the cliffed frontage from Flamborough Head to the River Tyne. Change at other locations is smaller than the positional errors in the photography and cannot be relied upon. The 1940s imagery have proved that coastal erosion can be detected where rates are greater than around 0.1m/yr, but lower rates of change are harder to precisely determine due to the relatively high positional errors in parts of the imagery. Where the accuracy of the imagery is low, the data can still be used to undertake a visual comparison of features.

In summary, the following conclusions can be made for change between 1945 and 2015:

- The average rate of cliff top recession of CBUs in Scarborough Borough Council area frontage is 0.22±0.08m/yr. CBUs 1 and 2 are the most rapidly eroding, with Filey Bay Flat Cliffs at 0.37±0.11m/yr and Filey Bay South of Hummanby Gap to Speeton Hills at 0.24±0.08m/yr. The average rate of cliff toe recession along the frontage is 0.22±0.08m/yr. Cliff toe advance, which may relate to runout of debris lobes, is on average 0.11±0.08m/yr.
- The average rate of cliff top recession of all CBUs in the Redcar and Cleveland Borough Council is 0.11±0.07m/yr. No cliff toe advance was detected.
- The average rate of cliff top erosion within the Hartlepool Borough Council area was 0.15±0.10m/yr.
- The average rate of cliff top recession of CBUs situated within the Durham County Council area during this period is 0.52±0.10m/yr. This figure is skewed by the high recession rates within CBU 59 at Horden to Seaham of 0.52±0.10m/yr and it is likely that actual change has been significantly less than this.
- The average rate of cliff top recession on the Sunderland City Council frontage is 0.31±0.04m/yr. This is comparatively high, and is likely that georectification errors in the 1940s aerial imagery have caused localised errors on undeveloped sections of the coast.
- The average rate of cliff top recession in CBUs in the South Tyneside Council area is 0.19±0.04m/yr.
- In the North Tyneside Council area, cliff top recession across all CBUs was on average 0.10±0.04m/yr.
- In the Northumberland County Council area, cliff top recession across all CBUs was on average 0.22±0.02m/yr.

For the frontage of Filey Bay to Cayton Bay, where additional photo epoch are available, the highest average erosion rate across all CBUs was between 1945 and 1968 in CBU 8 at Osgodby Point where a rate of 1.60±0.45m/yr was recorded. High erosion rates are also indicated in CBU 1 at Filey Bay over the epochs 1945-1968 and 1968-1996, and in CBU 6 at Cayton Bay (SE) 1945-1968. The highest average toe advance rate across all CBUs was between 1996 and 2015 in CBU 5 at Filey Brigg N to Cayton Bay, where the advance rate is generally over 1.00±0.11m/yr. The areas of greatest rates of change have occurred where debris run-out lobes from cliff failures have advanced the cliff toe.

Measurable change across the three epochs showed that 10-20% of all CBU transects experienced cliff top recession, with most recession occurring within the 1945-1968 epoch. Average cliff top recession rate during this time was 0.78±0.45m/yr. The remainder experienced no or insignificant recession. Maximum recession rates occurred in CBUs 0 and 1, between Filey Bay South and Speeton Hills in 1945-1968. Comparatively high recession rates also occurred in CBUs 4 to 6 between Filey Town and Cayton Bay (SE) in the epoch 1968-1996. High recession rates recorded using 1940s imagery may be in part error-related due to image inaccuracies, and are not at the scale suggested by the data. While change may have been measured at other locations, it is less than the RMS error and therefore cannot be relied upon.

Table 5.3: Average recession (and toe advance) rates for CBUs in Scarborough Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.08m/yr)	
0	2	Composite Cliff	Filey Bay South	No Data	None Detected
1	8	Simple Landslide	Filey Bay - South of Hummanby Gap to Speeton Hills	-0.40	-0.24
2	3	Complex Cliff	Filey Bay - Flat Cliffs	-0.08	-0.37
3	6	Simple Landslide	Filey Bay - North of Flat Cliffs to Filey Town	-0.15	-0.03
4	4	Simple Landslide	Filey Town to Filey Brigg S	-0.04	-0.10
5	12	Composite Cliff	Filey Brigg N to Cayton Bay	-0.12	None Detected
6	2	Simple Landslide	Cayton Bay (SE)	-0.23	-0.06
7	2	Complex Cliff	Cayton Bay (NW)	0.07	None Detected
8	2	Simple Landslide	Osgodby Point to White Nab	-0.24	None Detected
9	2	Composite Cliff	White Nab to Black Rocks (S. of Scarborough)	-0.16	-0.21
10	3	Relict Cliff	Scarborough South Bay	No Data	No Data
12	5	Relict Cliff	Scarborough Castle Cliff and North Bay (South)	No Data	-0.03
13	1	Relict Cliff	Scarborough North Bay (Central)	No Data	-0.16
15	2	Composite Cliff	Scarborough North Bay (North)	-0.14	None Detected
16	5	Simple Landslide	Scalby Ness	0.09	-0.03

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.08m/yr)	
17	1	Composite Cliff	Scalby Ness to Cliff Top House	0.18	None Detected
22	4	Complex Cliff	Redhouse Farm (E. Of Cloughton) to Ravenscar	-0.58	-0.03
23	1	Composite Cliff	Robin Hood's Bay (South)	-0.35	None Detected
24	4	Simple Landslide	Robin Hood's Bay (Central)	-0.41	-0.10
25	2	Simple Landslide	Robin Hood's Bay (Stoupe Beck to Boggle Hole)	-0.24	-0.07
27	1	Relict Cliff	Robin Hood's Bay (Village South)	-0.32	None Detected
29	3	Simple Cliff	Robin Hood's Bay Village to White Stone Hole	-0.14	None Detected
32	4	Composite Cliff	Lighthouse s. of Whitby to Whitby (inc. Saltwick Nab)	-0.13	-0.04
34	1	Relict Cliff	Whitby Harbour	No Data	None Detected
35	1	Simple Cliff	Whitby West Cliff (Harbour End)	None Detected	None Detected
36	2	Relict Cliff	Whitby West Cliff	No Data	-0.19
37	2	Simple Landslide	Upgang Beach	-0.25	None Detected
38	1	Simple Landslide	South of East Row	No Data	No Data
41	15	Composite Cliff	Sandsend to Runswick Bay (Hob Holes)	-0.04	-0.02
42	3	Complex Cliff	Runswick Bay (Hob Holes) to Runswick Village	No Data	-0.81
43	13	Composite Cliff	Runswick Bay Village to Staithes	-0.12	-0.03

Table 5.4: Average short-term recession (and toe advance) rates for CBUs in Scarborough Borough Council area from Filey Bay to Cayton Bay

CBU	Number of Profiles	CBU Type	Approximate Location	Average Rate of Cliff Toe Change m/yr			Average Rate of Cliff Top Change m/yr		
				1945-1968 (±0.45m /yr)	1968-1996 (±0.13m/ yr)	1996 to 2015 (±0.11m/ yr)	1945-1968 (±0.45m/ yr)	1968-1996 (±0.13m/ yr)	1996-2015 (±0.11m/ yr)
0	2	Composite Cliff	Filey Bay South	No Data	No Data	No Data	-0.50	None Detected	-0.29
1	8	Simple Landslide	Filey Bay - South of Hummanby Gap to Speeton Hills	-0.47	-0.37	-0.10	-0.53	-0.02	-0.10
2	3	Complex Cliff	Filey Bay - Flat Cliffs	-0.18	0.09	-0.18	No Data	No Data	No Data
3	6	Simple Landslide	Filey Bay - North of Flat Cliffs to Filey Town	-0.16	0.03	-0.19	None Detected	None Detected	-0.11
4	4	Simple Landslide	Filey Town to Filey Brigg S	-0.15	0.22	-0.32	None Detected	-0.15	None Detected
5	12	Composite Cliff	Filey Brigg N to Cayton Bay	0.17	-1.24	1.02	0.25	-0.11	None Detected

CBU	Number of Profiles	CBU Type	Approximate Location	Average Rate of Cliff Toe Change m/yr			Average Rate of Cliff Top Change m/yr		
				1945-1968 (±0.45m /yr)	1968-1996 (±0.13m/ yr)	1996 to 2015 (±0.11m/ yr)	1945-1968 (±0.45m/ yr)	1968-1996 (±0.13m/ yr)	1996-2015 (±0.11m/ yr)
6	2	Simple Landslide	Cayton Bay (SE)	-0.70	None Detected	0.13	None Detected	-0.16	None Detected
7	2	Complex Cliff	Cayton Bay (NW)	None Detected	0.60	-0.25	None Detected	None Detected	None Detected
8	2	Simple Landslide	Osgodby Point to White Nab	-1.60	0.80	-0.07	No Data	No Data	No Data
9	2	Composite Cliff	White Nab to Black Rocks (S. of Scarborough)	-0.43	0.42	-0.57	None Detected	None Detected	-0.38
10	3	Relict Cliff	Scarborough South Bay	None Detected	None Detected 0.00	No Data	No Data	No Data	No Data
12	5	Relict Cliff	Scarborough Castle Cliff and North Bay (South)	No Data	No Data	No Data	None Detected	-0.02	None Detected

Table 5.5: Average recession (and toe advance) rates for CBUs in Redcar and Cleveland Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.07m/yr)	1945 to 2015 (±0.07m/yr)
46	2	Composite Cliff	Cowbar Nab (North Side)	None Detected	None Detected
47	3	Composite Cliff	East of Boulby	None Detected	None Detected
48	6	Complex Cliff	West of Boulby	-0.14	None Detected
49	4	Composite Cliff	East of Skinningrove (Hummersea Scar)	-0.15	-0.04
51	8	Composite Cliff	Skinningrove breakwater to Saltburn	None Detected	None Detected
52	2	Simple Landslide	Saltburn (East)	-0.05	None Detected
54	9	Simple Landslide	Saltburn to Redcar	None Detected	-0.04

Table 5.6: Average recession (and toe advance) rates for CBUs in Hartlepool Borough Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.10m/yr)	1945 to 2015 (±0.10m/yr)
55	2	Simple Cliff	NW of Hartlepool Headland	No Data	-0.15

Table 5.7: Average recession (and toe advance) rates for CBUs in Durham County Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.07m/yr)	1945 to 2015 (±0.07m/yr)
56	1	Simple Landslide	Crimdon Park	No Data	None Detected
57	4	Composite Cliff	Blackhall Rocks	No Data	None Detected
58	3	Simple Landslide	Blackhall Colliery	No Data	None Detected
59	15	Composite Cliff	Horden to Seaham	No Data	-0.11
60	2	Simple Cliff	Seaham (South of Harbour)	No Data	None Detected
61	3	Simple Cliff	Seaham (North of Harbour)	No Data	None Detected

Table 5.8: Average recession (and toe advance rates) for CBUs in Sunderland City Council area. (NB CBU 62 partly in Durham County Council area).

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.04m/yr)	1945 to 2015 (±0.04m/yr)
62	7	Simple Landslide	Seaham Hall to Salterfen Rocks	No Data	-0.26
63	1	Simple Cliff	Salterfen Rocks (North Side)	No Data	-0.77
64	2	Relict Cliff	Grangetown to Hendon Frontage (Sunderland)	No Data	-0.21

Table 5.9: Average recession (and toe advance) rates for CBUs in South Tyneside Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.04m/yr)	1945 to 2015 (±0.04m/yr)
66	2	Simple Landslide	Whitburn South	No Data	-0.08
67	11	Simple Cliff	Whitburn to South Shields	No Data	-0.16

Table 5.10: Average recession (and toe advance) rates for CBUs in North Tyneside Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.04m/yr)	1945 to 2015 (±0.04m/yr)
72	3	Simple Cliff	Tynemouth Longsands	No Data	-0.16
74	1	Simple Cliff	Whitley Bay Promontory	No Data	None Detected
75	1	Relict Cliff	Whitley Bay	No Data	None Detected
76	2	Simple Landslide	Whitley Bay North	No Data	-0.02
77	1	Relict Cliff	Whitley Bay to St Mary's Island	No Data	None Detected

Table 5.11: Average recession (and toe advance) rates for CBUs in Northumberland County Council area.

CBU	Number of Profiles	CBU Type	Approximate Location	Long Term Retreat Cliff Toe (m/yr)	Long Term Retreat Cliff Top (m/yr)
				1945 to 2015 (±0.02m/yr)	1945 to 2015 (±0.02m/yr)
78	4	Simple Cliff	St Mary's Island to Seaton Sluice	No Data	-0.03
79	4	Simple Cliff	Newbiggin (South of Spittal Point)	No Data	-0.63
80	2	Simple Cliff	Newbiggin Point	No Data	-0.10
81	1	Simple Cliff	Newbiggin (Beacon Point)	No Data	-0.10
82	2	Simple Cliff	Snab Nab (Lynemouth)	No Data	-0.14
83	1	Simple Cliff	Creswell	No Data	-0.10
87	3	Simple Cliff	North of Boulmer	No Data	-0.06
88	1	Simple Landslide	Sugar Sands (Between Boulmer and Howick)	No Data	No Data
91	1	Simple Cliff	Howick Haven	No Data	No Data
92	0	Simple Cliff	Beadnell	No Data	No Data
96	5	Simple Cliff	Saltpan Rocks to Bear's Head	No Data	-0.10
97	11	Simple Cliff	Berwick to Scottish Border	No Data	No Data

6. Conclusions and Recommendations

This report is the second quantitative assessment of cliff recession and dune changes on the Cell 1 frontage. It uses the most recent 2015 aerial surveys and earlier high quality surveys from 2010 and 2012/13 to assess short-term change, and incorporates historical aerial photograph data from the 1940s to assess longer-term change. Additional aerial survey data from the 1960s and 1990s covering Filey Bay and Cayton Bay have also been assessed to show short-term rates of change through the 20th Century.

The cliff top, (and cliff toe for the frontages of Scarborough Borough Council and Redcar and Cleveland Borough Council), and dune front, has been interpreted and digitised from the aerial photography and change assessed along a series of pre-defined shore normal transects. Cliff Behaviour Units (CBUs) mapped previously (Halcrow 2010) were used to generate average rates of change for cliff units. The error of fit for the aerial photos (known as the root mean square error or RMSE) has been calculated, allowing rates of change to be quoted with an accompanying error. For the period 2012/13 to 2015, the combined RMS error is ±0.08m but error is significantly larger when comparing data from 2003 and 2008 to the more recent surveys, and when considering the data from the 1940s, 1960s and 1990s.

The results have shown that short-term change between 2012/13 and 2015 has been small but measurable, with 25% of CBUs having a statistically significant erosion rate of upto 0.5m/yr±0.1m. However, there are localised erosion peaks of ~2m/yr associated with episodic landslide events that have occurred on the frontage between Horden to Seaham. A limited amount of cliff toe advance has been detected associated with runout of debris lobes. Together, these data indicate that cliffs show widespread but low level activity. In some locations change is shown to have occurred on the cliff face that has triggered run-out of debris lobes to the shoreline, but has not yet led to cliff top recession.

The change in the position of the dune front has been evaluated using the same methodology. The dune front has been mapped using the limit of vegetation of an indicator of the limit of shoreline erosion and data from transects have been averaged to give rates of change for ‘dune units’. It is recognised that this proxy has limitations, for example a storm may deposit sand on top of dune vegetation giving the impression of erosion when the reverse has occurred), but nevertheless, a pattern of change is expected to emerge over the longer term.

The coverage and accuracy of data allowed assessment of dunes to be made between previous aerial surveys from 2008, 2010 and 2012/13 and the most recent 2015 survey. The data show significant variation over the two time periods. The data indicates that change of up to ±4m/yr change is widespread, but that change of >±10m/yr has been recorded. The 2015 aerial survey has enabled the assessment of the impacts of the December 2013 storm surge. The data reveals a spatial pattern whereby dunes south of the River Tees experienced greatly reduced levels of accretion post-surge, while dunes north became largely accretionary following the widespread erosion pre-surge. These data indicate the very dynamic nature of dunes and their ability to rapidly respond to storm events.

The 1940s aerial survey provides a longer-term assessment of coastal change. Given locally high RMS errors and low photograph resolution associated to the 1940s survey data, the ability to measure small changes in the coastline is limited. However visual identification of change since the 1940s indicates that the cliffs have experienced widespread but low levels of activity. Landslide and rockfall activity is particularly evident at Seaham, Salterfen Rocks and Robin Hood’s Bay, which concurs with the more recent survey data. Calculated rates of change since the 1940s are generally low, with few sections of coast showing average erosion of more than around 0.1m/yr. Despite the accuracy of the 1940s data being low, the results do suggest that erosion rates along the Cell 1 coast have been low overall, and that hotspots of activity have persisted from the 1940s to the present day.

The short term data for the assessment of coastal change between Filey Bay and Cayton Bay confirms that the rates of change have been persistently low in all time periods and locations since the 1940s. The peaks in erosion rate recorded between 1945 and 1968 probably reflect the much larger margin of error over this period.

High quality survey data collected since 2010 provides evidence for short term change that is often at a low rate that is close to the calculated margin of error. This suggests that the contemporary cliff erosion rate is low and reflects site observations. The conclusion is also supported by analysis of full and partial measures field-surveys of cliff positions that have suggested very low erosion rates of less than 0.5m/yr. Ongoing collection of high-quality aerial survey data is critical to establish longer-term patterns of coastal change and details of the magnitude and frequency of cliff recession events, particularly in response to storm surges, or periods of high antecedent rainfall. At present, the frequency of surveys is 2 yearly, but given the low levels of erosion recorded since 2010 (and probably since the 1940s) extending the frequency of future aerial surveys to 5 yearly would not significantly reduce the accuracy of findings. However, in the short-term maintenance of the current programme is recommended to gain a more precise understanding of the timing and location of coastal change.

8. References

Halcrow (2010) Cell 1 Coastal Monitoring Programme. Aerial Photographic Survey 2010: Areas of Change. Final report, August 2010.

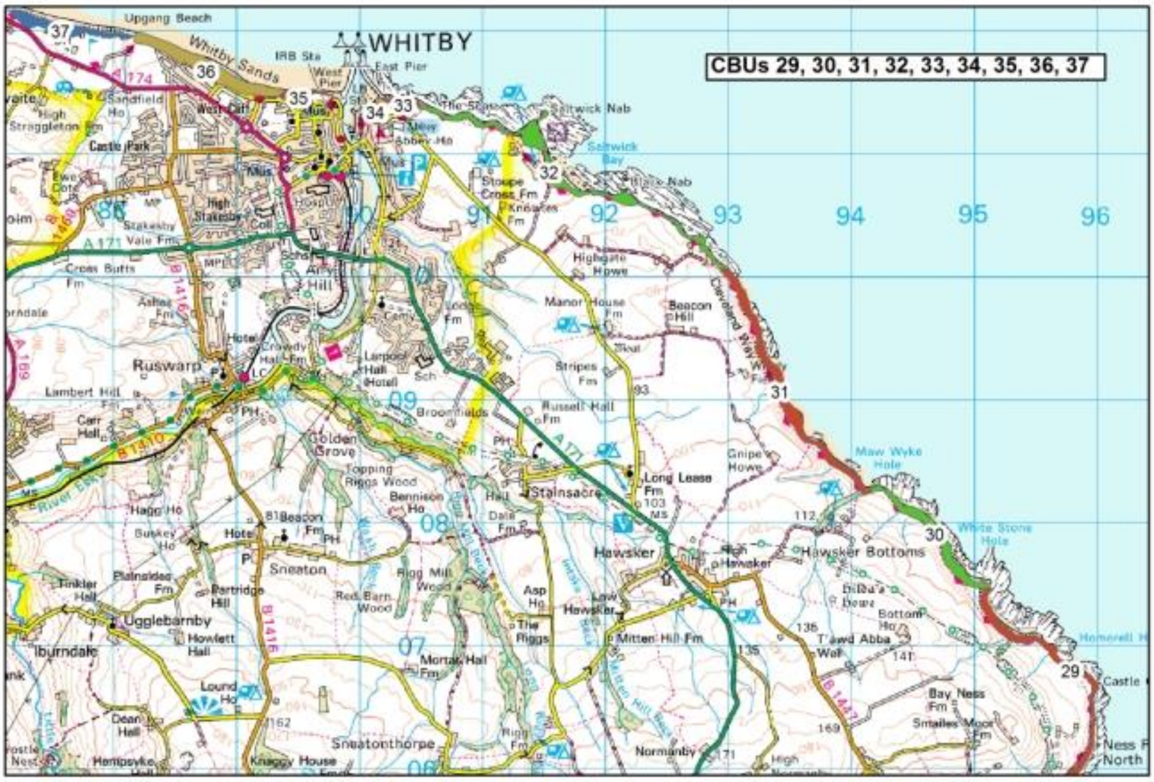
Halcrow (2013a) Cell 1 Regional Coastal Monitoring Programme. 2012/13 Aerial Survey Analysis Report. Final report December 2013

Halcrow (2013b) Walk-over Visual Inspections of Selected Assets following Storm Surge of 5th December 2013. Cell 1 Regional Coastal Monitoring supplemental report, December 2013.

Appendix A – CBU Location Maps

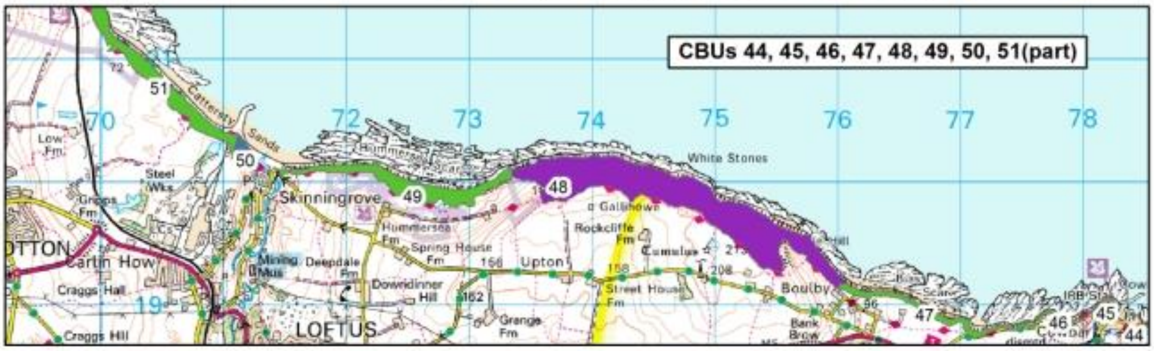
CBUs 17, 18, 19, 20, 21, 22
22
21
20
19
18
17
Hayburn Wyke
Wyke Hotel
Cloughton Newlands
Cloughton
Cloughton Wyke
Hundale
Cloughton Fields Fm
The Old Mill
Cliff Top Ho
Little Moor
Cober Hill
Shire Horse Fm
The Hulleys

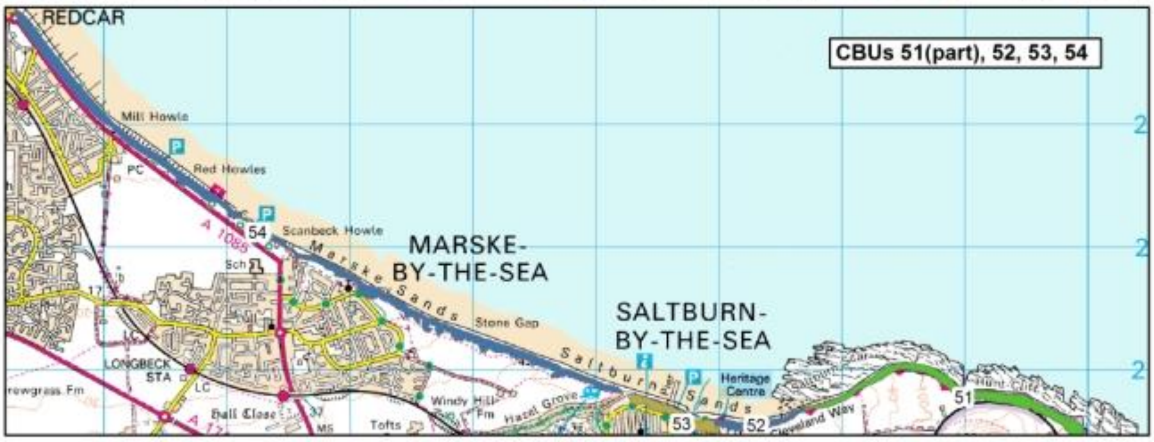
CBUs 22, 23, 24, 25, 26, 27, 28, 29
29
28
27
26
25
24
23
22
Robin Hood's Bay
Boggle Hole
Stoupe Beck Sands
Stoupe Brow Cottage Fm
Old Peak or South Cheek
Coastal Centre
Blea Wyke Point
Brow Moor
Howdale Moor
Robin Hood's Butts
Green Dike
Stony Marl Moor
Wellfield
Bell Hill Fm
Staintondale Moor
Prospect House Fm
Ravenscar



CBUs 29, 30, 31, 32, 33, 34, 35, 36, 37
WHITBY
Upgang Beach
Whitby Sands
East Pier
West Pier
37
36
35
34
33
32
31
30
29
Saltwick Nab
Saltwick Bay
Black Nab
Castle Park
High Stakesby
Ruswarp
Stainsacre
Hawsker
Sneaton
Ugglebarnby
Maw Wyke Hole
White Stone Hole
Hawsker Bottoms
Bay Ness
Normanby
Iburndale
Sneatonthorpe
Long Lease Fm
92
93
94
95
96


CBUs 38, 39, 40, 41, 42, 43
Staithes
Old Nab
Brackenberry Wyke
Port Mulgrave
Lingrow Knock
Hinderwell
Runswick Bay
Runswick Sands
Kettleness
Scratch Alley
Goldsborough
Loop Wyke
Overdale Wyke
Deepgrove Wyke
Sandsend Ness
Ellerby
Brockrigg
Northfields Fm
Westfields Fm
Mickleby
West Barnby
East Barnby
Lythe
Sandsend
Mulgrave Castle
East Row
Newton Mulgrave
43
42
41
40
39
38


CBUs 44, 45, 46, 47, 48, 49, 50, 51(part)
Cattersty Sands
Skinningrove
Hummersea
White Stones
Boulby
LOFTUS
Carlin How
Upton
Street House
51
50
49
48
47
46
45
44


CBUs 51(part), 52, 53, 54
REDCAR
Mill Howle
Red Howles
Scanbeck Howle
MARSKE-BY-THE-SEA
Marske Sands
Stone Gap
SALTBURN-BY-THE-SEA
Saltburn Sands
Heritage Centre
Cleveland Way
LONGBECK STA
54
53
52
51


CBU 55
HARTLEPOOL
Parton Rocks
Historic Quay and Ship
Art Gallery
CBUs 62, 63, 64, 65
Whitburn Bay
Parson's Rocks
Roker Rocks
SUNDER
South Rocks
Salterfen Rocks
Pincushion
Ryhope
Seaham Grange
CBUs 56, 57, 58, 59, 60, 61
SEAHAM
Featherbed Rocks
Liddle Stack
Nose's Point
Chourdon Point
Hawthorn Hive
Beacon Point
Shippersea Bay
Shot Rock
Loom
Fox Holes
Easington Colliery
Horden Point
Horden
Dene Mouth
Blackhall Rocks
Hesleden
Castle Eden


SOUTH SHIELDS
CBUs 66, 67, 68
Frenchman's Bay
Marsden Bay
Lizard Point
Souter Lighthouse
Coastal Park
Cleadon
Whitburn

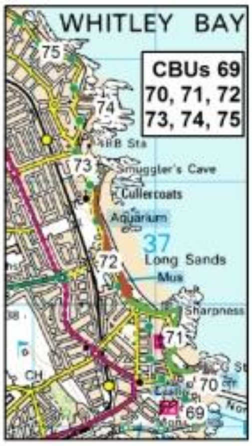

CBUs 82, 83
Brig Head
Seal Skears
Snab Point
Headagee
Lynemouth


High Hauxley
Low Hauxley
Low Hall
Elm Bush
Hadston Carrs
CBUs 84, 85


CBUs 86, 87, 88
89, 90, 91
Howick Haven
Sugar Sands
Howdiemont Sands
Longhoughton Steel
Red Ends
Boulmer Steel
Boulmer
The Torrs
North Reins
Boulmer Haven
Seaton Point
Fluke Hole


CBU 92
Greymare Rock
Castle Point
Dunstanburgh Castle
Queen Margaret's Cove
Cushat Stiel

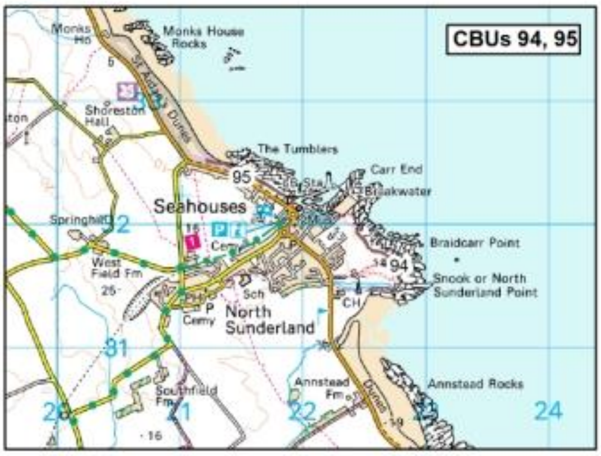

CBU 93
Linkhouse
Beadnell
Beadnell Harbour
Burn Carrs
Beadnell Bay
Bird Sanctuary
Robin Wood

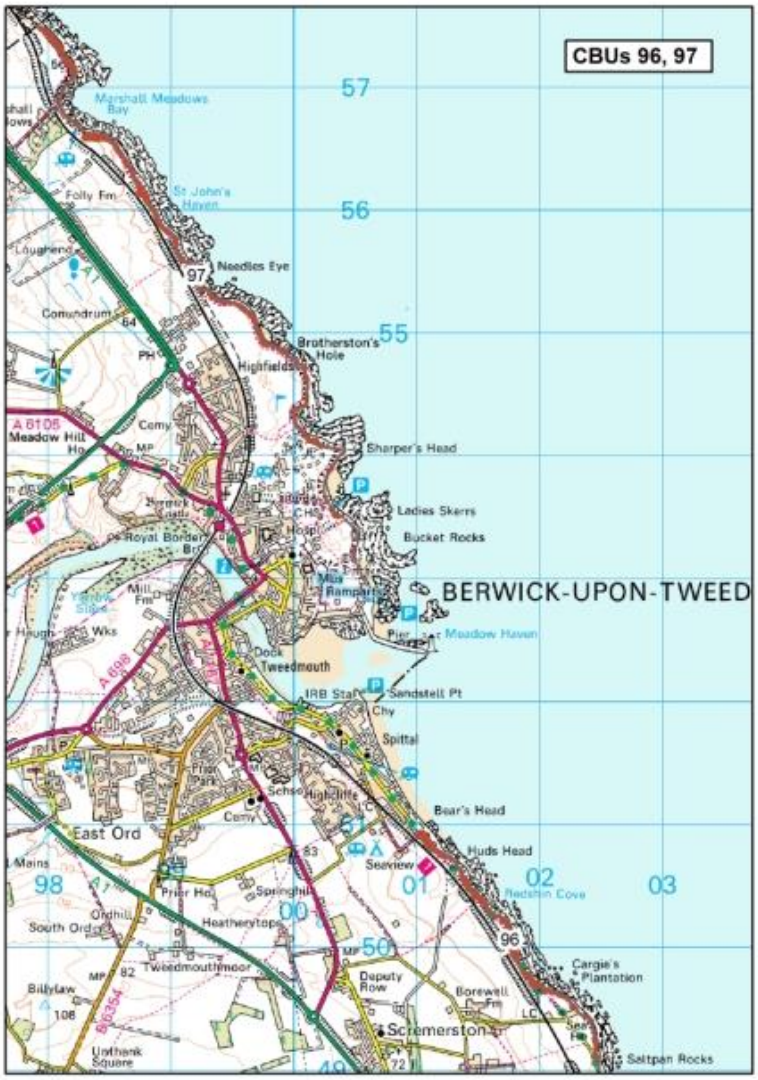

WHITLEY BAY
CBUs 69
70, 71, 72
73, 74, 75
Smuggler's Cave
Cullercoats
Aquarium
Long Sands
Sharpness


Seaton Sluice
CBUs 77, 78
Crag Point
St Mary's


NEWBIGGIN
Newbiggin Bay
Spital Carrs
Spital Point
CBUs 79, 80


CBUs 80, 81
Lyne Sands
Beacon Point
NEWBIGGIN-BY-
Newbiggin Bay


CBUs 94, 95
Monks House Rocks
Shoreston Hall
The Tumblers
Carr End
Breakwater
Seahouses
Braidcarr Point
Snook or North Sunderland Point
North Sunderland
Annstead Rocks


CBUs 96, 97
BERWICK-UPON-TWEED
Marshall Meadows Bay
St John's Haven
Needles Eye
Brotherston's Hole
Highfields
Sharper's Head
Ladies Skerrs
Bucket Rocks
Meadow Haven
Tweedmouth
Sandstell Pt
Spittal
Bear's Head
Huds Head
Seaview
Redshin Cove
Cargie's Plantation
Saltpan Rocks
Scremerston
Borewell
Deputy Row
Tweedmouthmoor
Heatherytops
Springhill
Prior Ho
Ordhill
South Ord
East Ord
Billylaw
Unthank Square
Conundrum
Folly Fm
Loughend
Meadow Hill Ho
Royal Border Br
A 6105
A 698
B6354
57
56
55
98
00
01
02
03
50
49

Appendix B – Summary Statistics by CBU

See accompanying electronic data

Appendix C – Cliff Change Data by Profile

See accompanying electronic data

Appendix D – Cliff Behaviour Unit Types

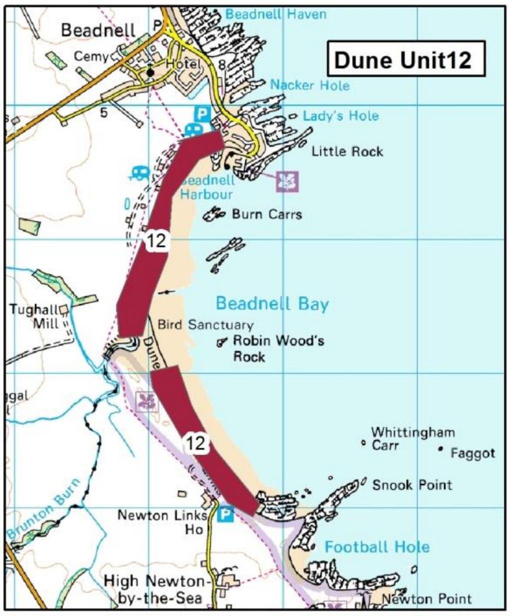
Simple Cliff

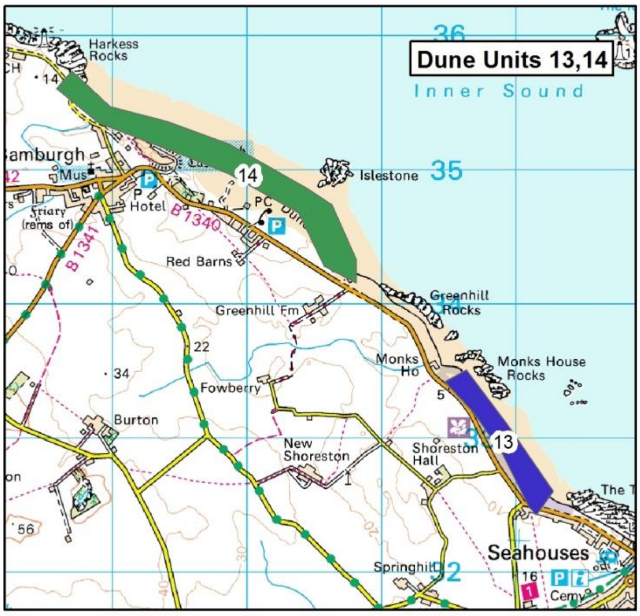
Composite Cliff -
Note different geological formations with differing properties forming different slope morphology in upper and lower cliff

Simple Landslide

Complex Cliff –
Multiple geological formations and failure mechanisms

Appendix E – Dune Unit Locations


Dune Unit12
Beadnell
Beadnell Haven
Nacker Hole
Lady's Hole
Little Rock
Beadnell Harbour
Burn Carrs
Beadnell Bay
Bird Sanctuary
Robin Wood's Rock
Tughall Mill
Whittingham Carr
Faggot
Snook Point
Newton Links Ho
Football Hole
High Newton-by-the-Sea
Newton Point
Brunton Burn
12
12


Dune Units 13,14
Harkess Rocks
Inner Sound
Islestone
Hotel
B1340
B1341
Red Barns
Greenhill Rocks
Greenhill Fm
Fowberry
Burton
Monks Ho
Monks House Rocks
New Shoreston
Shoreston Hall
Springhill
Seahouses
14
13

Appendix F – Dune Change Data by Profile

See accompanying electronic data

Appendix G – CBU and Dune Unit Source Maps

See accompanying pdf documents.