Study of Ords and Cliff Erosion on the Holderness Coast Using Digital Elevation Models Derived from Stereo Aerial Photographs.

by

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Abstract

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Stereo aerial photographs of the Holderness coast, UK, were acquired by NERC, as part of the Land-Ocean Interaction Study (LOIS). Images from July 1994, October 1996 and April 1997 of the area of the B.P. Gas Terminal, in the southern region of Holderness, were used to undertake a geomorphological study of the cliffs and beach. The area is characterised by the extreme cliff recession rates recorded ($1.2 myr^{-1}$; Valentin, 1954). A unique beach feature called an ord, which is a system of exposed shore platform and beach ridges, creates a lowering effect on the beach. This provides the opportunity for wave attack at most high tides at the bottom of the cliff and increases the rate of the erosion significantly over areas without ords.

The aerial images were digitized, and imported into the ERDAS Imagine Version 8.2 software package, in order to create Digital Elevation Models of the cliff and beach area. Models were produced for each of the photography dates and these were then compared using a number of methods. Elevation profiles were taken at three points along the cliffline, and these were used to relate the changes in the cliff and beach over time. An elevation profile was also used to demonstrate the deleterious effects of water present on the beach, on the DEM collection. Volumetric analyses were carried out with the ARC GIS package, involving two separate functions, CUTFILL and VOLUME, and the suitability of each was also discussed.

Results utilising the 1994 images were inconclusive, because of the inaccuracy of the DEM produced for this date, due to the photographs being acquired at mid-tide. The 1996 and 1997 data proved to be more accurate and the results of the VOLUME function enabled the calculation of a mean rate of southwards movement of the ord and the sediment input to the North Sea over time.

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1. Introduction

Stereo aerial photographs of the Holderness coast, East Yorkshire, acquired as part of the Land-Ocean Interaction Study (LOIS), have been used to undertake a geomorphological study of cliff erosion in the area. The photographs from 1994, 1996 and 1997 are used to examine unique beach features called ords, which move south along the Holderness coast, in order to study the possible relationship between the ords and accelerated cliff erosion. This study focuses on one ord which is at present in the vicinity of the village of Easington in the south of the Holderness coast and figure 1.1 shows a map of the area, including Easington.

The photographs are used to create Digital Elevation Models (DEMs) from digitised stereo pairs of photographs, and using these to calculate volumes of sediment removed from areas of the cliff over time. A DEM is a digital representation of the continuous variation of relief over space, and has many applications, such as the computation of slope and aspect maps, and also slope profiles and volumetric calculations, which are used here. They can be used, as in this particular application, to assist geomorphological studies and to estimate and quantify erosion. Other more general applications of DEMs include surveying and town planning (Burrough, 1987).

LOIS is the 6 year research project (1992-1998) of the Natural Environment Research Council (NERC), which aims to quantify and simulate the fluxes and transformations of materials (sediments, nutrients, contaminants) into and out of the coastal zone, extending from river catchments to the edge of the continental shelf. The main study area, enclosing river catchments, estuaries and coastal seas, is the East Coast of Great Britain from Berwick upon Tweed to Great Yarmouth. LOIS has components studying riverine, atmospheric, estuarine, coastal and shelf processes, and data from this project will provide information for the Coasts and Estuaries portion of the Rivers, Atmosphere, Coasts and Estuaries Study (RACS(C)).

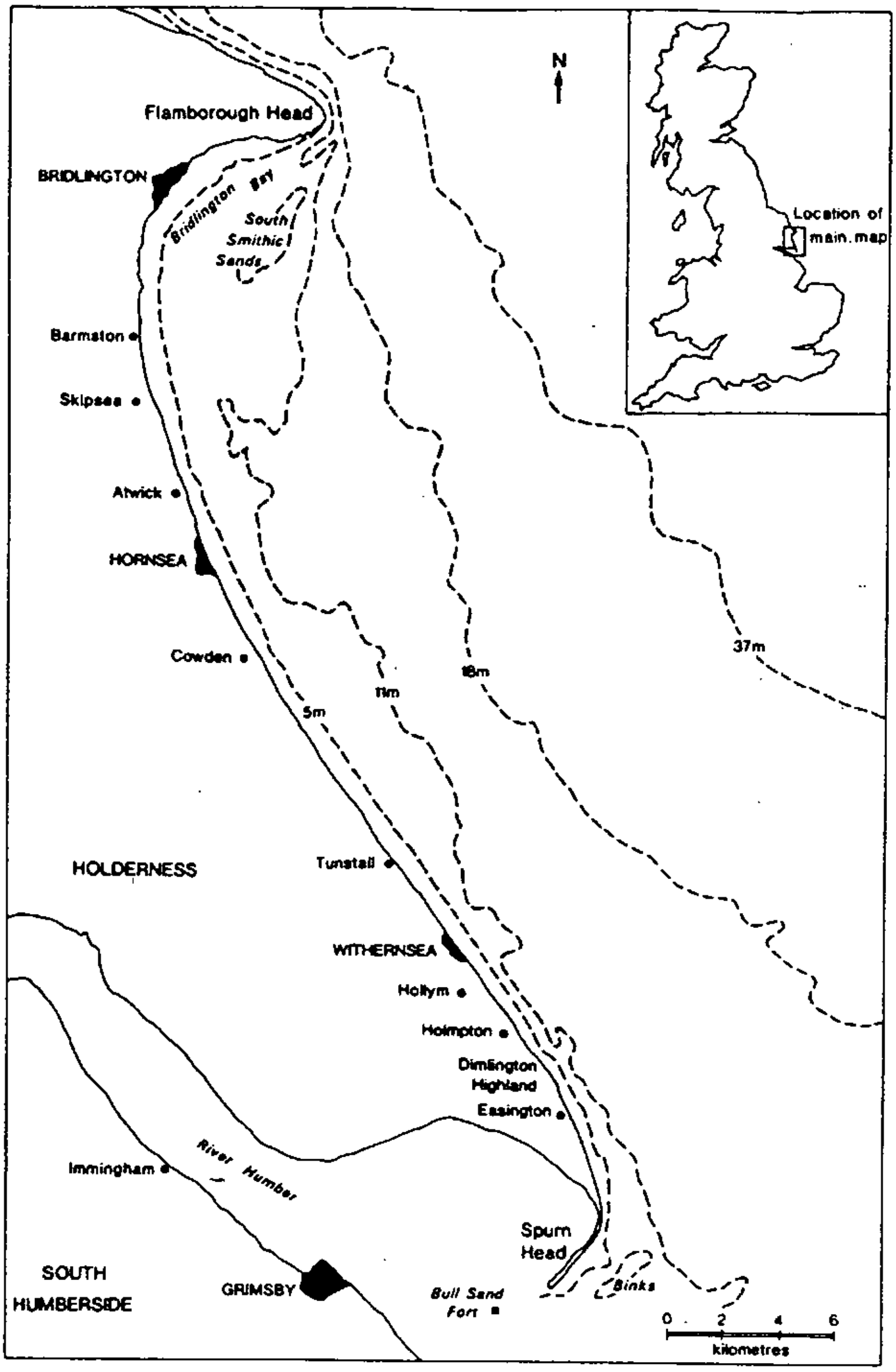


Figure 1.1 Map of the Holderness Coast

1.1 The Holderness Coastline

The Holderness coast extends for approximately 60km, from Flamborough Head in the north, to Spurn Head and the River Humber in the south, and is characterised by a rapid rate of erosion of the glacial till cliffs backing the beach. The erosion rate averaged over the length of the coastline has been calculated to be 1.2m per year (Valentin, 1954). The coast is one of moderate to high energy and once eroded, the till is rapidly broken up into its constituent parts. Sand and gravel from the cliff make up the beach (Pringle, 1985), but the finer silts and clays are suspended by wave action and removed from the beach and these form a major sediment source for the North Sea.

An ord occurs where the usual beach cross-sectional form (a defined upper and lower beach) breaks down. Figure 1.1.1 shows a generalised plan of an ord. To the northern end of an ord the upper beach decreases in height, becoming narrower and the junction with the lower beach moves closer to the base of the cliff. The lower beach widens and is raised up above the water table, until at the centre of the ord the beach reaches it's lowest level at the base of the cliff. Beach material is usually absent here for up to 100m along the cliff, exposing the till shore platform. To the south of the ord's centre the upper beach begins to reform at the foot of the cliff, with an exposed area of the till platform remaining on the seaward edge of the upper beach for some distance south (Pringle, 1981).

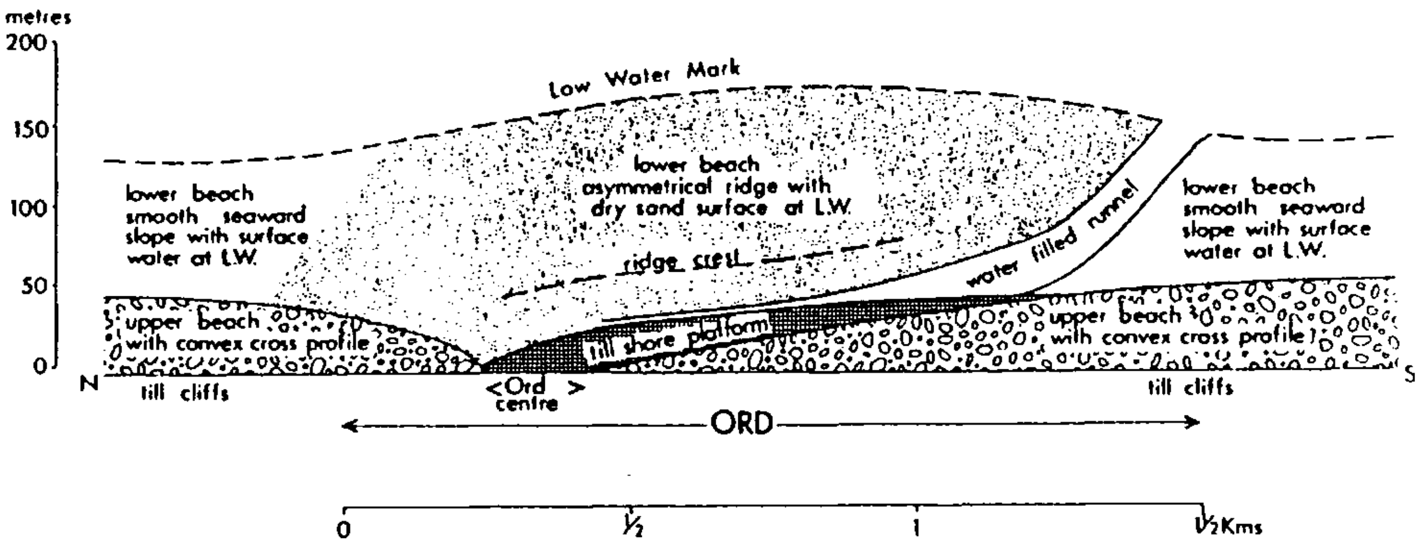


Figure 1.1.1 A Generalised Plan of an Ord (Pringle, 1981).

The ords vary between 1 and 2km in length; there are usually ten present between Flamborough Head and Spurn Head and over time they are thought to migrate southwards, with the dominant direction of longshore transport. Between ords, where the beach is developed in the usual way, only extreme spring high tides reach the base of the cliffs and it provides protection for the cliff from wave action. However, where there is an ord present the cliffs are afforded very little protection due to the decrease in the beach height, and waves reach the cliffs on all high spring and neap tides. This results in increased erosion of the cliffs in the area of the ord, where the undermining of the cliff by wave attack causes instability in the till and the cliff is steepened by processes including rotational slumping, mud flows and mass falls (Pringle, 1985).

In the region of the ord there is an increased rate of cliff erosion and this has important implications for both the residents of cliff-top houses and for coastal managers attempting to formulate a Coastal Management System for that particular stretch of coast. A Coastal Management System is an integrated approach to the "sustainable utilisation" of coastal resources, incorporating policy, planning and practice (Carter, 1988) and it is one of the aims of LOIS to form such a strategy for the North Sea coast of the UK.

1.2 Aims

It is the aim of the study to provide quantitative information on the volume of sediment removed from the cliffs and from this to estimate the volume of cliff material entering the North Sea, over the specified time period of 1994 to 1997. It is also possible to estimate the rate of recession of specific areas of cliff, pertinent due to housing and industry situated on the cliff-tops. From estimation of the centre of the studied ord from the aerial photographs it should also be possible to calculate the approximate rate of its movement southwards.

1.3 Structure of the Dissertation

The background section will introduce the study area more fully, including previous studies of the geomorphology and the geology, and of the extreme rates of erosion and cliff recession. There will also be a more complete description of an ord and a thorough review of the ords relation to increased erosion of the cliffs due to the lowering of the beach and the increased susceptibility to wave attack. A review of the processes of cliff and shore platform erosion will also be included. This will be followed by a review of the current literature on the uses of aerial photography in the coastal zone, and of their use in the production of Digital Elevation Models.

The methods chapter will describe fully the processes and software used in the production of the DEMs and the volumetric analyses, which will be used to calculate the volumes of cliff eroded over time. Profiles of the cliff and beach were taken from the surface of the DEMs and a description of this procedure will also be included.

The results chapter will include the volumes of material calculated as being lost from the DEMs, i.e. the beaches and cliffs, over time. Profiles of the cliff and beach taken at the same point for each time period will be used to compare the relative heights of the beach and the gradient of the cliff and how these have changed in relation to the ord itself. The profile analysis will also be used to evaluate the errors inherent in the software and accuracy of the DEMs. A qualitative description of the ords as seen from the aerial photographs, and any change in the position, or features of the ord will be included. It should be possible to evaluate the position of the centre of the ord and how this has progressed south over time.

The discussion will consider the results of the volumetric calculations, and the calculated rate of erosion of the cliffs, and review these in comparison with other workers findings. The accuracy of the Digital Elevation Models, and hence the volumetric calculations will be discussed, along with the errors inherent in the Imagine software. An analysis of the extent to which the proposed aims have been fulfilled will be included and the implications of the results for the future of this stretch of the coast, including the Gas Terminal and the village of Easington, will be reviewed. The conclusions will take the form of a summary of the study and will also include some suggestions for further research.

1.4 Principles and Techniques

Stereo aerial photographs, acquired of the Holderness coast from Flamborough Head to Spurn Head, are produced as hardcopy paper prints, and then digitized using a flatbed scanner. The resultant digital data are then used to create Digital Elevation Models, using the software package ERDAS Imagine. The DEMs are then compared using volumetric analysis.

Vertical aerial photographs are taken along flight lines and in order for the images to be used in 'stereo' each photograph must overlap by at least 60%. Fig. 1.4.1 demonstrates a stereopair, of two aerial photographs, acquired in 1996 of the Easington area, including the B.P. Gas Terminal. The area of overlap can be seen to cover most of the Gas Terminal. It should be noted that the photographs are geographically 'upside-down' as the flight-line is from north to south. Adjacent pairs of overlapping vertical photographs are sometimes termed 'stereopairs', and provide two different perspectives of the ground area in the region of overlap (Lillesand & Kiefer, 1994). Stereomatching has previously been used to create accurate DEMs from stereo satellite images, for example, SPOT images (Day & Muller, 1988; Heipke, 1992). The technique uses differences present in the stereo-images caused by topographic expression of the earth's surface.

Techniques used to produce DEMs from aerial photographs are discussed in Allison & Muller (1992). The only part of the processes of image-matching, parallax reading and DEM production which is not fully automated, within hardware and software systems, is the absolute orientation with respect to the precise measurement of the centre of signals on ground control points. At present an operator still has to identify the points (Torlegard, 1996). However, automatic ground control point identification has recently been developed for satellite images (Dowman, 1996). The software used for the project outlined here is ERDAS IMAGINE. This contains software for display, manipulation, transformation, analysis and output of digital spatial data, including aerial images and GIS information (Civco, 1994).

Figure 1.4.1 Stereopair of 1996 aerial photographs

2. Background

2.1 Introduction to the Area

The Holderness coast extends from the chalk cliffs of Flamborough Head, to the attached spit at Spurn Head, 57km to the south and comprises a sand and shingle beach, overlying a glacial till shore platform, and backed by rapidly eroding glacial till cliffs, of between 5 and 20 meters in height (Mason & Hansom, 1988). The area is characterised by extreme rates of cliff erosion, and calculations of the rates have varied from between 1.2myr^{-1} (Valentin, 1954), and 4.0myr^{-1} (Mason & Hansom, 1988). It is estimated that a strip of land at least four kilometres wide has been lost from the Holderness coast since the Roman times, and this has resulted in the loss of around thirty villages (Sheppard, 1912).

Most of the cliff-top land of Holderness is farmed, however, there are several villages, industrial sites and holiday caravan parks at present threatened by the continued retreat of the coastline. Only short stretches of the shore are protected, the towns of Bridlington, Hornsea, Aldborough and Withernsea are defended by concrete seawalls and groynes, and these areas have experienced an almost complete cessation of erosion. It would not be possible to protect the whole of the coastline, as the costs of the defences would far exceed the value of the land. Any scheme to protect parts of the coast would require careful planning to ensure that essential sediment inputs to the coastline, created by the erosion of the cliffs, continue. This is further complicated because the Holderness coast is the largest single sediment source to the North Sea (Pearce, 1993) and is thought to supply material to the coasts of countries around the North Sea, including Germany and The Netherlands.

Essential pre-requisites for a successful coast protection scheme include the establishment of cliff retreat rates, the rates of sediment transfer between the beach and the cliff, and the relationship between the condition of the beach and cliff erosion (Mason & Hansom, 1988). As already mentioned, estimates of the rate of cliff retreat vary considerably, and it has been discovered that the relationship between beach condition and cliff erosion is complicated by the presence of ords. The association of ords and accelerated cliff erosion has been recorded by Pringle (1985), however, it has not been fully quantified.

2.2 Erosion Rates

There have been many attempts at calculating the rate of the regression of the cliffs of Holderness, using several methods. Valentin (1954) carried out field studies along the coast, using a 100ft. tape to measure the distance to the cliff top from topographical features, such as old houses and the junctions of footpaths. These points were then identified on the earliest 6-inch maps, from 1852. On these maps it was possible to measure the distance from the reference points to the top of the cliff to within 10ft. He then found the difference between the two measurements taken 100 years apart, 1852 to 1952, and calculated the loss of land over the 100 year period with an accuracy of ±3m. He produced a mean retreat rate of $1.2myr^{-1}$, for the whole of the coastline. He also calculated parish values, by multiplying the annual recession by the length of the coast in each parish and the volume lost from each parish, by multiplying the area of land eroded by the average height of the cliff in each parish. For the area between Easington and Kilnsea the calculated annual recession exceeded 2 meters. The total amounts eroded at each site studied by Valentin are shown in figure 2.2.1.

Other workers have used cartographic and photogrammetric methods in order to calculate the erosion rate of the cliffs. Mason & Hansom (1988) calculated the mean retreat rate for the whole of the coast, using map data since 1850, as $1.34myr^{-1}$. The equivalent value as calculated from aerial photographs was $2.5myr^{-1}$. Estimates for the whole of the coast are generally around $1.5\text{-}2.0myr^{-1}$ for the unprotected coastline, but it is generally accepted that there is an increase in the erosion rate to the south of the coast, and in the region of Easington estimates include 3.2m and $2.75myr^{-1}$ (Steers, 1976).

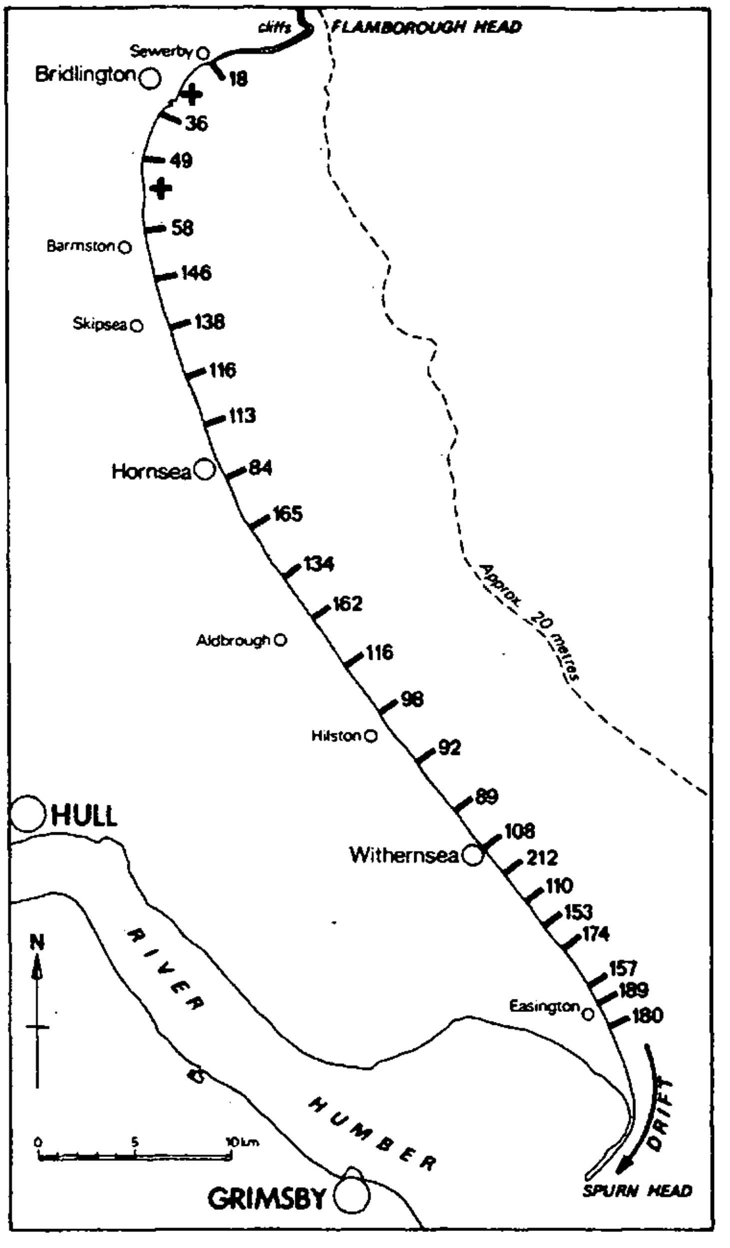


Figure 2.2.1 Recession of the cliff top at selected points along the Holderness coast (in meters), between 1852 and 1952 (after Valentin, 1954). + symbols indicate sites that have accreted in this time.

2. 3 Geology of the Area

The Holderness coastline is a dissected plateau of Cretaceous chalk overlain by a predominantly clay glacial deposit which extends to the surface (Butcher, 1991). The cliffs are made up of glacial till, which is the debris deposited by a glacier and forms a poorly sorted, unconsolidated sediment, containing a wider range of particle sizes. As with the Holderness sediments, tills include pebbles, and small boulders, set with a mixture of fine-grained matrix of silt and clay. The Holderness tills are deformation tills, which involves the assimilation of sediment into the deforming layer beneath the glacier. The sediments form a mobile layer beneath the glacier, as it flows over soft substrates, and the deformation occurs as the stress imposed by the glacier exceeds the strength of the material both in front of and below it. Deformation tills contain a diverse range of particle sizes reflecting that found in the original sediment, and also areas known as 'rafts' of the original sediment can be found, causing marked spatial variability in particle size (Bennet & Glasser, 1996).

The tills have been classified as three distinct types, the Basement Till which originates from around 20,000 B.P., and the overlying Skipsea and Withernsea Tills, which are both more recent. These, as deformation tills, were formed by the repeated onshore surging of the Late Devensian ice sheet over the muddy sea floor, and hence are primarily made up of marine sediments, mixed with soft chalk bedrock and gravels (Eyles *et al.*, 1994). Between each till type there are intervening layers of gravels, sands and silts (Hutchinson, 1986).

All three of the tills are present in the study area of Easington and all three contain clusters of clasts, which are irregular concentrations of pebbles and boulders. In most places along the cliff at Easington the complete succession of tills is visible, from the Basement Till at the cliff foot, overlain by the Skipsea, which is in turn overlain by the Withernsea Till (Pringle, 1985). The tills are characteristically unsorted, form soft soils and contain some fissures and discontinuities (Hutchinson, 1986) and these properties are important due to their influence on the erosion of the cliff, which will be discussed later.

2.4 The Form of the Beach

The beach runs without break along the entire coastline, but varies in form from the north to the south, with a series of ridge and runnel systems. At Bridlington in the north, it is approximately 300m wide at mean low water, and from south of Barmston takes on its characteristic cross section.

This usual form is divided into am upper and lower beach. The upper beach, adjacent to the base of the cliff, typically has a convex profile and is made up of coarse sand (1-1.5mm) and shingle (<20cm diam.) and shingle is often concentrated on the steeper lower slopes of the upper beach. The beach water table surfaces at the foot of the upper beach, and the lower beach extends from here to the low water mark. The division between the two parts of the beach is usually a clear line, along with a large change in the surface slope. The lower part is made up of medium sand (0.5-0.25mm) in the area of the junction with the upper beach, and finer sand (0.25-0.125mm) toward the low water mark (Pringle, 1981).

2.5 Ords

An ord occurs where the usual beach profile is broken down, and forms a linear depression on the beach. The depression extends obliquely at a low angle to the coastline from the base of the cliff. The shore platform cut in the glacial drift is exposed within the depression. The movement of the ord south, with the overall direction of the longshore drift along the Holderness coast, produces a temporal variation in the beach levels in front of the cliff at a given site along the cliff. The occurrence of marked erosion at and near the ords has been recognised but an exact correspondence has not been found (Sunamura, 1992). It is not known exactly how the ords form, the absence of sand bars below the low water mark, and lack of rip currents along the Holderness coast, suggest there are no cellular flows with which rhythmic features are usually associated, and ords are probably not related to edge wave formation due to their irregular spacing (Pringle, 1985). Figure 2.5.1 shows the characteristic features of an ord.

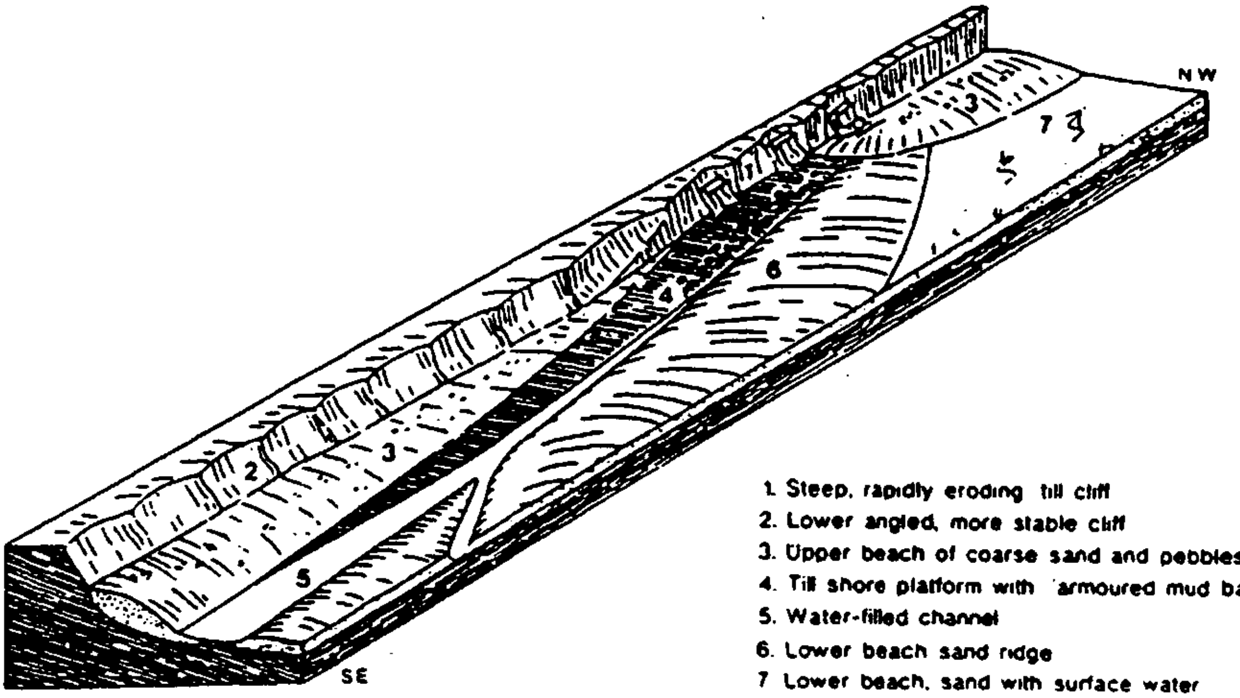


Figure 2.5.1 The characteristic features of an ord (Pringle, 1985).

Ords generally take on the following form; at the northern end the upper beach decreases in height, becoming narrower and the junction with the lower beach moves closer to the base of the cliff. The lower beach becomes wider and higher, and extends in a ridge of sand and shingle seaward. This ridge extends from the northern end of the centre of the ord, towards the sea at a low angle, disappearing below the low water mark toward the southern end of the ord. The ridge is asymmetrical, with a short, steeply sloping landward side and a longer, more gently sloping seaward side. The ridge traps water in a channel on its landward side and this drains toward the south. At the centre of the ord the beach reaches it's lowest level at the base of the cliff, behind the described beach ridge and beach material is usually absent here for up to 100m along the cliff, resulting in the exposure of the till shore platform. To the south of the ord's centre the upper beach begins to reform at the foot of the cliff, with the exposed area of the till platform remaining on the seaward edge of the upper beach for some distance south (Pringle, 1981; 1985).

2.6 The Movement of Ords

Severe storms from the north-east are capable of moving the ords and the intervening higher beaches southwards, through the development of a tongue of beach material from the upper beach, near the northern boundary of the ord (see figure 2.6.1;A-D). During periods of strong northerly winds, with the associated high energy waves and storm surge, a tongue builds up approximately perpendicular to the steep angle of approach of the waves (figure 2.6.1;B). After the storm when the angle of approach is reduced, or even parallel to the beach, the tongue will swing around until parallel to the main beach (figure 2.6.1;C). The tongue is then moved landward due to the transfer of material from the seaward to the landward side by the swash of the breaking waves, and within a few weeks will be incorporated into the upper beach (figure 2.6.1;D).

At the same time as the tongue develops to the north end of the ord, the upper beach at the southern end rapidly diminishes during the northerly storm conditions, and so the north is replenished as the southern part is eroded. Through this method the centre of the ord is moved southwards, maintaining the distinct shape of both the ord and the beach to either side.

Ords are not found to the north of Barmston, presumably due to the sheltering effect of Flamborough Head and the Smithic Bank from northerly storms, and are thought to develop at the point where the northerly waves refracted around the Head meet the coast, south of Bridlington Bay (Phillips, 1964). Due to their high angle of approach the waves set up the rapid longshore movement of sediment southwards (Pringle, 1981). The movement of the ords in this direction is partly due to an energy differential present between Bridlington Bay and the coast to the south under the northerly storm conditions (Scott, 1976). Winds from the north-east have the longest fetch and so are most effective at promoting destructive wave energy along the Holderness coast (Dossor, 1955). During onshore storms sand is removed from the beach and shallow offshore zone, resulting in the erosion of the shoreline (Winkelmolen, 1978).

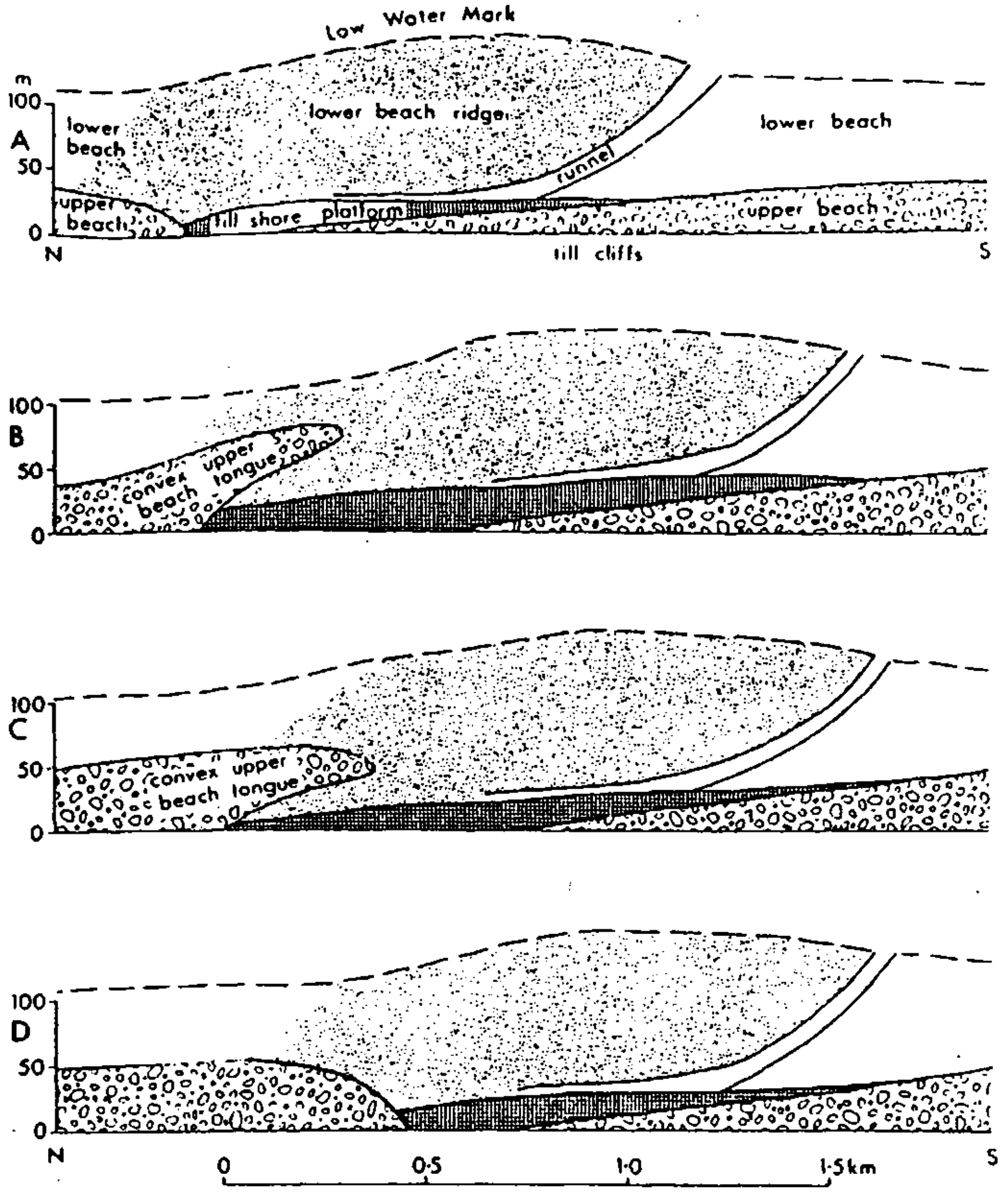


Figure 2.6.1 Form of Ord Movement, A: Classic ord morphology; B: Ord including Northern upper beach tongue; C: Ord showing tongue pushed landward; D: Ord showing tongue pushed to cliff foot, forming new upper beach (Pringle, 1981).

2.7 The Lowering of the Beach

Between ords, where the usual beach cross section is present, only extreme spring high tides reach the base of the cliffs, for example, at times of storm surges. This provides protection for the cliffs in the form of a wave energy dissipater (Sunamura, 1992).

However, in the presence of an ord, because of the substantial lowering of the beach level, it is possible for waves to reach the cliffs on all high tides, throughout the springs-neaps cycle. As a consequence there is greatly increased wave action and energy expended at the base of the cliffs. This results in an acceleration of the erosion at the exposed part of the cliff.

2.8 Study of an Example Ord

A study of one ord was carried out between 1977-1983 (Pringle, 1985), using beach profiling techniques and cliff top erosion measurements from which the volume of sediment eroded from the cliffs over time was calculated. It was also found that an ord is an intertidal feature that declines beyond the mean low water mark. The measurements taken of the cliff show an increased erosion rate in the presence of an ord, and this was found to continue for some time after the ord has migrated south, while the cliff reforms into a more stable and lower angled structure. Over four times the volume of sediment was eroded from cliffs adjacent to an ord, as compared with a cliff area adjacent to a higher beach area. The volume of the till cliff eroded increased from $9m^3m^{-1}$ in the area between ords, to $72m^3m^{-1}$ in the area of an ord (Pringle, 1985). Figure 2.8.1 shows the relationship between cliff-top erosion and the position of the ord studied by Pringle. By reading this diagram downwards through a specific site, it is possible to see the temporal variation in the erosion rate at that site.

The average rate of movement of the ord was $0.5kmyr^{-1}$ to the south, however, this masks considerable variation, and half-yearly rates recorded varied between 668m south and 355m North. This movement to the North was the only one recorded and was produced when the ord lengthened in both directions (Pringle, 1985).

Pringle (1985) reported considerable height variation within an ord, ranging from 0.9m to 5.37m above Ordnance Datum and the height of the shore platform varied between 0.9 and 3.55m OD, over the six year study period. These measurements were taken at the foot of the cliff, but height variations also occurred further seaward, the overall variation decreasing seaward, implying that the ord is essentially an intertidal feature. The ord varied in length from 265m to 1930m over the study period, and when at it's longest the ord was also at it's most well defined, forming a distinctive feature.

By using the measurements of the length and height, Pringle (1985) calculated the volume of the beach sediment absent due to the presence of the ord, within an area extending from the cliff foot to 80m seaward. The volume absent varied from between

10,400m^3 to 435,300m^3 and the mean loss was 157,600m^3, as compared with the inter-ord beach. The till exposure at the base of the cliff ranged in width from 50 to 168m with a mean width of 85m. Small gullies, generally to a depth of 0.5m, were sometimes visible in the till, running at right angles to the shoreline, and were thought to be due to the structure of the till. These gullies are common on unconsolidated rocks such as glacial tills, where there is a strong backwash (Davies, 1980).

2.9 Processes of Cliff and Shore Platform Erosion

The main mechanism involved in the erosion of coastal cliffs is the action of waves. Waves erode the base of the cliff and it becomes unstable, due to the increase in the angle of the slope, or in the slope stress caused by erosion at the base. This instability induces mass movement of the slope. Two governing factors are involved in wave erosion at the base of a cliff; the assailing force of the waves at the base, and the resisting force of the material forming the lower cliff. The relative intensity of the two determines whether erosion of the cliff occurs or not (Sunamura, 1992). The resisting force is primarily determined by the lithology of the rocks.

The wave assailing force is directly related to the assailing force exerted by the waves at the cliff base, and three factors indirectly influence the force exerted at the base, the water level, governed by the tides and surges; the beach and shallow water bottom topography directly in front of the cliff; and the beach sediment. The combination of the water level, the nearshore bottom topography, and the deep-water wave characteristics

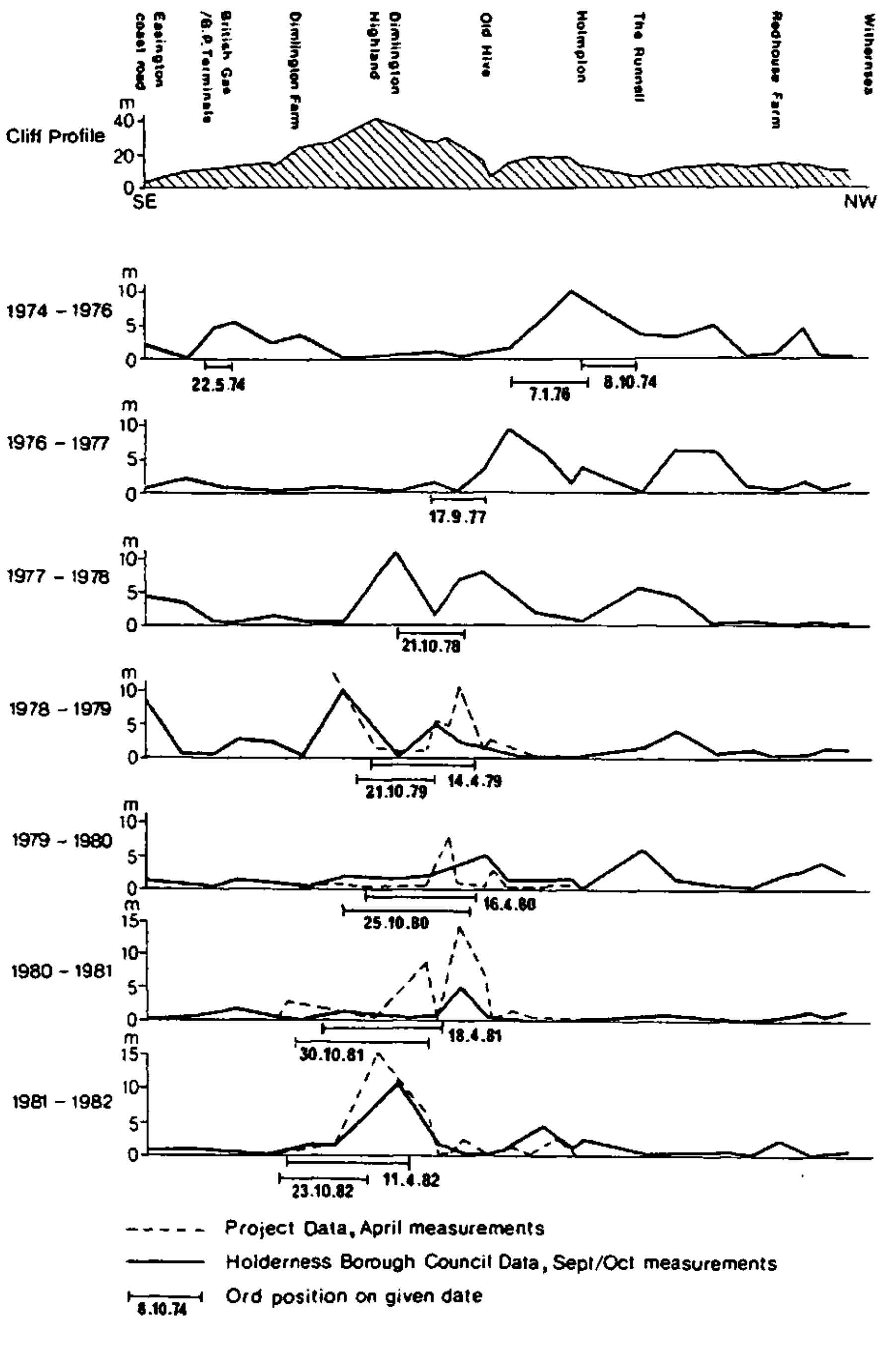


Figure 2.8.1 Cliff-top recession in relation to ord position on the south Holderness coast (Pringle, 1985).

determine the type and height of the waves in front of the cliff. Waves exert hydraulic action on a cliff face and this is combined with a mechanical action when the waves are armed with beach sediment. The sum of the hydraulic and mechanical actions is termed the wave assailing force (Sunamura, 1992).

The hydraulic action is made up of compression, tearing and shearing forces. As waves hit the cliff face a compressive force acts perpendicularly to the face, and if the cliff has faults or joints expresses as openings in the surface, air in these openings is compressed. As wave recession occurs the compressed air expands with explosive force, exerting an outward stress. These forces cause the gaps in the rock face to increase in size. Wave action will then remove the jointed, loose blocks of rock, via the process of quarrying. Tension forces acting as the wave recedes, also facilitate the removal of rock. The shearing force occurs as the wave hits a cliff face and the water mass ascends it. Hydraulic action alone is sufficient to cause erosion in soft clay materials, such as the glacial tills of Holderness (Sunamura, 1992).

The mechanical action is termed abrasion and is the erosion of the rock surface caused by the wearing, grinding or scraping action of sand or other coarse granular materials moved to and fro, or thrown against the cliff, by the waves (Griggs & Trenhaile, 1994). It can also be termed corrasion (Robinson, 1977) and is distinct from quarrying, because it implies the actual physical break-up of the cohesive rock. However, an increase in the amount of quarrying will also increase the levels of abrasion by rendering more tools available for the abrasive process (Davies, 1980). Abrasion tends to produce smoother surfaces than quarrying, but where structural weaknesses or lithological inhomogeneities occur, abrasion can cause local scouring or grooving of the bedrock (Griggs & Trenhaile, 1994).

The resistivity of the cliff forming material is governed not only by the lithology, described by the mechanical properties, such as the compressive strength, tensile strength and abrasive hardness, but also by the structure of the rock, for example, faults, joints or discontinuities (Sunamura, 1973). Compressive strength is often used as the test of the resisting force of a cliff material.

Cliffs of similar lithology, if subjected to different wave climates, should have higher erosion rates where the wave conditions are more severe, if all other controlling factors are constant (Sunamura, 1992). This of relevance to the Holderness coast where Valentin (1954) found in general that the recession rate of the cliffs increased in a southerly direction, and this is consistent with increased wave exposure to the south. Figure 2.9.1 shows erosion of the cliff related to wave height, and indicates that there is increased erosion in the area of higher waves. According to wave height predictions (Fleming, 1986) the waves are smallest in the Northern part of the coast, which is sheltered by Flamborough head and an offshore sandbank called Smithies Bank, and the waves are larger and more uniform in the central and southern parts of the coastline, toward Easington.

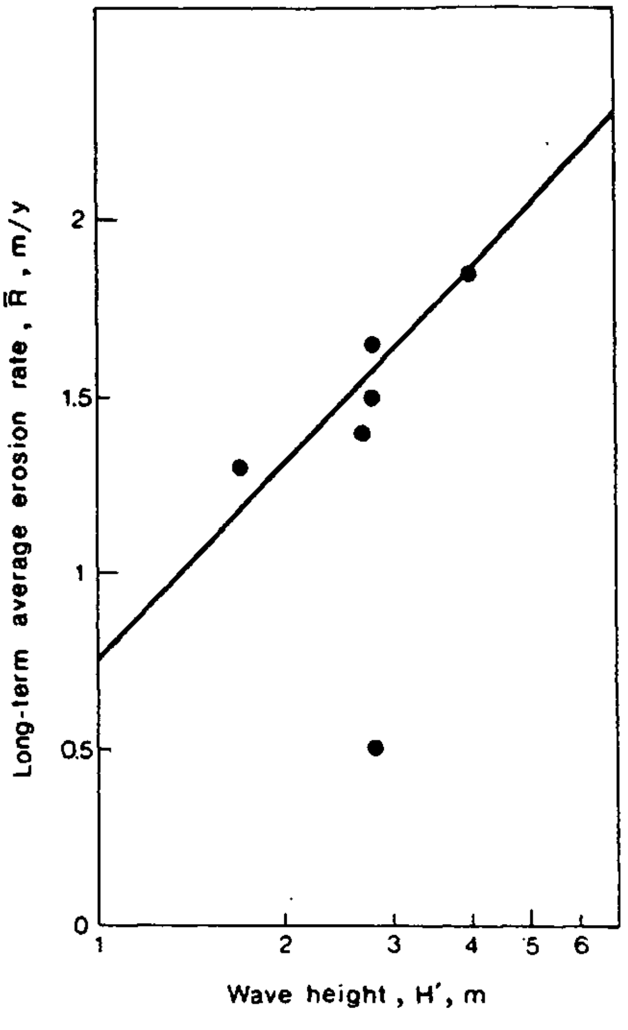


Figure 2.9.1 Cliff erosion rate related to wave height on the Holderness coast (after, Valentin, 1954).

Other factors, which are important to the erosion rate of a cliff, include coastal configuration, beach elevation, fetch distance and water level. Straight cliffs present less opportunity for successful wave attack than irregular cliffs, where the waves can work into clefts and around projecting points, increasing the erosion rate (Shepard & Grant, 1947).

The presence of the beach and its elevation appear to have conflicting influences on the cliff, depending on the type of beach sediment and the type of cliff material. The beach sediment can come from a number of sources, it can be produced from erosion of the cliffs by wave erosion, derived from the disintegration of debris masses at the foot of the cliff, or transported from adjacent coasts by longshore currents or from offshore by constructive wave action (Sunamura, 1983). Once present on the beach the sediment can intensify the wave assailing force by acting as an abrasive or reduce the wave assailing force by acting as a wave energy dissipater.

For example, Robinson (1977) reported that the presence of a beach increased the erosion rate of the shale cliffs of North East Yorkshire by 15-18 times, more than the rate recorded where the beach was absent. The removal of the shingle beach at Hallsands, Devon, however, resulted in extremely rapid cliff erosion. Changes in the beach elevation near Kilkeel, Northern Ireland, is one of the major causes of temporal variation in the erosion rate of the glacial cliff there (Sunamura, 1983). In 1984, the failure of the cliff at Holderness, demonstrated by the movement of blocks of till, coincided with unusually low beach levels and it was assumed that the slides were triggered by the low beach, and that the level of the beach has substantial impact on the stability of the cliff (Butcher, 1991).

The control of the wave assailing force by the beach sediment is thought to depend on the wave energy at the cliff base, the wave direction and the size and amount of the beach material (Sunamura, 1983).

The height of the cliffs was presumed to be important, because the undercutting of a high cliff would result in a larger volume of material at the bottom of the cliff after a mass slide or slope failure. It would take longer for this to be removed by waves, before recession could continue (Shepard & Grant, 1947; Emery & Kuhn, 1980). This theory is contested by Valentin (1954) who found that on the Holderness coast there was no long-term correlation between the height of the cliff and the rate of erosion.

The distance of the fetch is a governing factor on the rate of erosion, because of the importance of storm waves and storm surges. The southern area of Holderness is open to attack by storms from the north, north-east and east and the greatest fetch is toward the east, enabling large storm waves to attack the coastline.

The zone of greatest erosion by the waves has been determined by mathematical models, and these have found that the highest pressures exerted on vertical structures by standing, breaking or broken waves occur slightly above the still water level. This would imply that the long term level of greatest erosion is related to the neap high and low tidal levels, which are the levels most often occupied by still water level. However, wave energy is greater during high tidal periods due to greater water depth and decreased bottom friction. Highest and most effective waves occur during storms, when the water surface is above the still water level, and this is when wave run-up and impact reach the uppermost areas of the shoreline and the cliff is attacked most vigorously. This would mean that the zone of the greatest wave erosion is above the neap high tidal level (Griggs & Trenhaile, 1994).

2.10 Mode of Erosion of the Holderness Cliffs

The action of the waves, via the processes described above, causes the formation of a notch at the base of the cliff and this has been recorded in the area of Easington (Hutchinson, 1986). This undermining of the cliff causes instability in the till and the cliff is then steepened by processes including rotational slumping, mud flows and mass falls (Pringle, 1985). These processes vary in importance seasonally, in the wetter conditions of winter large mud flows develop increasing the loss of fine material to the beach (Pringle, 1981). These mass movements supply debris to the base of the cliff, which forms a structure called a talus. There is no more toe erosion while the talus is present, obstructing wave attack, however, continual wave action disperses the debris, transporting it alongshore and offshore. Once the base of the cliff is exposed again the erosion of the toe will continue.

Under strong marine attack the tills exhibit cyclic, rotational land sliding. This is because the rate of the debris removal from the toe of the cliff is greater than the rate at which it is supplied by mudslides and other shallow mass movements and it is also greater than can be supplied by deep-seated sliding. The high rates of toe erosion are therefore associated with the occurrence of large deep-seated rotational slips, which are general failures of the base of the cliff and result in a change in the cliff profile from over-steep to a more stable gradient. The mode of the retreat of the cliff is characterised by the rocking of the cliff profile between these upper and lower inclinations. The upper state is when erosion oversteepens the lower cliff by removal of insitu clay at the base, and the lower state is defined by the mass having slipped and forming a scarp at the bottom of the cliff. This cyclic erosion, characteristic of the Holderness area, appears to be controlled to some extent by the rate of migration and the presence of the ords (Hutchinson, 1986).

Other processes of cliff erosion such as weathering, bio-erosion, and solution are not discussed here, because they have not been reported to occur on the Holderness coast. Weathering is a slow process and because of the high erosion rates of this area, cliff material does not survive long enough for it to be a factor.

2.11 Future of the Area

The responsibility for the coastal defence of the area lies with Holderness Borough Council, who at present have plans for the protection of important portions of the coastline. The most recent plans are to create a series of 'hard' points along the coast, between which erosion will be allowed to continue. This will create sheltered bays, which will catch and hold material, and in the long run will help to protect the cliffs, and the shore platform. However, there is considerable concern that this would have detrimental effects on other parts of the coastline which currently receive sediment from Holderness cliffs, including the south east coast of England and The Netherlands. There are also plans to protect the B.P. Gas Terminal at Easington, due to its commercial value. The defences would take the form of a seawall, constructed either with large boulders, floated in on barges at high tide, or a reinforced concrete wall, similar to the one present at Withernsea, a town a few miles to the north of Easington and the study area.

2.12 Aerial Photography, Photogrammetry and Digital Elevation Models

Aerial photography is one of the most widely utilised forms of remote sensing and is an established source of data for the coastal zone (O'Regan, 1996). Vertical aerial photographs and photogrammetric techniques have been used to determine rates of shoreline change since the advent of high resolution vertical aerial photographs (Smith & Zarillo, 1990). Before this aerial photographs had only been used to qualitatively assess coastal morphology (Anders & Byrnes, 1991).

Aerial photographs have been used to quantify erosion rates and cliff recession in a variety of ways. Sunamura (1973) used aerial photographs to produce topographic maps, on which profiles were plotted and the eroded distance, at the cliff base was calculated. Other workers (e.g. Jones *et al.*, 1993) superimposed photographs in order to measure the change in the shoreline, using dimensionally stable acetates to trace the changes.

Aerial photographs are particularly suitable for the determination of coastline changes, because they present a record of the pattern of features on a coastline at the instant the photographs were acquired. By re-photographing an area at a later date it is possible to observe and measure changes which have occurred, although only net changes are apparent, and are available for interpretation (El-Ashry & Wanless, 1968). For many years it has been possible to extract numerical height data from stereo aerial photographs, by the use of stereoplotting machines, and these have been used extensively to study changes in shore platforms and cliffs (Kidson & Manton, 1973). Data from such machines has also been used to construct Digital Elevation Models, which are digital representations of the continuous variation of relief over space (Burrough, 1987).

Techniques used to produce DEMs from aerial photographs are discussed in Allison & Muller (1992). The only part of the processes of image-matching, parallax reading and DEM production which is not fully automated, within hardware and software systems, is the absolute orientation with respect to the precise measurement of the centre of signals on ground control points. At present an operator still has to identify these points (Torlegard, 1996). However, automatic ground control point identification has recently been developed for satellite images (Dowman, 1996).

Other methods for studying coastal change include the use of maps and charts, but this can be unreliable due to the selective information present, which has already been subjected to human interpretation in a processing stage, and also the often ambiguous position of the cliff foot and top. The standard field method for quantifying shoreline change, is through beach profiles, involving the repeated measurement of topographic surveys (Morton, 1991). However, this is expensive, involving considerable amounts of man hours and equipment and can be compared with the expense of aerial photography, where the only major outlay is the cost of the photographs themselves. The hire of the aircraft can constitute a major outlay as well, but this can often be shared between several projects.

Volumetric computations have been carried out using data from digitised contour maps and 2D profiles, but the accuracy of such methods depends upon the accuracy of the original data and the method of processing (Dick & Zeman, 1983).

Data on coastal evolution trends constitutes one of the basic pre-requisites for the proper planning of coastal development, and in the past have relied upon field measurements of erosion, or on the analysis of historical observations recorded on maps and plans, which are of questionable accuracy (Stafford & Langfelder, 1971). The most popular ways of measuring cliff erosion at the moment, are the use of the cliffline on old maps and charts, the comparison of old and recent terrestrial or aerial photographs, surveying, or micro-erosion meters. It is important due to the spatial and temporal variability of coastal erosion to calculate a rate over a suitable time-scale, and this is only possible using methods, such as, the comparison of photographs.

The use of photogrammetric analysis software recently developed, has provided a way to use stereopairs of images taken from aerial photographs, to measure changes in the coastline, through the production of DEMs. Topographic information such as slope, aspect, plan and profile curvature can be derived from DEMs (Moore, Grayson & Ladson, 1991) and these can be used to describe and classify an ord. The slope is a plane at an angle to the plane of the datum, and aspect is the direction of the slope. By determining characteristic slope, rate of change of slope and aspect for an ord, and for the area of cliff adjacent to the ord, it should be possible to automatically identify the feature and assess its movement over time. Within an ord, the depression formed at the centre will be apparent within the DEM, due to the slope on the seaward side of the depression facing toward the cliff. From the slope and rate of change of slope, cliff material volume differences due to the recession of the cliff can be determined, and changes in the gradient of the cliff, which occur when an ord is present, can also be identified. These parameters have been used by Moore et al. (1997) to successfully describe individual features.

3. Methods

3.1 Introduction

Vertical aerial photographs have been acquired as part of the LOIS project from 1992 to the present date and three dates were selected for analysis; these being 11.7.94, 26.10.96 and 8.4.97. The photographs were taken with a 60% overlap, characterising them as stereoscopic, and enabling them to be used to create Digital Elevation Models (DEMs). The prints were first digitized, and imported in digital format onto a Silicon Graphics UNIX workstation, for analysis in the image processing software package ERDAS Imagine Version 8.2 and the GIS package ARCINFO, Version 7.0.4. Within ERDAS Imagine, the Orthomax module, a softcopy terrain mapping and geopositioning package, was used to generate DEMs, which were exported into ARC in order to carry out volumetric analysis, and orthorectified images, which were used to produce perspective views of the terrain. These were subsequently used to aid visual representation of the profile analysis.

3.1.1 Principle of Parallax

Stereomatching is a technique used to create accurate DEMs from stereo images, which utilises differences present in the stereo-images caused by topographic expression of the earth's surface. Image matching techniques are used to identify coincident points in each of the two images of the pair and the relative disparity between each set of matched points are used to determine heights or elevations (Morris, 1995). This refers to the principle of parallax. Figure 2 illustrates the nature of parallax, on vertical photographs taken from successive camera positions S_1 and S_2.

The relative positions of A and B alter with the change in the viewing position, in relation to the principle points P_1 and P_2, according to the heights of the features above a given datum. Therefore features A and B appear at the same position a , b on S_1, but at different positions on S_2 (a_I and b_I). A measure of the parallax of A can be obtained by adding the distances P_1a and P_2a_1, on the two positives. The same can be done (with distances P_1b and P_2b_1) to obtain a measurement of the parallax of B. The difference between the two parallax measurements is due to the height difference between A and B. The ability to determine height of objects above an arbitrary datum is therefore dependent on parallax (Barrett & Curtis, 1982) and this principle is used within the Imagine software in order to create DEMs.

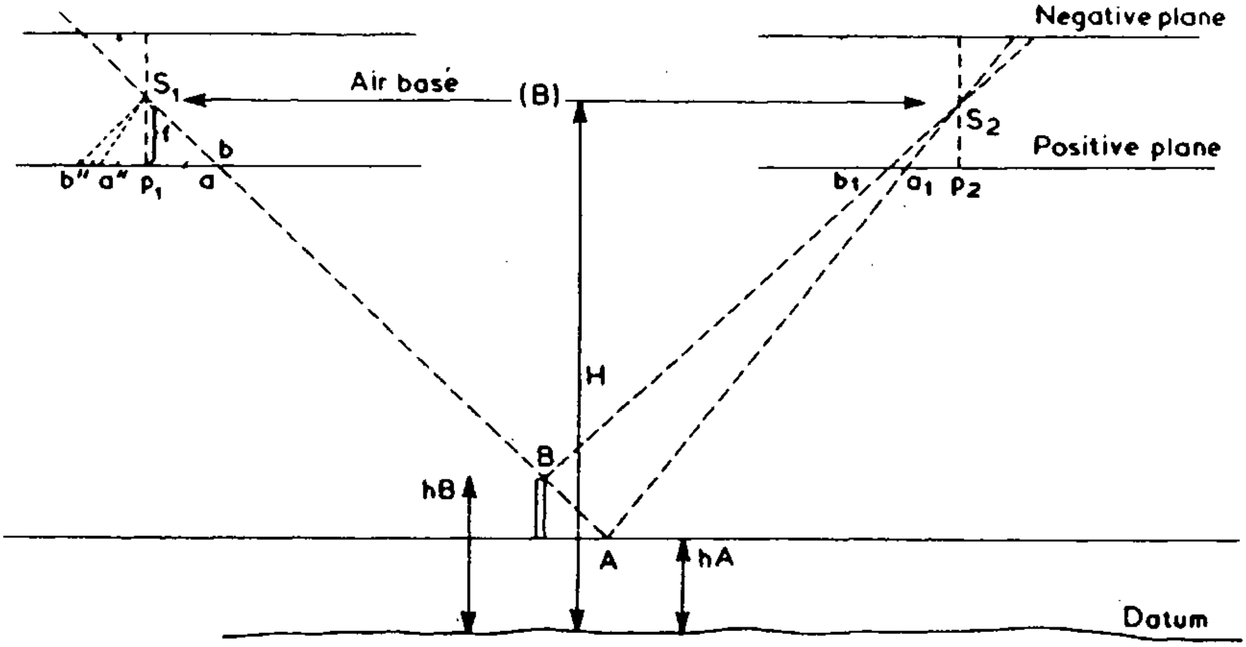


Figure 3.1.1: Diagram demonstrating the parallax of points A and B on two photographs taken at positions S_1 and S_2 (Barrett & Curtis, 1982).

3.2 Methodology

The aerial photographs were acquired at 1000 or 1200m altitude, using a Wild RC-10 aerial survey camera, with a Universal Aviognon II lens, aboard a NERC aircraft on flight lines covering the length of the Holderness coast, from north to south. The chosen study area of the British Petroleum Gas Terminal and the area immediately north of the village of Easington, is approximately 2 kilometres in length and consequently represented on four to five hardcopy paper prints. The scales of the photographs are dependent on the ratio of the focal length of the camera to the flying height, and this results in a scale of 1:7820.4 for the 1994 photographs, which were acquired at an altitude of 1200m, and scales of 1:6518.9 for the 1996 and 1997 photography (altitude 1000m).

The prints were digitized using a flatbed scanner, at 500dpi and in True Colour. Due to the availability only of an A4 scanner, the images were digitized in 2 portions and then were joined within the Imagine software, using the Mosaic Images function.

3.2.1 Orthomax

The Orthomax module is made up of several sub-modules, three of which were involved here; the Block Tool, the DEM Tool and the Ortho Tool.

3.2.2 Block Tool

The Block Tool is used for the entering of the scanned hardcopy imagery as frame data, the camera data and the ground control point (GCP) data, the measurement of the ground control point data and the triangulation of the imagery. The GCP data was provided as longitude, latitude and height co-ordinates, from the results of GPS ground surveying carried out by the British Geological Survey. Camera data was obtained from the camera calibration certificate and the relevant interior orientation element data were input into the Camera Editor portion of the Block Tool. The necessary data include the focal length, the co-ordinates of the principal point of the fiducial system (point of autocollimation), the radial distortion data and the co-ordinates of the four fiducial marks. The fiducial marks are denoted as numbers one to four, in the order bottom left, top left, top right and bottom right, with the top of the photograph indicated by the date, location and image number annotation, see figure 1.4.1 of the stereopair.

The images were imported via the Frame Editor into the Block Tool and once imported the measurement of the interior orientation can be carried out for each frame. The interior orientation of each image refers to the orientation of the digitized standard frame relative to the camera, and is identified by the measurement of the fiducials, which are the marks shown as cross-hairs, at each corner of an image. The optical centre of each photograph, or the principal point, is at the point of intersection of the lines joining two opposite fiducial marks. The purpose of measuring the interior orientation is to mathematically tie the digital imagery pixel co-ordinates to the fiducial system of the original photograph (ERDAS, 1994). After all four of the fiducials of an image have been measured the software automatically calculates the root mean squared error.

It was necessary to add the required map co-ordinate system in the Projection Editor of the Orthomax module. Specifically the UK National Grid reference system of the Ordnance Survey was added under the Transverse Mercator Projection of Great Britain, as shown in table 3.2.1.

Table 3.2.1 Transverse Mercator Projection of Great Britain Parameters

Projection Name	ukng
Central Meridian	2:0:0.0 W
Origin (latitude)	49:0:0.0 N
Scale Factor (at C.M.)	0.9996
False Easting (m)	400 000
False Northing (m)	100 000

The reference frame was set to WGS_84, which enables the use of the Ground Control Points in latitude and longitude. The photographs can then be related to the datum surface, by calculating the exterior orientation parameters of each photograph, within the block adjustment. The exterior orientation of a photograph defines its position and orientation in object space (Moffitt & Mikhail, 1980), and is given by the height and attitude (essentially the roll, pitch and yaw) of the camera.

Ground Control Points are defined in the Ground Point Editor within the Block Tool, which also indicates whether the points are active or not indicating whether they are to be used in the triangulation process, and gives precision estimates for each point. The type of the GCP is indicated by the characters "C", which is a full control point, having known horizontal (X,Y) and vertical (Z) co-ordinates, "H", which is a horizontal control point, "V", which is a vertical control point and "T", which is a tie point having unknown horizontal and vertical components.

The points are measured in the Ground Point Measurement section of the Block Tool. Generally at least three control points should be measured in the frames and should be as evenly distributed as possible, and if possible should be in the area of overlap of the photographs. The geographical position in latitude, longitude and the height in meters, and a brief description of the control points used here are given in table 3.2.2. A tie point is any coincident, easily identifiable and measured point present on two or more of the images, whose exact co-ordinate position is not known and which is used to "tie" together the images in a strip. Tie points should be included in every overlap, and due to the 60% overlap of stereoscopic photographs it is possible for several tie points to be present on three photographs. The software will accurately estimate the position of the tie point, during the block adjustment.

Table 3.2.2 Details of GCPs supplied.

ID	Description	Latitude	Longitude	Height (m)
002	Corner of stonewall	0:7:31.885479 E	53:39: 8.238367 N	4.0071
003	Corner of tarmac	0:6:54.761834 E	53:39: 6.660666 N	9.5097
004	Corner of concrete	0:7:17.555740 E	53:39:19.693961 N	12.7123
006	Corner of tarmac	0:7: 0.022798 E	53:39:29.754471 N	15.0999
009	Corner of tarmac	0:7: 1.812786 E	53:39:44.251639 N	19.4792
011	Corner of concrete	0:6:34.307554 E	53:39:46.733495 N	21.0716
012	Pillar 25 (Trig. Pt.)	0:6:46.826870 E	53:39:49.306557 N	25.7561

The identification numbers, descriptions and heights are as supplied by the surveying company, the latitude and longitude co-ordinates were calculated from the geographic grid values in meters, into Great Britain projection values in degrees, minutes and seconds using the PROJECT command within ARC.

In addition to the described Ground Control Points, other control points were available for the beach for the April 1997 data only. These are the results of a GPS survey carried out simultaneously with the aerial photography and were added to the Ground Control Editor as vertical points. This is due to the uncertainty of the exact positions of the data points on the images. No such data was available for the 1994 and 1996 images.

The block adjustment is the determination of the exterior orientation of the camera based on the measured image points corresponding to the ground control points, applied to the sequence of overlapping stereo photographs, and requires both ground control points and tie points. The adjustment relies on the physical condition that an image point, the focal point of the lens, and the object point all lie on a straight line, which is called the condition of collinearity. Block adjustment is carried out once all the necessary data as described above has been added to the Block Tool, and includes the process of triangulation. This determines the ground X,Y,Z co-ordinates of the tie points, links together the sequential images and as part of the block adjustment enables the exterior orientation of the images. The triangulation algorithm used is based on a "least squares block bundle adjustment" of the data, in which all parameters are fully weight-constrained and the full statistical measures and techniques are employed. This method minimises the effects of erroneous critical input data, which could include mismeasured or misidentified ground control points (ERDAS, 1994).

The triangulation process, within the Block Tool, should be successful within 3-5 iterations. Failure to reach convergence, where 3 to 5 iterations is normal and 10 is the maximum, was usually found to be due to incorrect input of the GCP data, poor and inaccurate measurement of GCPs, or poor distribution of tie or control points. The "View Results" section of the triangulation component was examined in order to review the results of the block adjustment, any obviously erroneous control or tie points could then be rendered inactive or deleted, respectively, and the triangulation process repeated until deemed to be of suitable accuracy. An example of the last page of the view results file is shown in figure 3.2.1. The triangulations of the image data from the three dates studied were achieved within 3 to 4 iterations, once unsuitable control and tie points had been removed from the process. Once the block adjustment has been performed the stereoimages can be used in the production of Digital Elevation Models, within the DEM Tool.

3.2.3 DEM Tool

The DEM Tool is used to automatically collect a user-defined ground space matrix of elevations from triangulated imagery (ERDAS, 1994). The DEM automatic extraction algorithm used by the Imagine software is an 'area' correlator in which patches of pixels from the source images are correlated during the matching process. The algorithm uses an hierarchical approach in which the correlations are performed at increasingly higher resolutions of imagery, using reduced resolution data sets, generated as required. The algorithm uses results from both the current resolution and the previous resolution to produce increasingly accurate models of the terrain. For a more thorough explanation of the DEM collection algorithm refer to the ERDAS Imagine Version 8.1 Manual (1994).

DEMs were produced for each photographic overlap of the three dates, supplying three DEMs for the 1994 and 1997 data and four for the 1996 data. These are denoted by the number of the images that were used to in the DEM collection. Table 3.2.3 shows the photographs acquired on each date which were used in the study.

Table 3.2.3 Details of the Acquired Photographs

Date of Photograph	Number of Photographs
11.07.94	634 635 636 637
26.10.96	6821 6822 6823 6824 6825
08.04.97	8201 8202 8203 8204

Figure 3.2.1 View Results file of Triangulation process within the DEM Tool, for the 1997 data (last page).

Point ID	Description	Current Correction Longitude	Current Correction Latitude	Current Correction Elevation	Current Position Longitude			Current Position Latitude			Current Position Elevation
Globe003	Corner of tarmac	0.000	0.000	0.000	0	6	54.788	53	39	6.634	9.755
Globe004	Corner of concre	0.000	0.000	0.000	0	7	17.511	53	39	19.521	13.516
Globe006	Corner of tarmac	0.000	0.000	0.000	0	7	0.142	53	39	30.103	17.758
Globe009	Corner of tarmac	0.000	0.000	0.000	0	7	1.791	53	39	44.179	18.035
Globe012	Pillar 25/Trig.p	0.000	0.000	0.000	0	6	46.747	53	39	49.231	23.106
JTPoo1	BL corner of red	0.000	0.000	0.000	0	6	54.203	53	39	42.253	17.032
JTP002	Corner of white	0.000	0.000	0.000	0	6	52.699	53	39	45.477	19.086
JTP003	TL hand corner o	0.000	0.000	0.000	0	6	52.842	53	39	52.276	23.446
JTP004	BL corner of con	0.000	0.000	0.000	0	6	36.971	53	39	45.534	16.314
JTP005	BL corner of lon	0.000	0.000	0.000	0	6	45.019	53	39	36.354	19.522
JTP006	Corner of concre	0.000	0.000	0.000	0	6	53.867	53	39	38.138	17.430
JTP007	Corner of concre	0.000	0.000	0.000	0	6	55.999	53	39	37.737	17.231
JTP008	BR Corner of car	0.000	0.000	0.000	0	6	57.766	53	39	35.718	19.279
JTP009	Corner of path a	0.000	0.000	0.000	0	6	47.417	53	39	33.308	16.207
JTP010	Corner of concre	0.000	0.000	0.000	0	6	39.557	53	39	37.590	15.420
JTP011	Corner of grass	0.000	0.000	0.000	0	7	1.625	53	39	13.871	13.840
JTP012	Corner of grass	0.000	0.000	0.000	0	7	3.321	53	39	22.459	20.414
JTP013	BL corner of bui	0.000	0.000	0.000	0	7	2.937	53	39	18.688	19.903
JTP014	Corner of drivew	0.000	0.000	0.000	0	7	7.370	53	39	4.268	7.147
JTP015	Corner of concre	0.000	0.000	0.000	0	7	25.315	53	39	10.413	9.832
JTP016	Corner of concre	0.000	0.000	0.000	0	7	17.774	53	39	23.589	19.379
JTP017	BR Corner of man	0.000	0.000	0.000	0	7	15.740	53	39	14.593	10.019
SEG001	Profile 1	0.000	0.000	0.000	0	6	55.345	53	39	52.812	3.156
SEG008		0.000	0.000	0.000	0	7	0.410	53	39	55.352	1.366
SEG203		0.000	0.000	0.000	0	7	4.897	53	39	45.294	-1.974
SEG302		0.000	0.000	0.000	0	7	6.582	53	39	41.934	0.287
SEG306		0.000	0.000	0.000	0	7	9.140	53	39	43.182	-1.487
SEG307		0.000	0.000	0.000	0	7	10.330	53	39	43.822	-1.641
SEG402	256	0.000	0.000	0.000	0	7	9.964	53	39	38.337	2.643
SEG407	2026	0.000	0.000	0.000	0	7	14.342	53	39	40.242	-0.106
SEG606	4377	0.000	0.000	0.000	0	7	27.734	53	39	26.465	-2.174
SEG702	5487	0.000	0.000	0.000	0	7	26.577	53	39	16.067	2.612
SEG703	5612	0.000	0.000	0.000	0	7	27.294	53	39	16.305	2.260
SEG704	6712	0.000	0.000	0.000	0	7	29.106	53	39	16.785	1.162
SEG705	6499	0.000	0.000	0.000	0	7	31.570	53	39	17.458	-0.260

The DEMs were each assigned titles composed of the numbers of the photographs involved, for example, the DEM produced using images 634 and 635 was given the numerical designation 634635. The area of the DEM to be collected from a pair of photographs must be specified within the Edit Collection Parameters section of the DEM Tool, and this is done by selecting the required area from one of the image pair, ensuring it only includes the overlap section. Various strategy parameters are used for the DEM production and the specific parameters, which it was necessary to change only, will be described. The default values are stated in table 3.2.4

Table 3.2.4 Default Values of the DEM Production Parameters

Strategy Parameter	Default Value
Minimum Threshold	0.600
Noise Threshold	0.400
Maximum Parallax	5
Minimum Template Size	7
Maximum Template Size	9
Minimum Precision	0.5
Rejection Factor	1.5
Skip Factor	2
Edge Factor	2.5
Start RRDS	4
End RRDS	0
Y-Parallax Allowance	0
Resampling	Bilinear
Post Processing	Yes

In order to reduce inaccurate extremes of elevation present in some of the DEMs it was necessary to alter the values of the maximum parallax and the rejection factor. The maximum parallax defines the maximum search range (in pixels) around a point and can be decreased to reduce the elevations of abnormally high or low points relative to the surroundings. The rejection factor is a 'smoothing' factor, which determines whether a particular point should be rejected because it appears to be an abnormal peak or dip in the elevation. For all the DEMs from the 1994 data the maximum parallax was altered to three, and for two DEMs from 1997, (82018202 and 82028203) the maximum parallax was altered to three and the rejection factor reduced to one. These adjustments appeared to have reduced the presence of abnormally high and low peaks and to smooth the surface of the DEMs to which they were applied. Once the DEMs have been collected for each pair of images the corresponding image areas, as specified in the Edit Collection Parameters section, are used to produce orthorectified images using the Ortho Tool.

3.2.4 Ortho Tool

Orthorectification is the resampling of imagery to remove the effects of sensor geometry and terrain variation and requires the input of both the image and a DEM of the ground surface. This process removes the effects of the elevation changes upon the image perspective and produces a data set with an even pixel spacing of Easting and Northing. The accuracy of the orthoimage is dependent on the accuracy of the triangulation, the resolution of the image source and the accuracy of the DEM. Again more details of the algorithm used can be found in the ERDAS Imagine Manual (Version 8.1, 1994). Orthoimages were produced corresponding to each of the DEMs, using the datum of WGS_84, and the ground spacing distance was set to 1m. The ground spacing distance determines the resolution of the orthoimage.

Both the DEMs and the orthoimages produced in the Orthomax module were resampled to the Transverse Mercator projection of Great Britain, with the units of meters in order that the orthoimages could be overlaid onto the DEMs, using the Perspective Viewer function. This provides a way of visually representing the data. The three or four orthoimages for each date were linked together using the Mosaic Images function of

Imagine to provide a complete orthoimage of the study area for each of the dates. This was also carried out for the DEMs of each of the dates.

3.3 Volumetric Analysis

Volumetric comparison of the Digital Elevation Models were carried out in ARC (Version 7.0.4). After the three or four DEMs for each date were joined using the Mosaic Images function of Imagine in order to create one DEM file for each of the three dates, each file was exported from Imagine using the Import/Export Module as Grid files. Due to the presence of water and buildings close to the required study areas of the cliffs and beach it was necessary to perform the volumetric calculations on specific areas. These areas were decided upon using the Viewer function and the orthoimages.

Five polygons were outlined using Vector coverages, specifically the area from north to south was divided into three, and the cliff and beach were also taken as distinct polygons. Each polygon was utilised with all three study dates, except the beach polygon, which was only applied to the 1996 and 1997 data, due to the inaccuracies of the 1994 beach as represented by the DEM, resulting from the presence of water on the beach. The cliff polygon was defined as a vector coverage using the position of the 1994 cliff area, and including an area landward of the top of the cliff, under the presumption that the cliff will have retreated from this position at the time of the 1996 and 1997 photography. Figure 4.1 shows the positions of the five polygons as described, overlaid onto the 1994 orthoimage.

Within ARC the polygons are built using the BUILD command, and then defined according to the Transverse Mercator Projection of Great Britain, using the PROJECTDEFINE command. The specific polygon was clipped from each of the DEMs (i.e. the DEM for each date) using the GRIDCLIP command within the GRID module of ARC. This produced a coverage file, of the same specific polygonal area, for each of the three dates, which were then used to perform two volumetric analyses.

The CUTFILL command was used within ARC, using the grid files of the polygons, in order to compare the volume of material present in the 'before' and 'after' polygons. CUTFILL summarises the areas and volumes of change during a cut and fill operation on an area represented by two grids (or lattices), one before and one after the cut and fill operation. For the purposes of this study the 'before' lattice is taken as the earlier date as compared with the 'after' lattice, is the later date. A cut and fill operation is a procedure where the elevation of a surface is modified by the addition or removal of surface material, rendering it suitable for use in this context. This is due to the probable change in the surface of the area, represented by the DEM, due to the erosion or possible accretion over time. The formula for the volume at a lattice point is:

$$\text{Volume} = d^2 * \Delta Z \text{ ;} \qquad \text{where } \Delta Z = Z_{before} - Z_{after}$$

The CUTFILL command requires the input of a 'before_lattice'; here the earlier date of the pair, an 'after_lattice'; here the later date of the pair, an 'out_lattice'; this is the output lattice created by subtracting the 'after' from the 'before'. Mesh point Z values in this output file represent the net change in the surface Z values following the cut and fill operation, or here the possible erosion of the cliff and beach. Another output file, an 'out_cover' file, is also generated, producing figures for the volumes of cut, fill, the net result, or balance, of the two, the total cut area, the total fill area, the graded area (area of data), the not graded area (area of NODATA) and the total area, which is the area of the designated polygon. A sample of the format of these results is given in table 3.3.1. The units of the calculations are meters, because both the projection of the polygons and the DEMs is the Transverse Mercator Projection of Great Britain, the units of which are meters, and the Z values of the surface of the DEMs are also in meters.

A positive value for the Balance Volume indicates that there is more material in the 'before' lattice than in the 'after' lattice, and for the purposes of this study indicates that there has been a net erosion over the area of the polygon. A negative balance value would indicate that there is not enough material for the fill operation, which would mean in this context that there had been accretion, with material supplied from outside the designated polygon.

The results file also characterises the areas of the cut and fill operation as to their net change using a specified code. Table 3.3.2 summarises the surface change classifications and the Cut Fill code.

Table 3.3.1 Sample of the CUTFILL Results. (units in meters)

Cut_Vol	73998.063
Fill_Vol	45304.89
Balance_vol	28693.173
Cut_area	13025.0
Fill_area	16798.0
Graded_area	29823.0
Not_graded	0.0
Total-area	29823.0

Table 3.3.2 The CUTFILL code of surface change

Net Change	CF-Code
No Change	0
Cut region	1
Fill region	2
NODATA region	-9999

The cutfill operation was carried out for each of the five polygons, comparing each of the dates in turn. The 1994 data was compared with the 1996 data, the 1996 data with the 1997 and the 1994 with the 1997, for each of the five polygons, except Polysouth, where the 1996 and 1997 data were compared only with 1994, and not each other, and Polybeach, where only 1996 and 1997 data was utilised. This was because of the inaccuracies present in the 1994 DEM, in the area of the beach.

The second method of calculating the difference in the material present between the dates of the aerial surveys uses the VOLUME function, within ARC. This calculates the area and the volumetric space between the surface of a TIN and a specified datum level, using linear interpolation. In order for this to be carried out on the polygons clipped from each DEM, each polygon grid file had to be converted to a TIN file. This was carried out for each of the polygons separately using the LATTICETIN command. VOLUME was then used to calculate the volume of each of the previously specified areas for each DEM, now represented by a TIN. A base value is used to specify the base elevation from which the calculation of the volume begins. Due to the presence of minus Z values in areas of the beach where the shore platform is exposed, and the need for a constant value for all the calculations a base value of -5m was chosen. This base value was used in all the VOLUME calculations. The VOLUME calculation produces the following results; the maximum Z value and the minimum Z value of the TIN, the specified datum which is set at -5m for all the calculations and the area and volume in meters.

The VOLUME command was carried out for each polygon, for the data of each study date, except the 1997 data was not used for the Polysouth area, and the 1994 data was not used for the Polybeach area.

3.4 Surface Profiles

Within ERDAS Imagine profiles were produced of the DEM surface, at points of interest of the terrain, using the Spatial Profiles command. By repeating the profile at the same point of the cliff at each of the study dates the changes in the profile of the cliff and the elevation of the beach over time can be evaluated. Profiles were also used to examine inaccuracies in the DEM collection, demonstrated by areas of erroneous extremes of elevation of the surface.

4. Results

The individual orthoimages for each date were mosaiced together Imagine and these are shown in figure 4.1 for 1994, figure 4.2 for 1996 and figure 4.3 for 1997. The polygons and the profile lines are shown in figure 4.1, overlaid onto the 1994 orthoimage.

4.1 Description of the Images

The individual orthoimages generated for each date were mosaiced to produce one for each of the three dates and these were visually analysed in order to assess the position of the ord, according to the description given by Pringle (1985).

In the 1994 orthoimage (figure 4.1) the till platform is exposed at the base of the cliff, in the northern portion of the image, in an area around 100m in length immediately adjacent to the cliff. This can be seen as the grey section at the base of the cliff. From here the exposed till depression extends at a low angle seaward for approximately 600 meters, however, it is difficult to see exactly how far it extends, due to the water present on the beach. This is a consequence of the photographs being acquired at the time of mid-tide. The till exposure is particularly well-defined at the centre of the beach. A lower beach ridge appears to be present seaward of the exposed till, due to paler, drier and elevated sand which appears to be present, and is further suggested by the presence of water on the landward side of this sand.

An upper shore beach ridge also appears to be present on the landward side of the exposed till and is again suggested by the paler sand visible. To the south of the till exposure the upper beach increases in width, as the lower shore becomes more uniform. The beach appears to take on the usual cross-sectional form at this point, to the east of the northern boundary of the Gas Terminal. This would perhaps have been confirmed

Figure 4.1 Orthoimage of the 1994 aerial photographs.

Figure 4.2 Orthoimage of the 1996 aerial photographs.

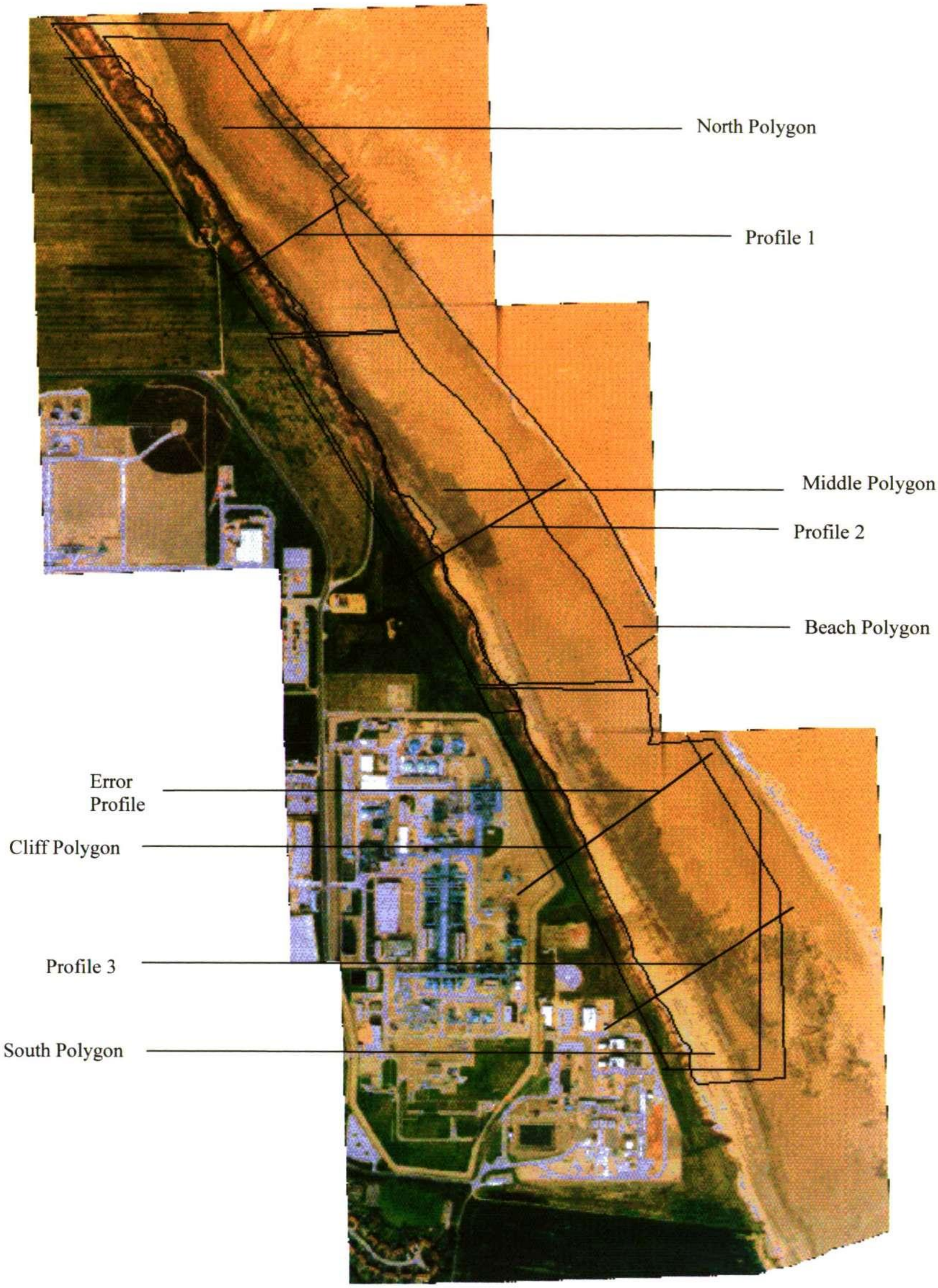


Figure 4.3 Orthoimage of the 1997 aerial photographs, showing the five polygons used for the volumetric calculations and the line used for each profile.

by the DEM of the area, but this DEM is inaccurate due to the presence of water on the beach. At the southern end of the orthoimage it is possible to see some of the effects of the water, where the cliffs appear 'stretched'. The effects of water on the beach are discussed in a later section and can also be seen on the greyscale image of the 1994 DEM, see figure 4.3.2.

The cliffs in the northern section of the image appear to be partly vegetated, and considerably wider than the same area of cliffs in subsequent years. There is some evidence of a landslide where the vegetation appears in a strip below the top of the cliff, but the width of the cliff would suggest a lower gradient, than in the 1996 and 1997 image.

In the 1996 image (figure 4.2), the exposure of the till is generally much more defined than in the 1994 image. It could be due to a storm having a destructive effect on the beach and removing sediment, leaving the whole surface of the beach at a lower elevation, resulting in the exposure of more till. Pringle (1985), however, noted that the ords went through phases, where the various sections became more or less well-defined.

The area at the base of the cliff appears only to have moved approximately 300 meters to the south in the 27 months since the 1994 image was acquired. This would mean a rate of movement of $0.133kmyr^{-1}$, compared with Pringle's (1985) mean rate of ord movement of $0.5kmyr^{-1}$. Over this time the ord appears to have lengthened, with the exposed area of till extending for more than 1400 meters to the south. It is unlikely that it extends further than this, although it cannot be seen on the image, because the till has already reached the level of low tide.

The till is only exposed at the base of the cliff for around 100 meters before it begins to extend at a low angle toward the sea. It also remains parallel to the cliff, seaward of a narrow band of upper shore for approximately 200 meters. At this point it is only around 10m wide, but increases to around 100 meters in width at the low tide level. Beach ridges are visible to both the landward and seaward side of the till depression, and both are well-defined as wide bands of sand. Parallel grooves running approximately normal to the shoreline are visible in the till, especially where the till is at it's widest.

More exposed till is visible at the extreme south of the image at the junction of the upper and lower shore, and also at the low tide level at the northern end of the image. It is unclear as to whether these areas are part of this ord or random exposures of till, or part of another ord system.

In the 1997 orthoimage (figure 4.3) the till is exposed at the base of the cliffs to the east of the northern boundary of the Gas Terminal, and appears to have moved approximately 400 meters in six months, giving a rate of movement of $0.8kmyr^{-1}$. This does not fit with Pringle's mean value for the movement of an ord, of $0.5kmyr^{-1}$. The exposed area at the foot of the cliffs measures around 300 meters in length, which is the largest it has been. The till depression follows the normal structure of moving seaward at a low angle, but the till areas are again less well-defined, with an area around 200 meters in length that has been covered over by beach material. This is further suggested by an increase in the elevation on the DEM at this point, compared with the areas to the north and south. This could be due to 'constructive' waves, beginning the restoration of the summer beach profile, as the photographs were acquired in April, and it could also be a consequence of the mild winter experienced, between 1996 and 1997.

There appears to be a beach ridge seaward of the disjointed till depression and to the landward side at the far south of the image, and both are confirmed by the presence of paler, drier sand. The ord itself appears to be compressed, the exposed till covering only around 1100 meters, however, it is difficult to judge exactly where the exposure of the till ends, as the image may not extend far enough to the south. In the northern area of the image a further band of till is visible as in the 1996 image, and it is still unclear as to whether this represents another ord or the northern part of this one.

Due to the difficulties of defining exactly where the ord begins in the north and ends in the south, the exact length of the ord has not been recorded. However, Pringle used the length of the central section, where the till platform is exposed at or near the cliff-foot as a measure of the ord's size. Measurements taken from the photographs of the study area, of 100, 100 and 300 meters, for 1994, 1996 and 1997 respectively, are considerably shorter than Pringle's mean length of 1187 meters, although the individual measurements vary between 265 and 1930 meters. The discrepancy between these measurements and Pringle's may be due to the lack of definition of 'at or near' the cliff foot.

4.2 Results of the DEM Production

The results of the DEM collection procedure is a greyscale grid, where the colour is related to the elevation. Figure 4.2.1 shows the three DEMs collected from the 1997 data, mosaiced together. On the left side of the image it is possible to see the buildings of the Gas Terminal as light areas. The cliff runs approximately down the centre, and can be seen where the greyscale changes from light to dark, representing the drop in elevation at the cliffs. On the far right of the DEM grid the sea can be seen as an area of light and dark, due to the effects of water on the DEM, which is discussed in the next section. Figure 4.2.2 shows a perspective view of a 1996 orthoimage overlaid with a DEM. The exposed till shore platform can be seen in the foreground, as dark areas, and it is also possible to see grooves in the till. The upper shore can be seen as the paler area at the base of the cliff.

4.3 Effects of Water on DEM Collection

The 1994 images were acquired at around mid-tide, and water is still present on the beach. This can clearly be seen on the orthoimage, figure 4.1, as pale areas. As the surface of water bodies changes between successive aerial photographs, the triangulation process within the software is unable to correctly identify common points and their heights in areas of water. On the sea this has the effect of creating peaks and troughs of the magnitude of several hundred meters in the DEMs, and these can be seen on the right of the 1997 greyscale image, figure 4.2.1. The peaks are represented as white areas and the troughs as black areas.

Figure 4.2.1 Mosaic image of the 1997 DEM greyscale grid.

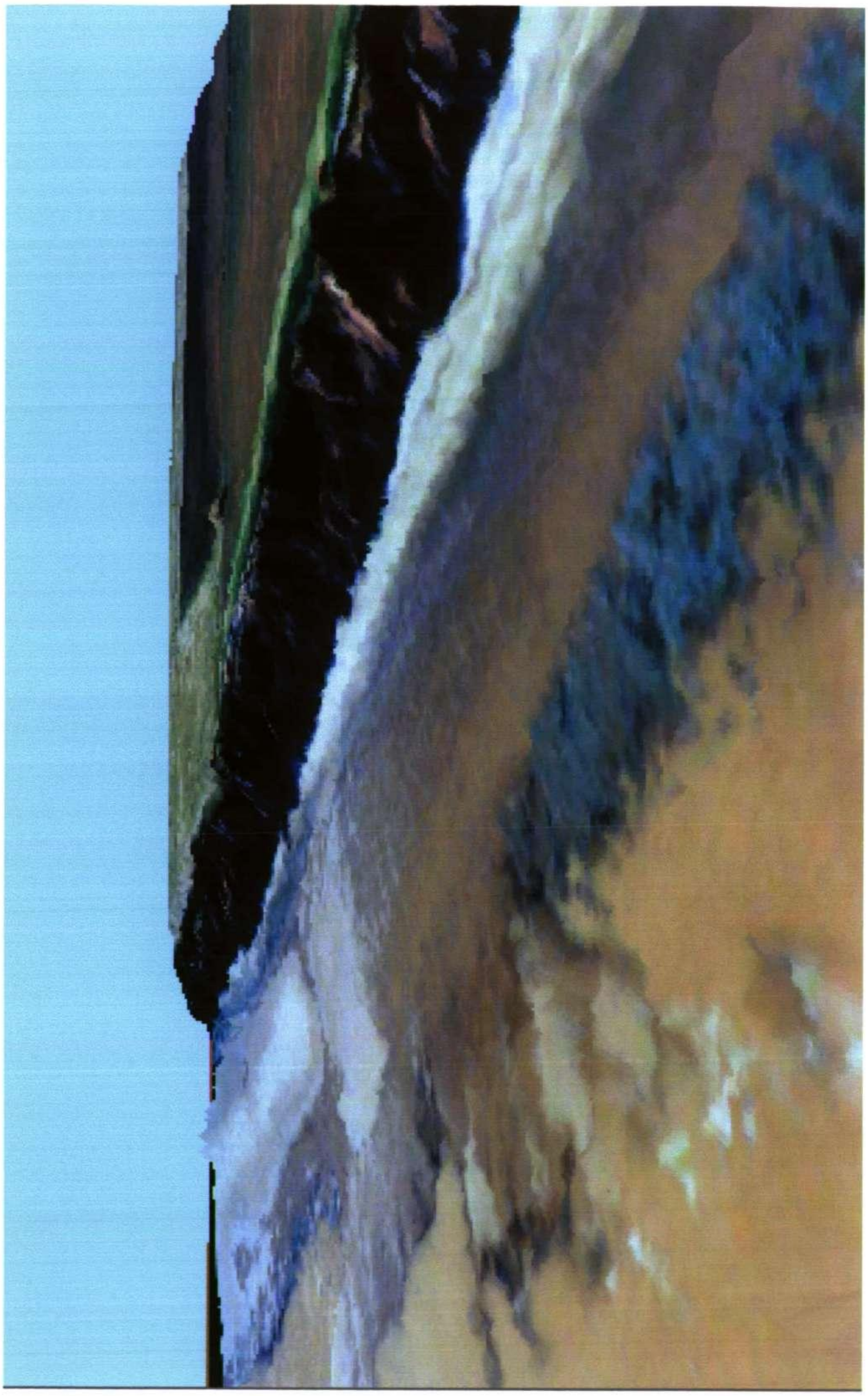
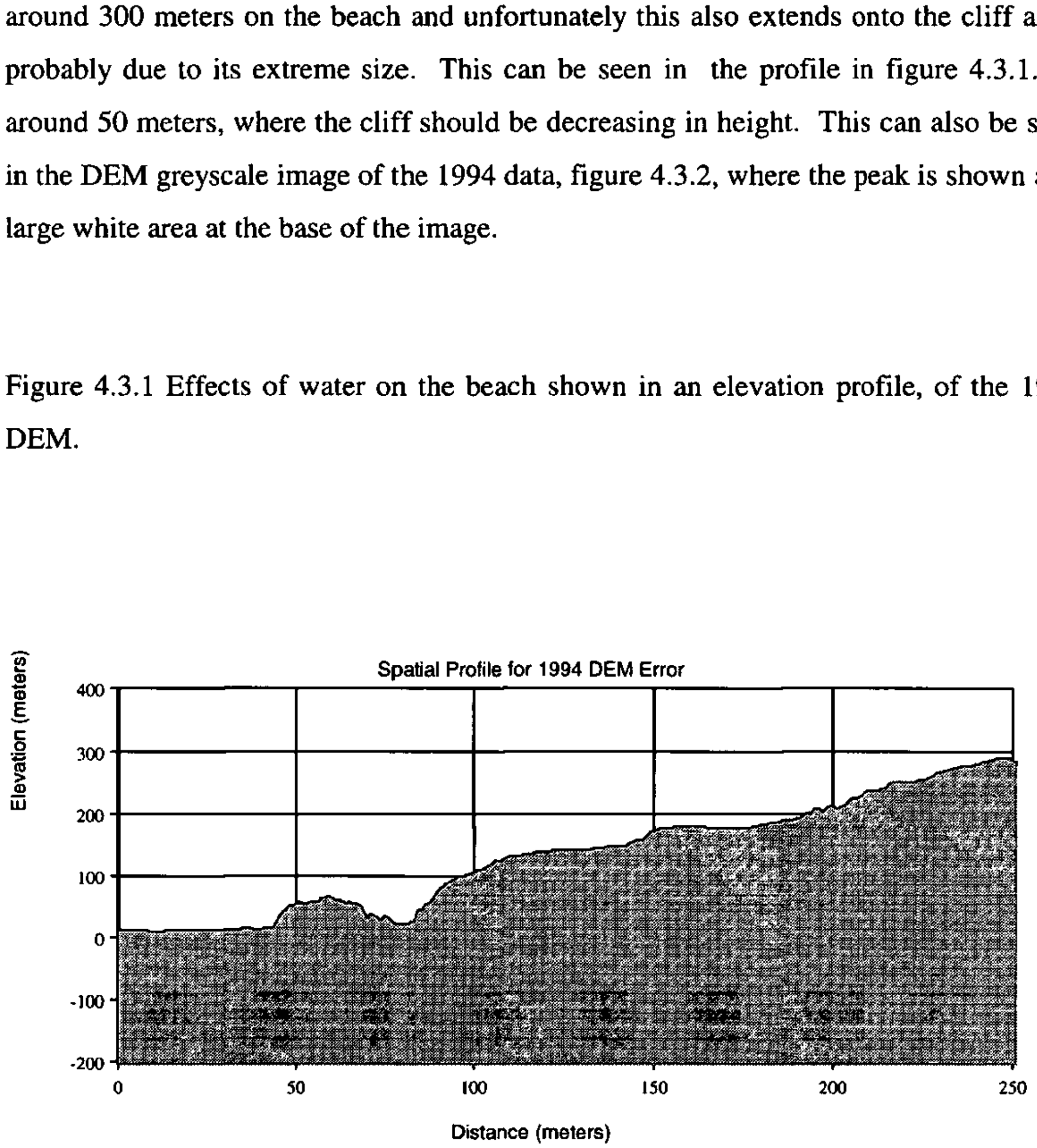


Figure 4.2.2 Perspective View of a 1996 orthoimage overlaid onto a DEM.

Water on the beach has a similar effect, of disturbing the elevations of points on the beach. In the southern area of the 1994 images, this is combined with another effect to produce the elevation profile in figure 4.3.1. A thin strip of water was present on the beach, approximately at the junction of the upper and lower shores, and this strip appeared to be reflecting the sun and appears on the image as a silvery streak. The combination of the high pixel value and the movement of the water has caused a peak of around 300 meters on the beach and unfortunately this also extends onto the cliff area, probably due to its extreme size. This can be seen in the profile in figure 4.3.1. At around 50 meters, where the cliff should be decreasing in height. This can also be seen in the DEM greyscale image of the 1994 data, figure 4.3.2, where the peak is shown as a large white area at the base of the image.

Figure 4.3.1 Effects of water on the beach shown in an elevation profile, of the 1994 DEM.



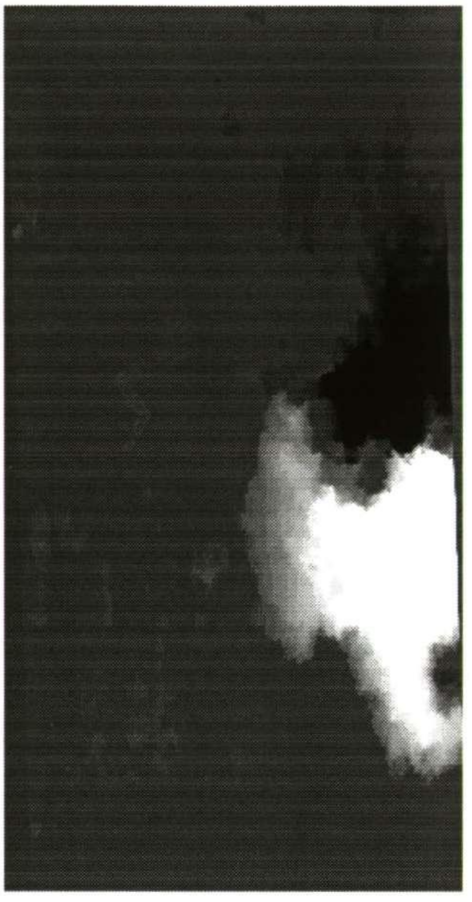


Figure 4.3.2 Greyscale grid of the 1994 DEM, showing extremes of elevation due to the presence of water.

4.4 Volumetric Calculations

The cut and fill operation was performed on each of the five polygons, as seen in Figure 4.1, denoted North, Middle, South, Cliff and Beach. Each study date was compared with the others as described in the Methods, section 3.3.

Generally the cutfill command produced much more inaccurate results, than the volume command, because the cutfill does not use a base value, it takes into account all the elevation values as specified in the DEM. This can include values such as -151 and

+315 meters, which are obviously not possible for the area of Holderness. As the beach area of the 1994 DEM was rendered hugely inaccurate by the presence of water, all cut and fill measurements involving the 1994 data are erroneous. The use of this data produced values for the cutfill which differ from the volume values by 250,000m^3. The volume results are more accurate because it requires the specification of a base value and this was set at a realistic value for the beach at -5 meters. Figure 4.4.1 represents the difference in the calculation methods.

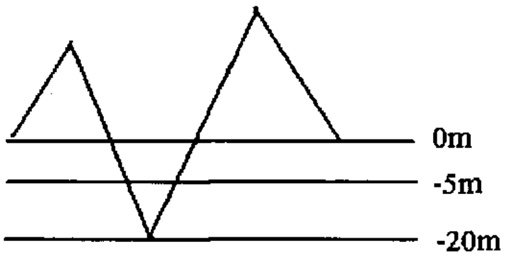


Figure 4.4.1 Diagram to demonstrate the difference in the calculation methods of the cutfill and volume commands.

The volume calculation will only take into account the material down to the -5 line, but the cutfill function will include everything down to the base at -20m. As a consequence the cutfill results will only be discussed where large extremes of elevation are not present. The full results are shown in the Appendix, section 7. Table 4.4.1 shows the volume results for each polygon, in terms of the difference over time, the rate of change over time, and the cutfill result where it is deemed to be accurate.

Table 4.4.1 Volume and Cutfill Results for the Polygons

Polygon	Date	Volume difference (m^3)	Rate of erosion/accretion from the Volume (m^3/month)	Cutfill result* (where applicable) (m^3)
North	1994-6	-55690.2	-2062.6	
	1996-7	2568.9	428.2	-4193.6
	1994-7	-53121.3	-1609.7	
Middle	1994-6	88207.0	3266.9	
	1996-7	-455240.0	-75873.3	455843.4
	1994-7	-367033.0	-11122.2	
South	1994-6	-7093841.0	-262735.0	
Cliff	1994-6	99291.6	3677.5	-107260.0
	1996-7	-158292.0	-26382.0	145460.0
	1994-7	-59000.5	-1787.89	38199.5
Beach	1996-7	-822489.0	-30462.6	820236.6
		Average rate of volume change over time (m^2/month)	-36787.5	

* The cutfill result has the opposite sign (+/-) to the volume result, because this is the balance volume figure as described in the Methods, section 3.3. The signs have been left the same for continuity.

It was not possible to carry out any statistical analyses of the results due to the small sample size. It would have been necessary to include more sets of photographs in the study. The results of the volumetric calculations will be discussed in the Discussion, section 5.

4.5 Cutfill diagrams

The graphical results of two of the cutfill calculations are shown in figures 4.5.1 and 4.5.2. The A diagrams show the results according to the cut and fill code as described in section 3.3 of the methods and the B diagrams show the output as a lattice file, which gives the actual result as a greyscale image. This therefore gives a graded result rather than the positive or negative result with the cutfill code. Using both these results it is possible to see that although the cutfill code may signify erosion in the form of 'cut', it may only be very slight.

On figure 4.5.1, the comparison of the 1994 and 1996 DEMs, diagram A shows one large patch of 'cut' towards the south end of the cliff, and this is confirmed by diagram B as a large area of extreme cut, displaying that there has been considerable erosion, by the white colour. Areas of certain 'fill', such as at the far west of the images, can be seen to show black on the greyscale image B. Other areas which on A show as cut, for example along the north eastern edge, do not differ from the colour of the areas of fill to any great extent on diagram B, and it is reasonable to assume that at these points the erosion is not extreme.

On figure 4.5.2, comparing the years 1994 and 1997, diagram A shows large areas of 'cut', along the eastern edge and down the centre, as well as the large area in the south, which was evident on the previous figure. Apart from this area, few others on diagram B show much evidence of erosion, and the line of 'cut' down the centre of image A can only be seen as a slightly paler area on B. This would suggest that the erosion at this point is only very slight and due to it's position in the centre of the cliff, unlikely. The evident 'cut' could be due to inaccuracies in one or both of the DEMs. There is a small area at the northern end of the cliff, which appears to have eroded considerably in both diagram A and B, as it is shown by an almost white area in the greyscale image, B.

Due to the ambiguity of the cutfill results as displayed here, only the volume results will be considered in the Discussion section.

Figure 4.5.1 Cutfill results of the cliff polygon, 1994 (before) and 1996 (after).

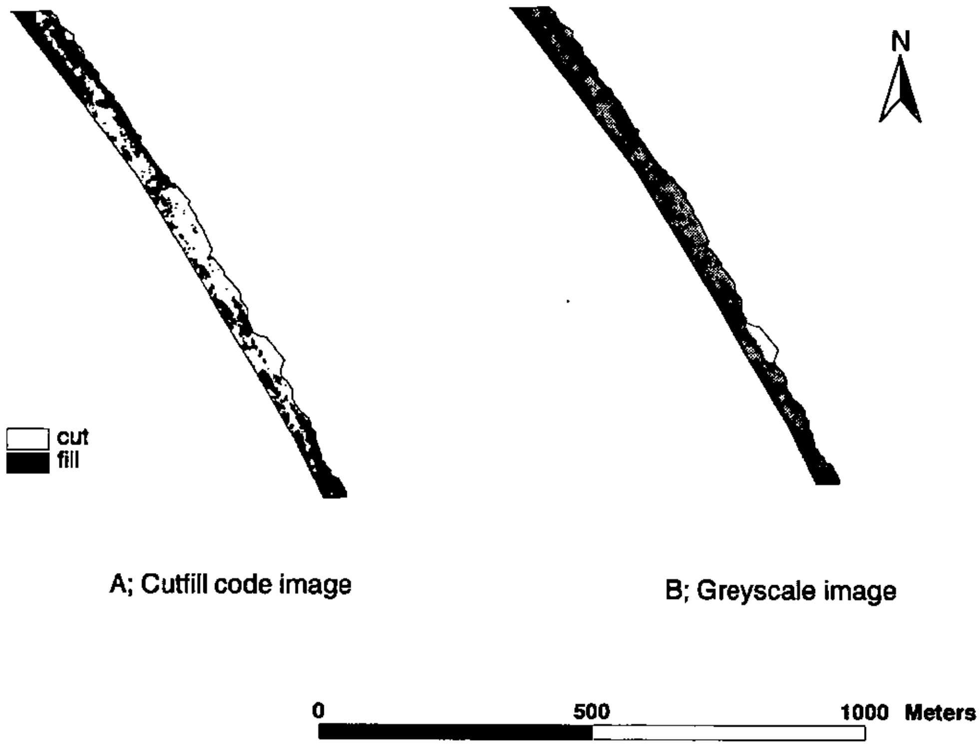


Figure 4.5.2 Cutfill results of the cliff polygon, 1994 (before) and 1997 (after).

4.6 Elevation profiles

Three elevation profiles were measured for each of the three study dates and these are shown in figures 4.6.1 to 4.6.9. The positions at which the profiles were obtained from the DEMs of each date are shown in the orthoimage of 1994, figure 4.1. Figures 4.6.1, 4.6.2 and 4.6.3 show the profiles 1,2 and 3 for the 1994 DEM. All three of the profiles appear to be inaccurate, profile 1 (figure 4.6.1) has peaks of several meters on both the cliff and the beach, profile 2 (figure 4.6.2) has two considerable peaks on the beach area of 15 meters and at least 30 meters, although the cliff appears to be more representative of the actual situation. Profile 3 (figure 4.6.3) is very inaccurate and it is not possible to determine the beach area from the cliff area. As a result of this figures 4.6.1 and 4.6.3 will not be considered further.

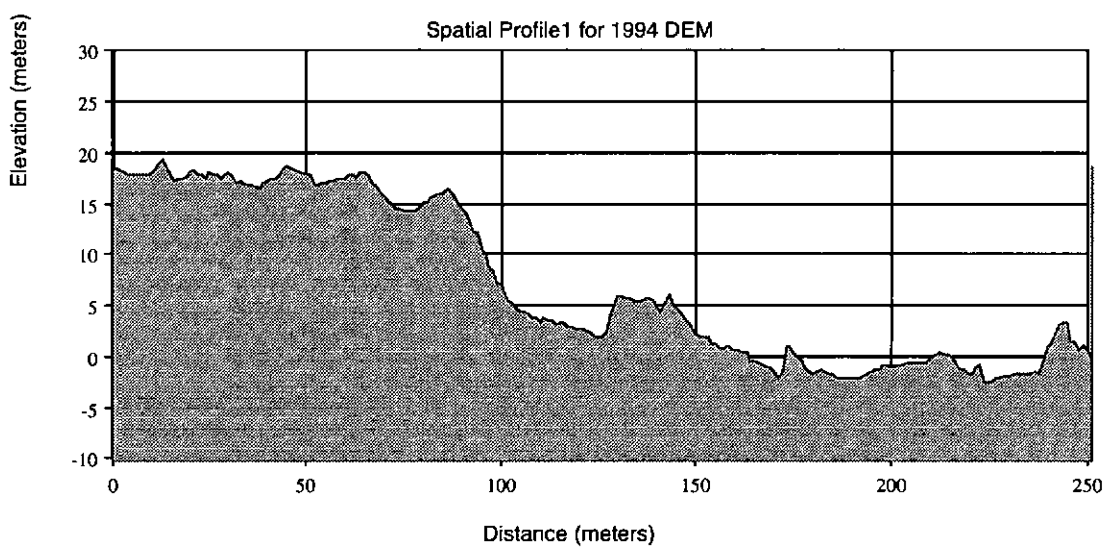


Figure 4.6.1 Profile 1 for the 1994 DEM

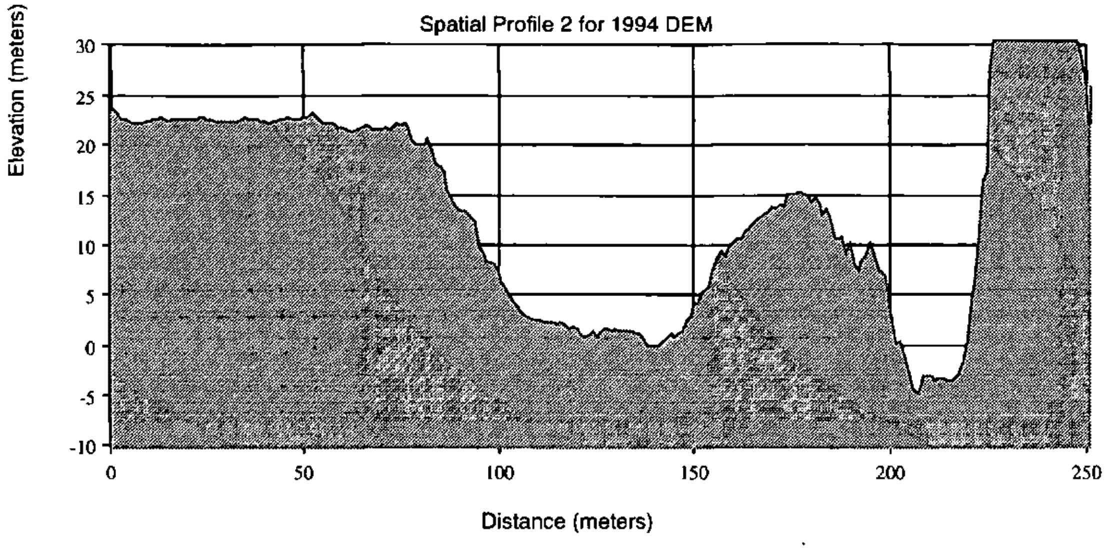


Figure 4.6.2 Profile 2 for the 1994 DEM

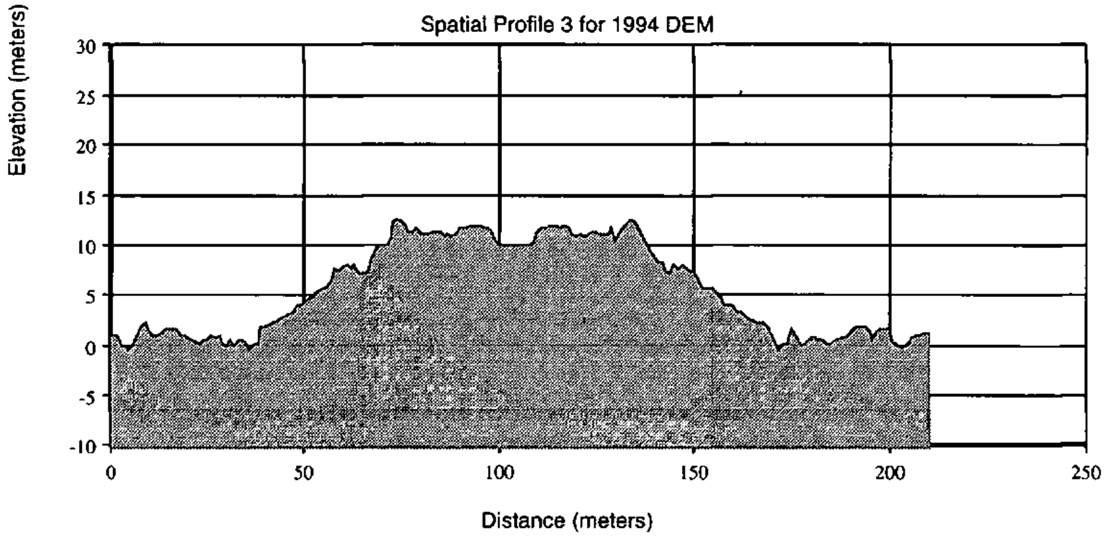


Figure 4.6.3 Profile 3 for the 1994 DEM

Figure 4.6.4 and 4.6.5 show profile 1 for the DEMs of 1996 and 1997 respectively. It can be seen that the top of the cliffs appear to have moved eastwards from around 90 meters in the 1996 profile to around 80 meters in the 1997 profile, and by 1997 the cliffs also appear to have dropped around 4 meters. This is unlikely to have happened in reality. The 1997 cliff does appear to have become steeper than in 1996, and it is possible to observe a change in the beach slope from 1996 to 1997. The peak at the far right on figure 4.6.4 is probably due to the profile reaching the sea.

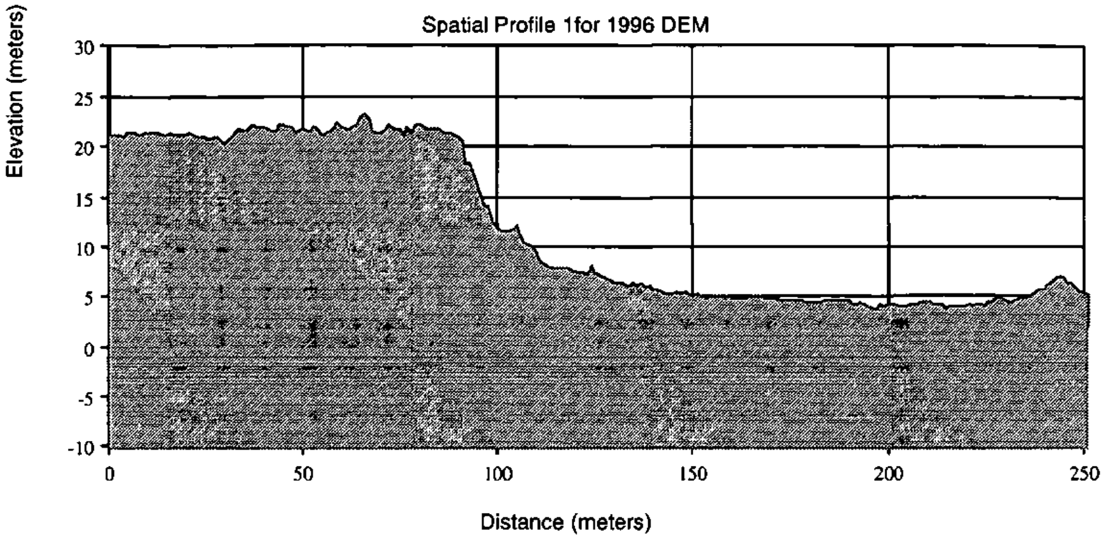


Figure 4.6.4 Profile 1 for the 1996 DEM

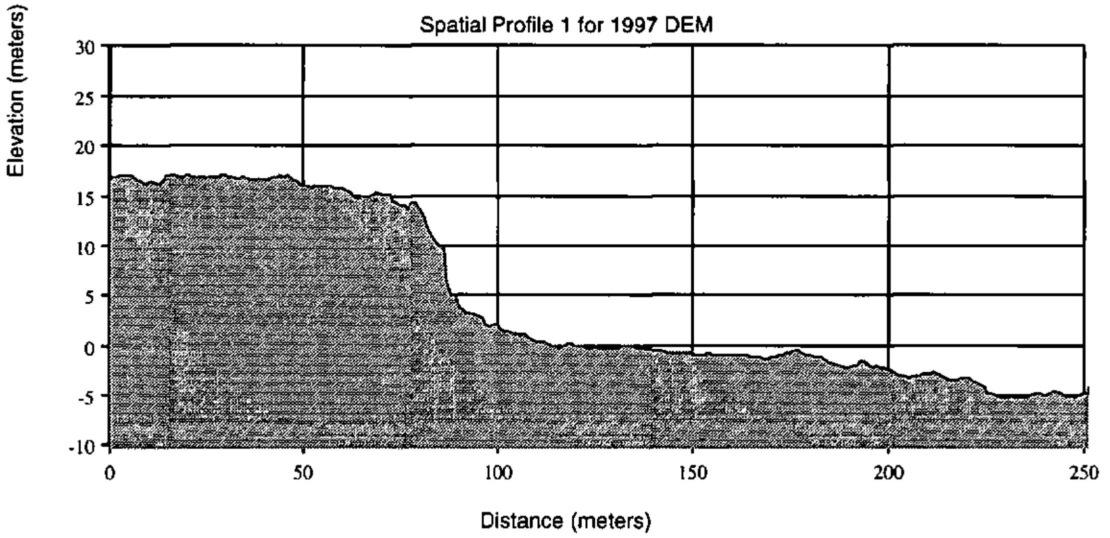


Figure 4.6.5 Profile 1 for the 1997 DEM

Figures 4.6.6 and 4.6.7 show profile 2 for the years 1996 and 1997 respectively. From the comparison of the two profiles it would appear that the 1996 cliff was considerably steeper than the 1997 cliff and the base of the 1997 cliff has been infilled to a large extent. This infilling could be partly due to a landslide, however it is more likely at the scale involved to be due to the inaccuracies of the DEM. The cliff top has also receded in the 1997 profile by several meters. Unfortunately if the DEM from the 1994 data is also considered the cliff has accreted between 1994 and 1996, by approximately 10 meters.

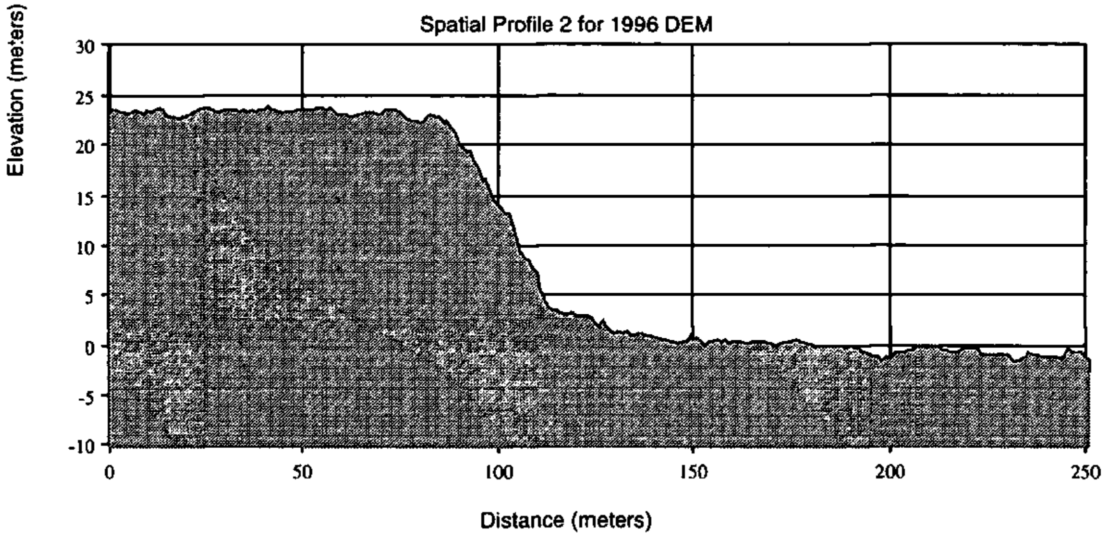


Figure 4.6.6 Profile 2 for the 1996 DEM

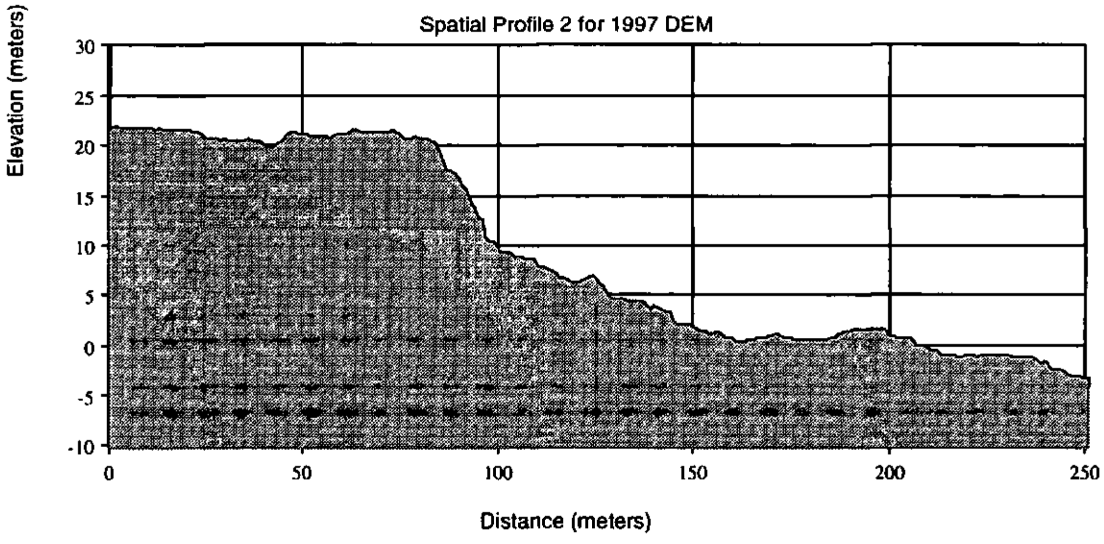


Figure 4.6.7 Profile 2 for the 1997 DEM

Figures 4.6.8 and 4.6.9 show profile 3 for the years 1996 and 1997, respectively. Apart from the dip in the beach of figure 4.6.8, both the profiles appear to be compatible for comparison. The cliff heights are quite similar, both having a maximum of around 15 meters and the beach levels on both the figures also have corresponding values of approximately 2-3 meters. The cliff top has retreated in figure 4.6.9 by around 8 meters, from the 1996 value. Recession to this extent could only be experienced in specific areas, and not generally along the cliff-line, in light of comparison with other workers rates of recession of 1-4 meters per year (e.g. Valentin, 1954; Steers, 1976).

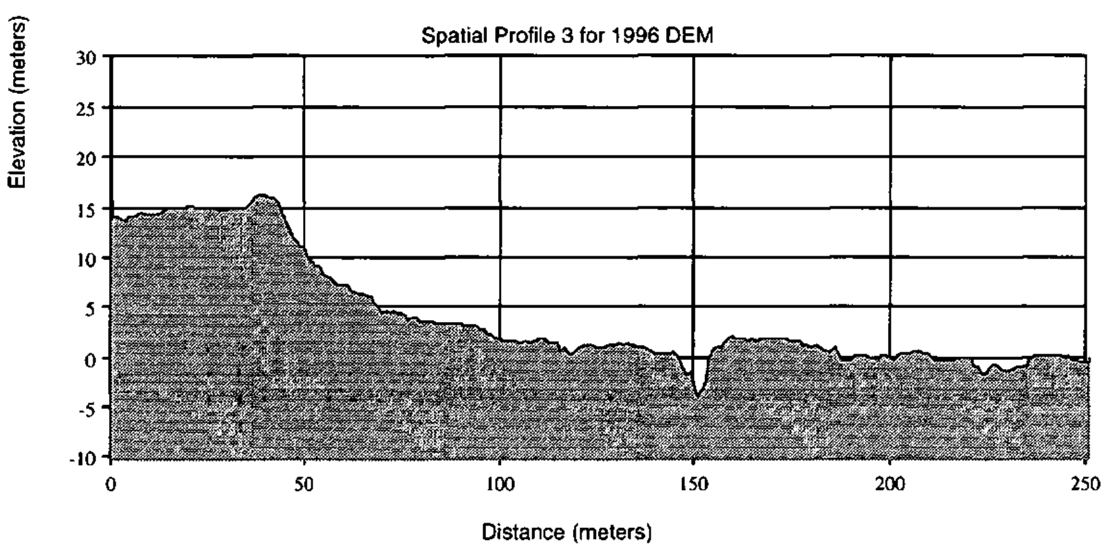


Figure 4.6.8 Profile 3 for the 1996 DEM

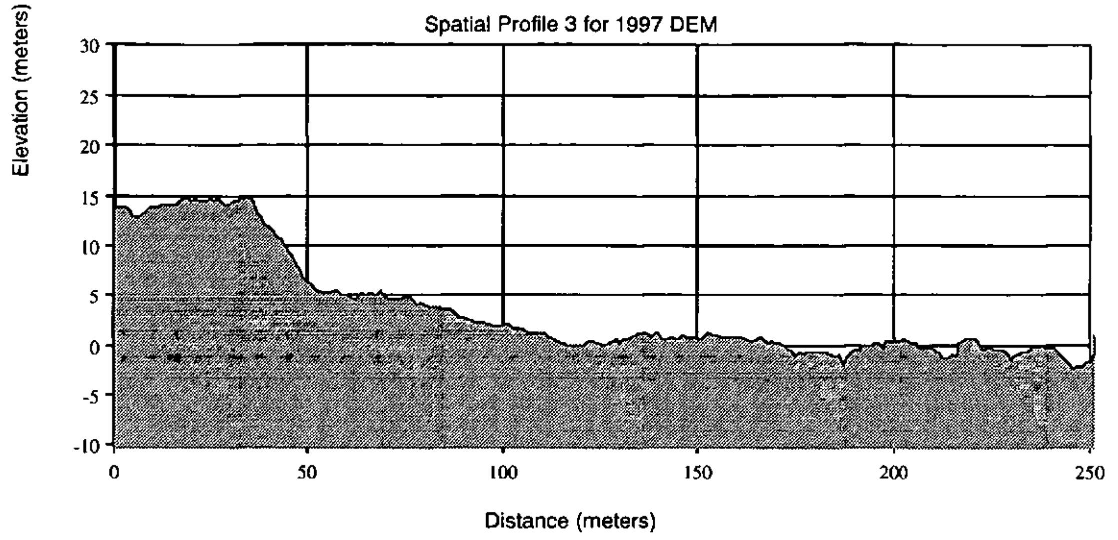


Figure 4.6.9 Profile 3 for the 1997 DEM

The profile results are only to be used as a qualitative guide for the purposes of the discussion, due to their obvious inaccuracies, and because it is not possible to determine an absolute value for the errors involved. It is therefore not possible to calculate an annual rate of cliff recession for this area, and using this data.

5. Discussion

The 1994 images show the cliff as being partly vegetated and also considerably wider than in the subsequent years, these conditions fit with the appearance of a cliff which has not been substantially eroded recently, as described by Pringle (1985). The width of the cliff suggests a gentle, stable gradient, which when compared with the 1996 and 1997 images, where the cliffs are narrower, and therefore presumably steeper, would suggest that this area has not yet been subjected to the increased erosion experienced in the area of an ord.

Between 1994 and 1997, the study ord has moved southwards with the net direction of longshore drift for the Holderness coast and this is apparent from the analysis of the orthoimages as described in the Results, section 4.1. The centre of the ord, as defined by Pringle (1985) as the centre of the exposed till area at or near the base of the cliff, has moved around 700 meters in 33 months. This gives a mean rate of movement of $0.254 kmyr^{-1}$, although the rate varied over this time between $0.13 kmyr^{-1}$and $0.8 kmyr^{-1}$. The mean rate of movement is considerably less than Pringle's value of $0.5 kmyr^{-1}$, but this could be due to a number of factors.

The ords movement is thought to be controlled by wave action, and so requires waves to approach at an angle, which would cause sediment to move toward the south. Scott (1976) records that there are no sandbanks or bars present in the nearshore zone, as the result of an echo-sounding survey and this would suggest the lack of cell circulations in the nearshore zone, such as rips. This is also confirmed by Pringle (1985), who states that rip currents and other cellular flows do not occur off the Holderness coast and it therefore follows that such currents could not be responsible for the longshore movement of the sediment.

Waves must be of a certain height and period in order to suspend and carry sediment, dependent on the size of the material. The medium and fine sand of the lower shore would obviously require lower energy conditions for their movement than the coarse sand and shingle of the upper shore. As the centre of the ord is measured at the base of the cliffs, in the region of the upper shore, it will require high energy conditions to mobilise the sediment in this area and if these conditions have not been available in the form of storm events, the movement of the material will not occur. The storm events must also be from the north, north-east or east, to move the beach sediment to the south.

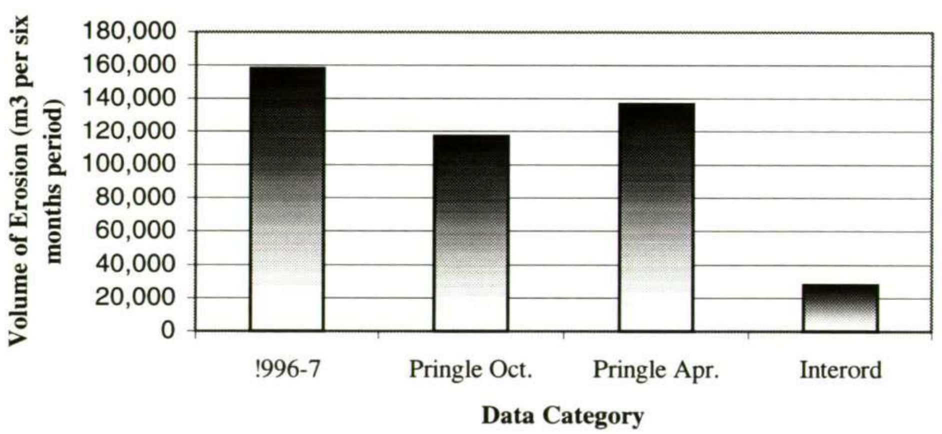
Winkelmolen (1978) observed that the Holderness coast was only usually eroded by storms from the east, and Dossor (1955) noted that winds from the north-east have the longest fetch across the North Sea and were most effective at promoting destructive wave action along this coastline. If such conditions were not prevalent during the winters of 1994 and 1995, it would be likely that the ord would remain almost stationary. If storms did occur but were not from the north or east, the ord would have not moved or moved to the north. This could explain the lack of movement, but it would be necessary to ascertain the position of the ord, between the dates of the images in 1994 and 1996.

If the weather was mild during this time and the area received few storms, it would be expected that the ord would experience some infilling, but this does not appear to be the case, as the 1996 images show the ord to be much more defined after this period. It was not possible to obtain a record of the weather conditions for this period of time and it was not considered within the scope of this study. The acceleration of the movement of the ord, between 1996 and 1997, is not possible to account for without more data, for example, wave statistics or weather reports.

The results of the volume calculations demonstrate that the cliff area as a whole had accreted between 1994 and 1996, by 99,291.6m^3, although this is difficult to justify. It is most likely due to the inclusion of the 1994 data in the calculation, for which the cliff polygon included an erroneous peak of 43.8 meters, which was recorded in the results of the volume command as the Z maximum (see Appendix, section 7). However, the cliff erodes from 1996 to 1997, with the loss of 158,292m^3. This is over a six month period, from October to April, and if the same rate of loss had continued would provide an annual loss of 316,584m^3. This is considerably more than Pringle's mean annual value for cliff volume loss, of 233,916m^3 (October data), or 273,893m^3 (April data), but it is probably because the data obtained here is winter data, and represents a higher figure than would be found for the summer. It is unlikely that the same rate of loss would be experienced over the following six months, as Pringle estimates that 80% of erosion takes place in the winter and only 20% during the summer. The figure of 158,292m^3 is, however, roughly consistent with the values obtained by Pringle for a six month period and is presented for comparison in figure 5.1.

The erosion of the cliff measured in this study equates to Pringle's cliff top erosion study in the area of an ord and so can be compared with the inter-ord data stated in the 1985 paper. Measurements were only taken in October of each year and a mean annual value of 55,634m^3 recorded. This is compared with the data stated here for the cliff top, in figure 5.1. The erosion has been significantly greater in the ord areas, and the data obtained in this study confirms the presence of the ord in the Easington area, due to the much larger value obtained for the cliff erosion than would be recorded in an inter-ord area.

Figure 5.1 Comparison of Pringle's 1985 Data of Cliff Erosion, with Data from This Study



The loss of beach material from the ord area was calculated for the 1996 to 1997 period, at 822,489m^3. Unfortunately, due to the 1994 data inaccuracies it is not possible to compare this figure to other dates. Pringle (1985) states values of the loss of beach sediment due to the presence of the ord, in comparison with the inter-ord beach and presents a mean figure of 157,600m^3, for the whole of one ord. The large value obtained by the volume calculation is difficult to justify, especially because this loss occurred within six months. It could be due to the large area covered by the beach polygon and could also be related to the increased rate of ord movement recorded in the six months. The loss of beach sediment is also visible in the drop in the beach level between the profiles 1 and 3 of 1996 and 1997 (figures 4.6.4, 4.6.5, 4.6.8 and 4.6.9).

Loss of material from the beach is perhaps one of the most important results, because the decrease in the height of the beach is the controlling factor in the erosion of the cliffs. The lowering of the beach level, by the presence of the ord, enables almost all high tides to reach the foot of the cliff, increasing wave attack and so erosion.

It would appear from the data derived from the volume calculations that the winter of 1996 to 1997 produced an extreme change in the ord, both in it's rate of movement and the amount of material which was eroded from the beach. This could be due to extreme weather conditions as previously discussed.

The area in the north, described by the polygon North, eroded during 1994 to 1996 with the loss of 55,690.2m^3 and during this time the area in the middle of the images (the polygon Middle) accreted by 88,207m^3. It is possible that some of the material arriving in the Middle area was derived from the North area, provided by the erosion of the cliff and beach. At the same time the South area also eroded, but by a massive 7,093,841m^3. This could also have supplied the Middle area, particularly because the ord and the sediment could have moved to the north or south during this time. This huge loss of material is probably due to the erosion of the area of cliff observed in figure 4.5.1, the cutfill diagram of 1994 and 1996.

During the 1996 to 1997 period the northern area accreted by 2568.9m^3; this is because the ord has moved southwards by a small amount, allowing accretion to begin in the north, where the beach regains it's usual cross-section, and height. Overall, between 1994 and 1997 the area has eroded due to the presence of the ord for the majority of that time.

The Middle area as stated, accreted between 1994 and 1996, perhaps due to the lack of movement of the ord in this time and the presence of the beach ridge to landward of the exposed till, which may act as a protecting barrier against wave action. This could also be because of the inclusion of the 1994 data. From 1996 to 1997 the area eroded with the loss of 455,240m^3, and this is due to the movement of the ord south, the centre of the ord, where the beach elevation is at it's lowest is now in the area of the Middle polygon. The most extreme rates of erosion will be experienced in this area. Overall, material was eroded, with a volume of 367,033m^3 lost from the area.

The parallel grooves observed in the exposed till areas, especially in the 1996 data (figure 4.2), which run at right angles to the coastline are common erosional features towards low tide level on exposed shore platforms. It has not been possible to measure the grooves in any way, but they are usually of the order of a few tens of centimetres in depth and width. The spacing and orientation are controlled by the lithological structure of the exposed bedrock, such as the presence of joints and similar discontinuities (Hutchinson, 1986).

The discussion has served to highlight an important question posed during the project, which must be how to determine the accuracy and error involved in each process. The software provides some estimate of the error in the triangulation process, where the results of each iteration can be viewed, and the end result of the computed heights of the Ground Control Points compared with the actual heights as surveyed. Beyond this it is unable to quantify the accuracy of the process. Once the DEM collection has been performed it is possible to view the Raster Results, which represents the elevations as a greyscale image and by examination of these it is possible to ascertain if any extreme peaks are present. After remeasuring all Ground Control Points and deselecting any points which have an adverse effect on the elevations computed, it is not possible to increase the accuracy, except by the inclusion of more GCPs. Unfortunately, this was not possible due to their unavailability.

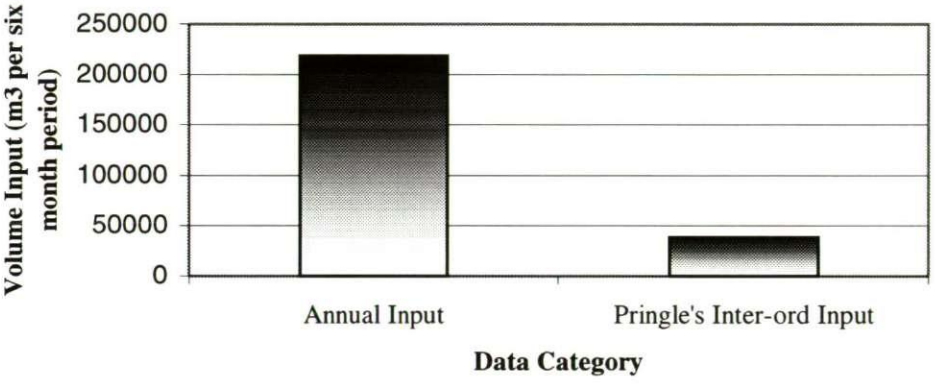
The accuracy can be increased by the availability and use of more suitable aerial photographs, rendering it unnecessary to use photographs acquired at the wrong tidal state. In order to obtain more comprehensive results, including a rate of cliff recession, more photographs over a longer timescale should be used. Cliff retreat is an intermittent process, and it is only over longer timescales that more general patterns emerge (Cambers, 1975). Recession rates measured over short periods of time are not generally as reliable as those calculated over longer periods (Dick & Zeman, 1983). Modern aerial photographs could be combined with historical data, including archival aerial photographs, as well as maps and charts.

In order to obtain more reliable information for the short-time period studied here, and to be able to determine the summer and winter differences in erosion, it would be necessary again to use more photographs acquired at times between the datasets used here.

The results as discussed have shown that the study ord has increased the erosion of the cliff, as compared with the inter-ord area researched by Pringle (1985). The ord has moved south at a rate comparable to that of Pringle's example ord and there appears to have been some form of recovery of the cliff, with a decreased erosion rate, to the north. The volume of the sediment input to the North Sea can be estimated from the eroded volume from the cliff between 1994 and 1997. Sand and coarser sediments make up on average 31% of the total cliff material (Pringle, 1985), and such coarse material is thought to remain on the beach, while the finer silts and clays are suspended by wave action and removed from the intertidal area. It has been calculated that the volume lost from the cliff between 1996 and 1997 is 158292.0m^3, and following the typical breakdown of sediments, 69% must represent the fine fraction. This would mean that over this six month period 109,221.5m^3 of material entered the North Sea, from the Easington area, most of which is a result of the presence of the ord.

This gives an annual input of 218,443.0m^3 from the area of the ord, approximately 1700 meters in length. This has been compared with the value for the inter-ord areas, calculated from Pringle's data, which has a mean annual cliff erosion of 55,634m^3, and an input to the North Sea of 38,387.5m^3, in figure 5.2. The sediment input to the North Sea due to the presence of the ord is substantially greater than from the inter-ord area. It can be seen that the presence of the ord has significant impact on the erosion of the cliffs and the sediment budget of the North Sea. The fine sediment from the Holderness coast is known to move in an anti-clockwise direction around the Southern North Sea, where it accretes on the coasts of Belgium and The Netherlands (Moffat, 1995), where at present in some places, such as the Wadden Sea, the rise in sea level is being matched by the rise in the level of nearshore areas (de Ronde, 1994). A decrease in the fine sediment input to the North Sea, caused by the construction of protection and defence works will affect these areas long term.

Figure 5.2 Comparison of Pringle's Inter-ord Data with Data from This Study, of Input of Fine Sediment to the North Sea



Ords causes the increase in erosion by lowering the beach level, and the present rise in sea level will increase the elevation of the water at the coast. The increase in the water level was quoted by Valentin (1954), who stated that "recorded rates of erosion are consistent to a relationship with the height of the sea surface" and the erosion was faster where the sea level was higher. A continued rise in sea level will hence increase the rate of erosion of the Holderness coastline, due to extended access to the base of the cliffs at more states of the tide.

6. Conclusions

This study of the ord present to the north of the village of Easington, on the Holderness coast, has confirmed that the ord does cause enhanced erosion of the cliffs. This creates an increased input of fine sediment to the North Sea, reinforcing this piece of coastline as one of the major sources. The measurements of volumes and rates reached within this study have also been found to be in agreement with those figures quoted by Pringle (1985), who first defined the 'ord' and confirmed its presence on the Holderness coast.

At present the residents of Easington and other similarly threatened villages, are campaigning for the coast adjacent to their homes to be defended, and plans for the protection of the B.P. Gas Terminal are set to go ahead in the near future. If more areas of the Holderness coast are protected, preventing erosion, it would remove, or seriously deplete the main source of beach material to the area, as well as to the North Sea. Waves would increasingly remove the foreshore during destructive storm events, and undermine any defensive works in place. The best option for the future of the area would appear to be to allow the erosion to continue, especially in areas of low commercial value and this has been recommended by various workers, including J. Pethick (Pearce, 1993), acting as an advisor to the Holderness Borough Council. This strategy would also benefit the coasts of several low-lying countries around the Southern North Sea, by continuing their supply of fine material.

The study begun here could be continued with the use of more aerial photographs, covering a longer timescale in order to assess the net changes over time which the ord has on the cliffs. In order to assess more fully the variability of the ord system, it would be appropriate to utilise photographs acquired within the 1994 to 1996 period. This is a considerable length of time over which to assess the changes in a transient feature and only the net change could be reviewed here. The analysis of the stereo aerial photographs could be combined with accurate wave data, making it possible to quantify the effects of storm events and moderate wave events on the height and movement of the ord.

All data obtained from the study of the ord and relating to the erosional characteristics of the Holderness region could be utilised within an Integrated Coastal Zone Management system. Integrated Coastal Management is becoming increasingly important, especially in areas such as this where there are huge conflicts of interest to be resolved. This approach incorporates the social, environmental, economic and legal aspects of the coastal zone (Moore *et al.*, 1997), and is particularly suited to the Holderness situation, where attention must be paid to all the factors involved, before a solution can be reached.

7. Appendix

POLYNORTH

CUTFILL:
1994 and 1996

Cut Vol.	199085.128
Fill Vol.	597128.267
Balance Vol.	-398043.140
Cut area	27125.0
Fill area	64251.0
Graded area	91376.0
Not graded	0.0
Total area	91376.0

CUTFILL:
1994 and 1997

Cut Vol.	202422.306
Fill Vol.	604659.066
Balance Vol.	-402236.760
Cut area	34109.0
Fill area	57267.0
Graded area	91376.0
Not graded	0.0
Total area	91376.0

CUTFILL:
1996 and 1997

Cut Vol.	95046.756
Fill Vol.	99240.376
Balance Vol.	-4193.620
Cut area	48357.0
Fill area	43019.0
Graded area	91376.0
Not graded	0.0
Total area	91376.0

VOLUME

The base value for all Volume calculations was -5m.
Z values in m, area values in m^2, and volume in m^3.

1994 TIN

Z max	55.028
Z min	-78.224
Area	91314.156
Volume	981503.937

1996 TIN

Z max	27.986
Z min	-4.515
Area	91314.156
Volume	925813.75

1997 TIN

Z max	27.244
Z min	-5.402
Area	91314.156
Volume	928382.625

POLYMIDDLE

CUTFILL:
1994 and 1996

Cut Vol.	294903.797
Fill Vol.	929251.396
Balance Vol.	-634347.599
Cut area	25879.0
Fill area	75248.0
Graded area	101127.0
Not graded	0.0
Total area	101127.0

CUTFILL:
1994 and 1997

Cut Vol.	500793.26
Fill Vol.	679297.498
Balance Vol.	-178504.238
Cut area	64370.0
Fill area	36757.0
Graded area	101127.0
Not graded	0.0
Total area	101127.0

CUTFILL:
1996 and 1997

Cut Vol.	457609.916
Fill Vol.	1766.555
Balance Vol.	455843.361
Cut area	97192.0
Fill area	3935.0
Graded area	101127.0
Not graded	0.0
Total area	101127.0

VOLUME

All values in m.

1994 TIN

Z max	86.033
Z min	-154.283
Area	101136.539
Volume	1168939.000

1996 TIN

Z max	24.286
Z min	-0.507
Area	101136.539
Volume	1257146.0

1997 TIN

Z max	21.496
Z min	-8.579
Area	101136.539
Volume	801906.187

POLYSOUTH

CUTFILL:
1994 and 1996

Cut Vol.	7209577.087
Fill Vol.	273494.828
Balance Vol.	6936082.26
Cut area	60345.0
Fill area	18178.0
Graded area	78523.0
Not graded	0.0
Total area	78523.0

CUTFILL:
1994 and 1997

Cut Vol.	7272342.079
Fill Vol.	266404.767
Balance Vol.	7005937.312
Cut area	62205.0
Fill area	16318.0
Graded area	78523.0
Not graded	0.0
Total area	78523.0

VOLUME

All values in m.

1994 TIN

Z max	315.421
Z min	-151.668
Area	115425.484
Volume	8120635.500

1996 TIN

Z max	21.312
Z min	-27.399
Area	115425.484
Volume	1026794.563

POLYCLIFF

CUTFILL:
1994 and 1996

Cut Vol.	41819.879
Fill Vol.	149080.345
Balance Vol.	-107260.465
Cut area	6478.0
Fill area	41050.0
Graded area	47528.0
Not graded	0.0
Total area	47528.0

CUTFILL:
1994 and 1997

Cut Vol.	85760.725
Fill Vol.	47561.231
Balance Vol.	38199.494
Cut area	26571.0
Fill area	20957.0
Graded area	47528.0
Not graded	0.0
Total area	47528.0

CUTFILL:
1996 and 1997

Cut Vol.	163983.368
Fill Vol.	18523.409
Balance Vol.	145459.959
Cut area	41557.0
Fill area	5971.0
Graded area	47528.0
Not graded	0.0
Total area	47528.0

VOLUME

All values in m.

1994 TIN

Z max	43.754
Z min	-4.136
Area	47520.281
Volume	971348.125

1996 TIN

Z max	26.781
Z min	0.139
Area	47520.281
Volume	1070639.750

1997 TIN

Z max	25.765
Z min	-0.292
Area	47520.281
Volume	912347.265

POLYBEACH

CUTFILL:
1996 and 1997

Cut Vol.	968122.081
Fill Vol.	147885.511
Balance Vol.	820236.57
Cut area	195224.0
Fill area	88979.0
Graded area	284203.0
Not graded	0.0
Total area	284203.0

VOLUME:
1996 TIN

Z max	104.179
Z min	-27.399
Area	284225.0
Volume	2433925.0

1997 TIN

Z max	11.787
Z min	-31.03
Area	284225.0
Volume	1611436.125

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