The use of terrestrial laser scanning, differential GPS surveying and panoramic photography to characterise the landslides and recession of the Holderness Coast, Yorkshire, England

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ABSTRACT
Results are presented from the first 11 months of a 2 year field monitoring program which is currently being undertaken on the Holderness Coast, Yorkshire, England. The research includes the use of terrestrial laser scanning, GPS surveying and panoramic photography to investigate the processes that are occurring within the cliff component of this coastal system. The results indicate a predominance of translational landslide types and illustrate significant variability in the mode of recession along this coastline, which is more complex than is often suggested in the published literature.

RÉSUMÉ
Les résultats présentés proviennent des 11 premiers mois d'un programme de 2 ans de survie du retrait de la cote Holderness (Yorkshire, Angleterre). Cette étude combine l'utilisation de repérage lasers, GPS ainsi que des photographies panoramique dans le but de documenter les processus de retrait en suivant l'évolution temporelle du profil de la falaise. Malgré une prédominance des glissements de terrains translationnels, nos résultats indiquent une large variabilité des modes de retrait de la cote ce qui démontre une complexité des phénomènes d'érosion côtières jusqu'ici insoupçonnée.

1 INTRODUCTION

The cliffs of the Holderness Coast, England recede extremely rapidly, generally displaying a median average cliff top loss of 1.3m/yr. However, they also show significant temporal and spatial variability, with 25% of the point measurements obtained by the local Council since 1951 having experienced values of land loss in excess of 11.5m in a single year. The recession of this region has been studied as far back as the 14th Century, with many studies having been undertaken at various times throughout the 1900s. These investigations have principally concentrated on providing a number for the annual rate of recession using the position of the cliff top, with few studies having been undertaken on the remainder of the coastal system. More recently studies have been undertaken to understand the fluctuations in the beach level and sediment transport processes (Pringle 1981; Prandle et al. 2001), but to date there has been no systematic study of the short term changes that occur within the cliff.

A monitoring program has been initiated in order to understand the pattern of events that occurs within the cliff throughout a two year period. The monitoring consists of monthly surveys of representative cliff sections using differential GPS (dGPS) and panoramic photography together with seasonal surveys using a terrestrial laser scanner. The combination of these techniques has allowed for the rapid collection of a vast amount of qualitative and quantitative data, which has been used to assess volumetric land loss, cliff top retreat, and the contribution of landslides to these processes. Results are presented of the data available at the time of publication, which is based on the first 11 months of surveying.

2 BACKGROUND INFORMATION

2.1 Location and Geological Setting

The Holderness coastline is approximately 85km long and is located in the south-eastern corner of Yorkshire in the north of England (Figure 1). The land is generally low lying, but exhibits an undulating topography, with the cliff heights varying between 36m above Ordnance Datum (AOD) at Dimlington High Land to less than 5mAOD at Easington and other low lying areas. However the cliff top is generally between 15mAOD to 20mAOD with beach heights of between 2mAOD to 4mAOD, resulting in the majority of the cliff line ranging between 11m to 18m in height.

The land use is dominated by agriculture, with occasional small villages and hamlets, three towns, oil and gas terminals and a small onshore wind farm. Sea defences are often associated with these settlements and industrial installations with a combined total of 11.35km of the coastline being protected (East Riding of Yorkshire Council 2004).

The cliff line is dominated by glacially derived material; predominately subglacially deposited deformation till, locally interspersed with glacial sand and gravel and post glacial deposits such as alluvium, tidal flat deposits and littoral material. Three till units are present in the cliffs, the most extensive of which are named the Skipsea and

Withernsea Tills and are believed to be late Devensian in age (23ka – 15ka BP). The other till unit, which underlies the Skipsea and Withernsea Tills across the entire coastline, is only visible in the cliffs at very few locations. This unit is named the Basement Till and is thought to be pre-Ipswichian in age (>128ka BP) (Catt 2007).

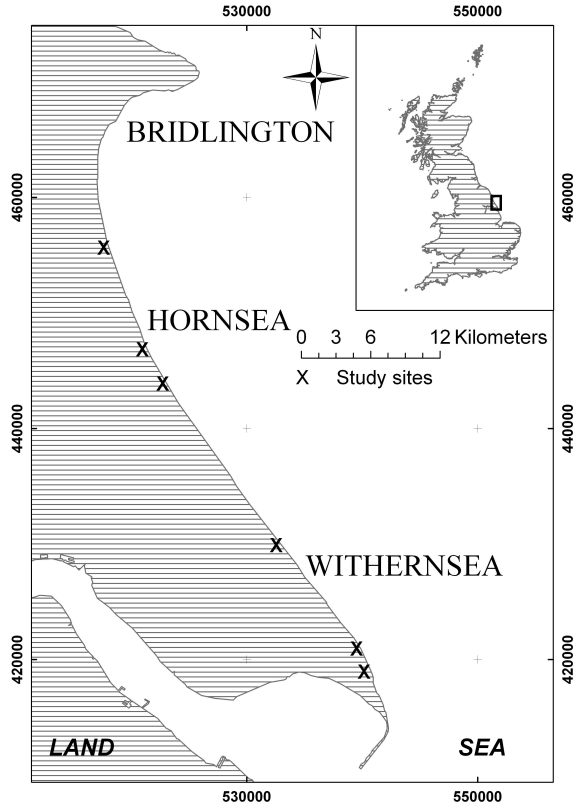


Figure 1. Location map

The cliff sections often display several subhorizontal discontinuities, even where only one till unit is present, together with shearing and the inclusion of sand beds and laminations, all of which are considered to be glaciotectonic deformation features associated with movement of glacier ice. These features represent weaknesses in the cliffs, which generally have peak c' and Φ' values of 17kPa to 42kPa and 16° to 36°, and residual values of 0kPa to 5kPa and 18° to 35° (Bell 2002).

2.2 Recession Rates

Early studies of recession in this area concentrated on producing annualised values of land loss by either comparing quantities of arable land with the quantities stated in the Doomsday Book (1086), comparing the distances of buildings from the cliff edge with the distances from the cliff edge at the time of construction, which is often written on plaques on buildings in this region, or, more commonly, by comparing the cliff line position on various historic maps (Sheppard 1912; Valentin 1954; Dosser 1955).

These methods relied on data of questionable reliability and provided no information relating to the annual variations in land loss. Therefore, in 1951 the East Riding of Yorkshire Council commenced a program of taking annual measurements of distances from the cliff top from structures located roughly 500m apart along the coastline. In 2003 this was supplemented with dGPS surveys at bi-annual intervals of the cliff top, selected areas of the base of the cliff, and of the beach, in order to view the spatial patterns of erosion at a finer scale and to map fluctuations in the beach level. However, these surveys could also be criticised as they only represent the changes occurring on the cliff top and the beach and ignore the processes occurring within the cliff system.

Between 1851 and 1952 the spatial pattern of recession indicated generally higher erosion in the north than in the south (Valentin 1954), however, the measurements made by the local Council illustrate that the highest recession is now in the central and south-central regions. This is likely to be a result of the construction of sea defences, as the recession rates to the north of the major sea defences has decreased and the rates to the south have increased since Valentins study.

The annual measurements made by the local Council illustrate that the recession of this coastline is episodic; years of high land loss are preceded and succeeded by years of lower land loss, with the pattern repeating on a cyclical pattern.

The average annual erosion rate ranges from 0.0m/yr to 5.0m/yr, but the distribution is skewed with a predominance of lower values, resulting in a median annual recession rate of 1.3m/yr.

3 METHODOLOGY

The purpose of this study is to characterise the changes that occur within the cliff component of this coastal region throughout two annual cycles, to assist in explaining the spatial and temporal variation in recession and landslides.

3.1 Selection of Study Sites

In order to characterise fully the processes that occur in the cliff face along this coastline it was necessary to select an appropriate number of study sites that were sufficiently contrasting as to represent the overall variability of this region.

In order to achieve this study sites were selected based on cliff height, composition, erosion rate, distance and direction from coastal protection works and also on accessibility.

Six sites were selected according to these criteria (Figure 1) which are located at varying distances and directions from coastal protection, have heights ranging from approximately 5mAOD to 21mAOD, recession rates ranging from 0.5m/yr to 2.7m/yr and are composed of either Skipsea or Withernsea Till, or both, with one site also including Basement Till at the base of the cliff.

3.2 Selection of Monitoring Techniques

When choosing the techniques to be used to survey the sites the main considerations included precision, accuracy, speed and how easily the results could be used to understand the processes. Secondary considerations related to the amount of time that is required to process the results and whether the technique had been used successfully in other areas.

The use of dGPS surveying of the top and bottom of the cliff and beach would provide results that could be directly compared with the larger scale dGPS surveying that the local Council were already undertaking, but would provide no data for the cliff area. Terrestrial laser scanning would provide a great amount of quantitative data on the cliff sections and has been used successfully on neighbouring coastal areas (Hobbs et al. 2002; Rosser et al. 2005; Lim et al. 2005), but requires a significant amount of post processing and can be difficult to interpret if used in isolation.

Therefore a combination of these two methods was selected including: dGPS surveying of the top and bottom of the cliff and beach, which would be used to assess change in these areas and would be used to align the point clouds that result from the terrestrial laser scanning to the British National Grid. The laser scanning data would be used to assess changes in the cliff region and the interpretation of this data would be aided by panoramic photography.

To improve the overall accuracy of the data, use was made of a national GPS network, provided for the whole of the UK by the Ordnance Survey of Great Britain, when processing the results of the GPS surveying.

3.3 Selection of Measurement Frequency

It was considered necessary to survey the selected sites with a frequency sufficient to determine the full sequence of events involved in their landsliding and recession. Consequently, a survey frequency equal to that of the landslide frequency was required. As this was not accurately known, but was believed to be sub-annual (Pethick 1996), a monthly reoccupation of these sites was made for the dGPS surveying and panoramic photography. It was decided that the dGPS surveying and panoramic photography would be supplemented with laser scanning on a seasonal basis, with one survey roughly every three months. This is due to speed and relative ease that the dGPS and panoramic photography can be performed compared with the laser scanning. However by combining the techniques in this manner it has been possible assess the change at these sites in an efficient and accurate manner, both in a qualitative and quantitative sense.

3.4 Data Handling

In addition to the surveying and processing it was necessary to establish several GIS databases in which the data could be collated and analysed. By making use of 3D visualisation facilities built into the ArcGIS suite of programs it was possible to create shapefiles of the landslides, which were initially identified on the panoramic photographs. Once the shapefiles were created it was possible to obtain the geometric measurements detailed in the Working Party on World Landslide Inventory (WP/WLI) report (1990) for the landslides using the laser scan data. The depth component of each landslide was obtained by taking profiles from the centreline of the area occupied by the landslide from before and after it occurred and directly measuring the depth to the rupture surface (Figures 2 and 3).

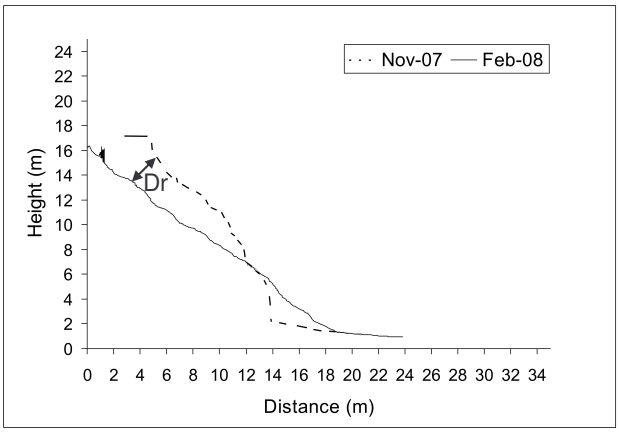


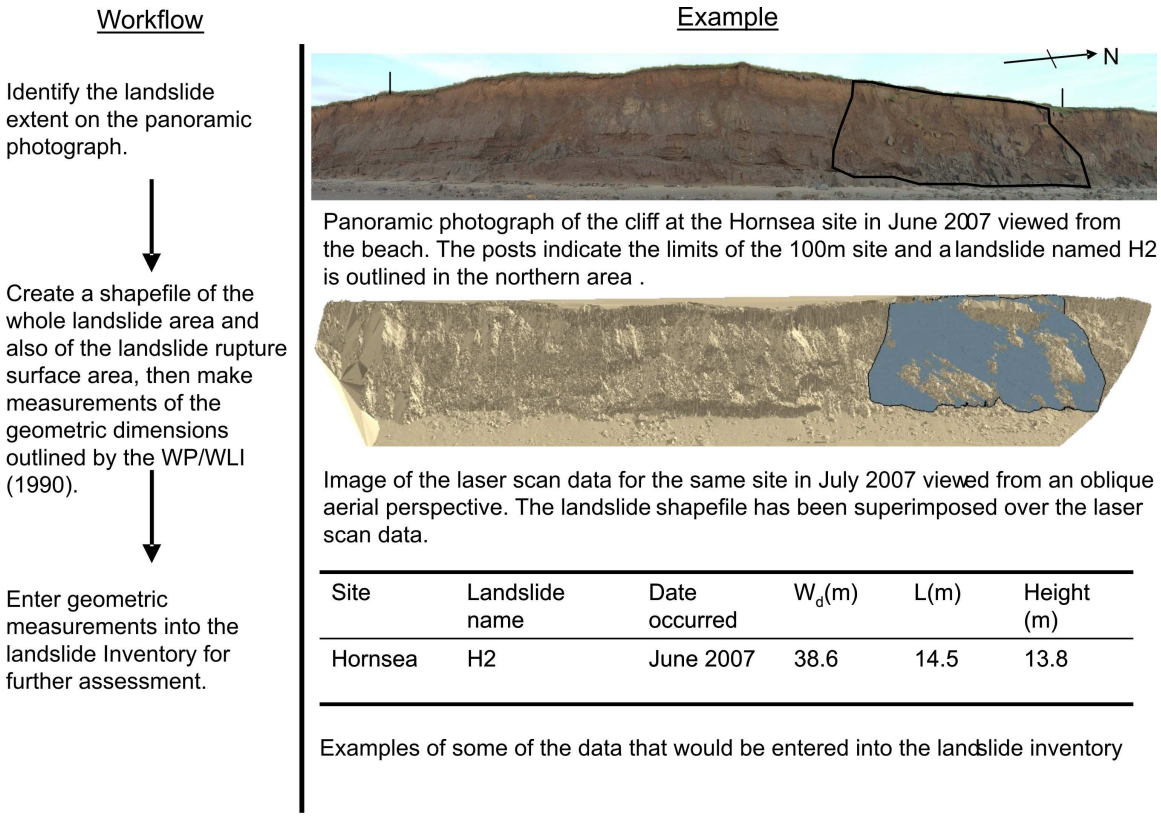
Figure 2. Example profile of a landslide, illustrating the ground surface for two separate dates.

Assessments of change between survey dates were also undertaken using GIS analysis tools. The assessments undertaken included measuring the amount of cliff top recession using the top of the cliff dGPS survey lines, measuring the change in beach level at the base of the cliff using the base of the cliff dGPS survey lines, and assessing the volumetric change in the cliff using the laser scan results.

Following the GIS analyses the data obtained was used to create a landslide inventory for viewing patterns such as seasonality of failures and the contribution of landslides to the net volumetric land loss and the amount of cliff top recession.

4 RESULTS

Over the period of 21 March 2007 to 14 February 2008 a total of 35 landslides were observed at the six monitoring sites. The majority occurred in the winter months, which is likely to be a consequence of low autumn beach levels and an unusually high rainfall throughout the summer. Approximately 6% occurred in Spring (March – May), 20% occurred in Summer (June – August), 11% occurred in Autumn (September – November) and 63% occurred in Winter (December – February). A summary of landslide geometries is listed in Table 1, which shows that the landslides are typically shallow failures that generally encompass the majority of the cliff height and have an average width: height ratio of 1.5. It should be noted that for the purpose of this study the term landslide has been used to refer to translational slides, rotational slumps, wedge failures, falls and topples that display a generally



Site	Landslide name	Date occurred	W_d(m)	L(m)	Height (m)
Hornsea	H2	June 2007	38.6	14.5	13.8

Figure 3. Workflow and example data used in the production of the landslide inventory.

intact slipped, fallen or toppled mass of obvious provenance and/or show an identifiable slip plane or rupture surface. Debris from small scale failures, which have an uncertain origin or ambiguous failure method, have been discounted from the landslide classification, together with failures of a flow type. Flows have been discounted to facilitate comparison with other studies that also discounted this mechanism (McGreal 1979) and because of difficulties with quantification. Failures of this type are comparatively rare along this coastline and their exclusion will have little impact on the volumetric assessment of landslides.

With regards the shape of the landslides, 88% of the slides observed were essentially translational failures, 9% were fall type failures and the remaining 3% represented one wedge failure.

When a volumetric assessment is made of the overall land lost and the volumes of the landslides, the contribution of the landsliding to the overall erosion of this region can be assessed. The net volume of land lost from the study sites, which cover an area of 7246m^2, is 12,448m^3 and the net loss from landslides, corrected to account only for the portion of the landslide entirely within the monitored area and to account for the portion of landslide material still present on the February scan, accounts for 6808m^3 (55%). Consequently 5640m^3 (45%) of material was removed by a mechanism other than a landslide occurring and transporting material to the base of the cliff to be removed by the sea. Such factors would include erosion by overland flow, piping through the sand layers and laminations, mudflows, debris flows, failures that are too small to have been identified as landslides and mechanical erosion by the sea. The volume of the landslides used in this assessment was calculated by multiplying the area by the depth, as opposed to the calculation presented by the WP/WLI (1990). This will result in a slight overestimate of the landslide volume, but the calculation fits the landslide shapes better than the half ellipsoid model presented by the WP/WLI.

Table 1. Landslide geometric features

Landslide feature	Minimum	Maximum	Mean
Width (W_r) (m)	3.8	84.3	13.2
Length (L_r) (m)	1.7	18.7	9.5
Height of failure (m)	1.5	14.5	9.2
Ratio of height of failure: height of cliff	0.1	1	0.7
Depth (D_r) (m)	0.3	4.5	1.7
Volume (m^3)	1.9	6320.3	394.8
Pre-failure angle (base of failure) (^{o})	23	66	46
Pre-failure angle (top of failure) (^{o})	31	73	50

This assessment is inhibited by the fact that landslide material was present on the cliff sections on the first scan in March 2007 at three of the study sites. Therefore, the above figures underestimate the contribution of landslides to the recession of this region. From an assessment of the panoramic photographs and laser scan data it is estimated that approximately an additional 20% of the net loss can be attributed to marine erosion of previously failed material. Consequently the landslide mechanism is deemed to have been responsible for roughly three quarters of the net volumetric loss at the study sites over the monitoring period. This value is very similar to values from studies on the Norfolk coast, England and Kilkeel coast, Northern Ireland, which showed landslides to contribute 80% and 70% to the overall volumetric loss respectively (Cambers 1976; McGreal 1979). For the three sites where landslide material was not present in the cliff on the first scan, the percentage contribution of landslides to the overall volumetric loss shows considerable variability, as detailed in Table 2.

Table 2. Variation in the contribution of landslides to the net volumetric land loss at three sites.

Site name	Cliff height (m)	Beach level (m)*	Sand layers present?	contribution of landslides to volumetric loss (%)
Hornsea	14.5	2.1	No	84
Withernsea	8	3.5	Yes	49
Easington	3.5	3.3	No	0

*Beach level refers to the average beach level at the base of the cliff over the monitoring period.

A similar assessment has been made of the contribution of landslides to the cliff top recession. This included taking the area of lost land at the top of the cliff in regions that have experienced landslides within the cliff and dividing it by the length of these regions. This was then compared with the same calculation for areas that have not experienced landslides (Table 3). The contribution of landslides can then be assessed by subtracting the average recession for regions where landslides have not occurred, which can be considered a 'background value' of recession, from the areas where they have occurred.

This assessment was problematic at Hornsea and Mappleton because all areas of these sites were subjected to landslides within the study period, therefore it was not possible to subtract a 'background value' of erosion from the areas that had experienced landslides. The Easington site displayed the opposite situation to that of Hornsea and Mappleton, because this area, as a result of its very low cliff heights, has not experienced any identifiable landslides, and subsequently all of the recession is attributable to factors other than landsliding. For the sites that contained regions with and without landsliding there was considerable variation in the amount that landsliding accelerated recession. The difference column in Table 3 for these sites, i.e. the amount of recession attributable to landsliding, varies between 633% of the 'background value' of recession at Dimlington, to 83% at Withernsea and 33% at Skipsea.

Table 3. Comparison of cliff top recession in areas that have and have not experienced landslides.

Site name	Average recession (m)▲	Average recession (m)•	Difference (with landslides – without) (m)
Dimlington	2.2	0.3	1.9
Easington	0	3.2	-3.2
Hornsea	4.5	0	4.5
Mappleton	6.2	0	6.2
Skipsea	0.4	0.3	0.1
Withernsea	2.2	1.2	1
Average	2.6	0.8	1.8

▲Refers to regions of the sites where landslides have occurred within the cliff during the monitoring period.
•Refers to regions of the sites where landslides have not occurred within the cliff during the monitoring period.

The variability of these values is deemed to be attributable to the geology and manner of recession at these sites. The Skipsea and Withernsea sites contain sand layers, which promote undermining through seepage and piping erosion, resulting in proportionally high 'background values' of cliff top recession. Also, the presence of the sand layers draining the slope together with the generally high beach levels and moderate cliff heights at these sites combine to reduce the susceptibility of these areas to significant sized landslides. By contrast, the Dimlington site does not contain a continuous sand layer or a sand layer near to the top of the cliff, but does have a surface water pipe draining onto the slope causing a 'background value' similar to that of Skipsea. However, this site does not benefit from the stabilising effect of drainage from sand layers or a low cliff height and subsequently experiences landslides typical of those of the whole coast described previously, causing cliff top recession far in excess of the 'background value'. By implication it can be considered that areas of similar cliff heights and geology, such as Hornsea and Mappleton, would have a similar 'background value' of recession, which is of little significance compared with the contribution of landslides.

Another factor that has been monitored during this project is the fluctuations in beach level, as fluctuations at the base of the cliff have previously been claimed to have a significant influence over the amount of cliff top recession (Pringle 1985). Table 4 shows that the beach level at the toe of the cliff varied markedly throughout the 11 month monitoring period with a maximum fluctuation of 2.2m.

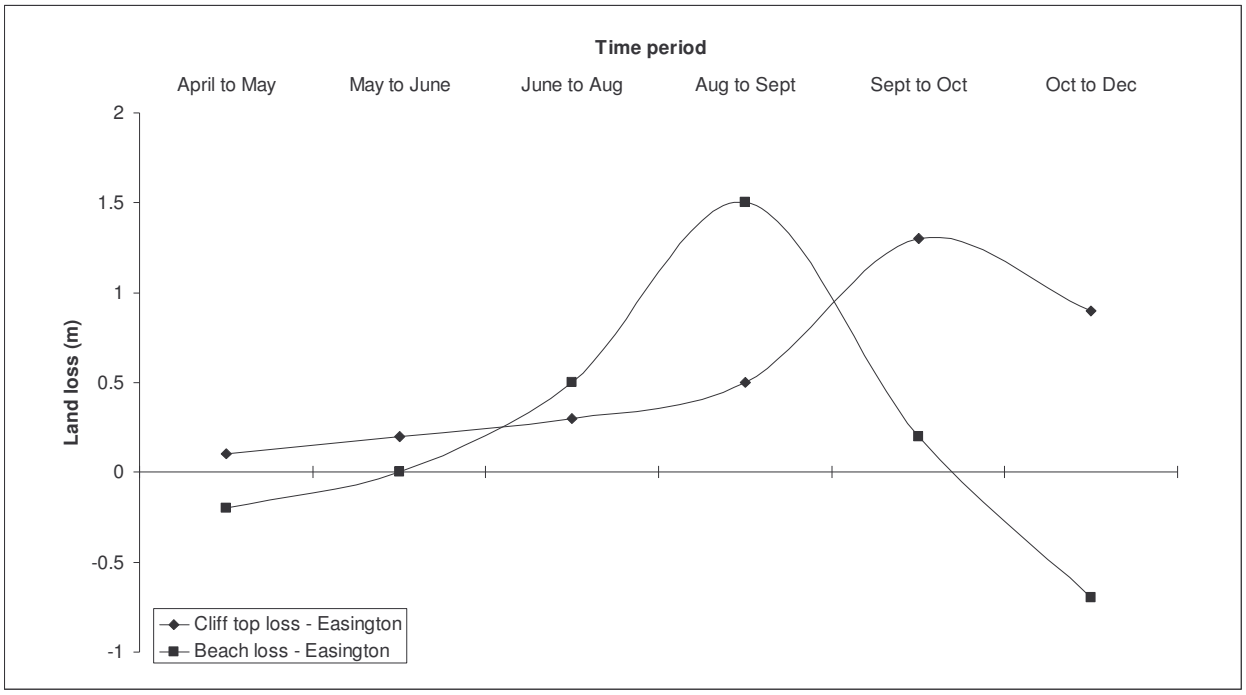


Figure 4. Fluctuations in beach level and cliff top recession at Easington.

Major variations in beach level occur rapidly on this coastline with a maximum fluctuation over the one to two month measurement intervals of 1.6m and an average change of 0.4m. On the low cliffs of Easington this change in beach level results in an obvious and identifiable link with cliff top recession (Figure 4); a loss of beach in one month results in increased cliff top loss in the following month.

On the higher and structurally more complex cliffs this link is not apparent because, as previously discussed, there are several other factors influencing volumetric and cliff top loss in these areas. As a result of this, and because of the delayed response in cliff top loss with beach level change at Easington, there is no direct correlation that can be made between either beach level or beach level change and cliff top recession for this coastline. A correlation assessment of beach level and cliff top recession produces an r^2 value of 0.12 and the same assessment using beach level change and cliff top recession produces an r^2 value of 0.00.

Table 4. Variations in beach level over the 11 month monitoring period.

Site name	Maximum (m)	Minimum (m)	Mean (m)	Maximum -Minimum (m)
Dimlington	3.8	1.7	3.1	2.1
Easington	4.2	2	3.3	2.2
Hornsea	2.5	1.7	2.1	0.8
Mappleton	3.3	2.1	2.5	1.2
Skipsea	4.5	3.2	3.9	1.3
Withernsea	4.0	2.1	3.5	1.9

5 DISCUSSION

5.1 Significance of Results

The previously published studies of the recession of this region have concentrated on accounting for the cliff top recession (Sheppard 1912; Valentin 1954; Dosser 1955), fluctuations in beach level (Pringle 1981; Gun et al. 2006) and the landslides that occur (Pickwell 1878; Richards & Lorriman 1987), but few have concentrated on linking these aspects together (Pringle 1985; Pethick 1996). The continued monitoring of the cliff line and beach by the local Council provides an excellent medium term account of cliff top loss and beach morphology change. However, this monitoring provides no information on the changes occurring within the cliff, it does not account for the contribution of landslides and it does not provide any information regarding the very short term changes. These are all aspects that need to be understood in order to fully define the nature and behaviour of cliff recession, as defined by Lee (2002). The systematic monitoring included in this study is helping to fill this knowledge gap by measuring short term changes in the cliff top, cliff, and beach, and illustrating the relative contribution of different land loss mechanisms to the net recession.

5.2 Testing of Hypotheses

Throughout the former studies of this region various hypotheses and statements regarding the recession of

this coastline have been made, which can be tested with the data obtained from this study:

A description of the landslides of the Holderness coast was provided by Hutchinson (1986) in which it was claimed that the failures are deep seated, rotational, base, toe and slope failures that generally fit into the Type 2 classification of coastal slope failures developed for London Clay cliffs (Hutchinson 1973). The Type 2 failure cycle is described as starting with a virtually stable slope with an upper slope angle of between 15^o – 20^o and marine attack at the base, which progresses to a deep seated failure that extends along the cliff for a distance of between 3.1 and 7.1 times the height of the cliff and causes between 10m – 30m of cliff top recession. This is followed by several stages of erosion of the failed material and degradation of the back scarp through small scale failures until the initial state is returned to. The cycle is claimed to repeat on a cycle of between 30 to 40 years at Warden Point on the Isle of Sheppey.

The general pattern of events detailed in this classification scheme is roughly supported by the field evidence collected in this study for three of the sites which show basal erosion of intact material initiating a shear failure encompassing the majority of the cliff, and the failed material subsequently being removed through marine erosion. However the details of the failures of these cliffs are significantly different to the description of Type 2 failures, as the shear failures on this coastline are almost exclusively translational with a vertical back scarp and a slight rotation towards the base of the slope, as opposed to the rotational shape described. The upper slope is generally far steeper, with an average of 50^o and the size of the failures are usually far smaller with width/height of cliff ratios of between 0.3 and 5.1, with an average of 1.0. Subsequently, the return period of the failure cycle is significantly less, reoccurring on subannual frequencies at the Hornsea and Mappleton sites. The Skipsea study site, which has a moderate cliff height (9m to 10m), high beach levels and contains sand layers, exhibits failures more akin to the Type 1 classification of slope failures (Hutchinson, 1973), where removal of material at the base of the slope is in balance with supply by shallow translational landsliding. However, at Easington where erosion is entirely the result of factors other than landsliding, none of the recession types suggested by Hutchinson are appropriate. Therefore, the data obtained shows that the description of Holderness landslides presented by Hutchinson is only partially applicable for the majority of the coastline, typified by the Hornsea, Mappleton, Dimlington, Skipsea and Withernsea sites and that it is not at all applicable at the areas of low cliff height, such as the Easington site.

Pethick (1996) stated that the recession of this coastline is driven by landslides that are generally between 1m to 2m deep, between 10m and 20m wide and occur at sub-annual frequencies.

Whilst this hypothesis is roughly applicable for the Hornsea and Mappleton sites, when a view is taken of all of the study sites there is a far greater variety of failure sizes than those stated, which, in areas, occur less frequently than sub-annually. Furthermore, this hypothesis implies that landslides are the dominant factor in the coastal recession, whereas the results of this study show that the influence of landslides varies depending on factors such as cliff height, beach height and cliff composition.

Other explanations of the recession and landslides of this coastline exist within the published literature such as those of the IECS (1994) and the East Riding of Yorkshire Council (2004), who define a process of basal erosion leading to cliff collapse, similar to the Type 2 process described previously. However, all of the descriptions of the cliff processes proposed to date for this coastline suggest a single slope process to occur across the entire coastline; an assumption that this study has shown to be incorrect. It is hoped that the results of this study will enable the identification of different types of slope failure along this coastline, similar to the classification scheme of the London Clay cliffs, and enable its subdivision into units of similar cliff behaviour (Lee 2002). This would allow the sensitivity of different cliff sections to factors such as sea level rise and increased precipitation to be estimated with greater confidence.

6 FUTURE WORK AND CONCLUSION

This study has revealed that the recession of the cliffs of the Holderness coast is complex and cannot be defined by a single set of processes, but varies in accordance with the height and composition of the cliff and the level of the beach. Subsequently it is not possible to draw simple correlations for this region such as linking the height of the cliff or height of the beach and the amount of cliff top recession.

The next stage of this study will include combining the topographic data obtained with published geotechnical data for this region to numerically model the slope failures and assess the response of these cliffs to differing rates of basal erosion and different groundwater conditions. Further to this, the monitoring of the selected study sites will continue to assess the response of the cliffs over a two year period. Due to the first 11 months of this study showing recession well in excess of the average values at three of the study sites, the results of the second year of monitoring could potentially help further the knowledge of the cyclic nature of the cliff retreat.

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