PRELIMINARY INVESTIGATION INTO MONITORING COASTAL EROSION USING TERRESTRIAL LASER SCANNING: CASE STUDY AT HAPPISBURGH, NORFOLK

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ABSTRACT

The methodology and findings of the application of terrestrial laser scanning to monitor coastal erosion are discussed and put into the wider context of coastal erosion and geology. A terrestrial laser has been used in conjunction with a highly accurate differential Global Positioning System (dGPS) to orient the laser survey and obtain point data of cliff and beach surfaces. These data are captured annually to enable the modelling of cliff retreat over time. The conceptual model generated from this research on cliffs south of Happisburgh, Norfolk, are described to illustrate the value of the methodology. Rates of cliff retreat and volume loss have been calculated and an erosion model for Happisburgh has been developed.

INTRODUCTION

On the soft sediment coasts of eastern and southern England, the problem of coastal erosion is an increasingly important issue. This is due to apparent increase in observed rates of rapid coastal change, the heightened public awareness of sea level rise and climate change, and the perceived threat to the existing buildings on, and increased development of the coastal zone.

Coastal erosion is a serious issue for many coastal communities. The consequences to life, assets and the environment can be enormous - especially as owners do not usually receive any form of compensation for the loss of their homes and livelihoods. It is, therefore, important that cliff retreat is measured accurately so that people can plan for life and work in this dynamic environment.

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The ongoing Slope Dynamics project at the British Geological Survey (BGS) aims to address some of these issues. In this project the influence of geology, geotechnics and climate change on the process of cliff recession is being assessed at twelve test sites around the 'soft rock' coasts of England specifically in Dorset, Kent, Sussex, Norfolk and North Yorkshire (Table 1). These test sites were selected to satisfy the following criteria: (1) natural slopes with little or no engineering remediation, coastal protection or occupation (although some of the sites are affected by adjacent sea defences, or have been defended in the past but have not been maintained, or have failed, e.g. Happisburgh); (2) soft rock geology (clay, chalk etc.) typical of the coastal unit and the geological materials involved; (3) variety of cliff heights; (4) variety of coastal aspects; (5) variety of landslide mechanisms and complexity; (6) variety of geological complexity; (7) likelihood of active landslide movement and recession; (8) reasonable access to the site; and (9) availability of data.

Each studied site comprises approximately 200 to 500 m of coast and contains one or more landslide features. Many of the sites are situated within an area of classic coastal landslides and have a considerable legacy of research, photography, and analysis over several decades (Lee & Clark, 2002).

METHODOLOGY

The coastal sections are surveyed using a variety of remote methods, accompanied by geological mapping and geotechnical probing, sampling, and testing. The principal methods of surveying the cliffs are long-range terrestrial laser scanning, and terrestrial photogrammetry. Surveys are carried out at all the sites annually and the results are processed to provide data for models of coastal recession. The data collected in the field by laser scanning and GPS are entered into a modelling package (GoCad 2.1.3). The resulting computer model enables volume calculations and observations to be made as to the way in which the coast is eroding.

LONG RANGE TERRESTRIAL LASER SCANNING

Laser scanning has been used for a variety of applications such as the monitoring of volcanoes (Hunter *et al*., 2003), earthquake and mining subsidence, quarrying, buildings, forensics (Paul & Iwan, 2001; Hiatt, 2002) and terrestrial- (Rowlands *et al*., 2003) and coastal- (Hobbs *et al*., 2002) landslide modelling.

The Riegl LPM2K terrestrial laser (Fig. 1a) records accurate data for 3D modelling. It has a long- range capability of up to 2 km and a best achievable range finding resolution of around 25 mm. The relative distance, elevation angle and asimuthal angle between the laser and the cliff face are measured semi-automatically in each scan (Fig. 1b) and, once processed, a 3-D surface model can be generated. Multiple scans taken from different aspects (for instance from the beach and cliff top) at the same site are carried out in order to minimise ‘shadows’ (i.e. areas invisible to the laser). These are later combined in the software so that these shadow areas are minimised and a more accurate and complete 3D image is recorded. For multiple scans, it is important to have at least three common points in each scan to assist with orientation.

Irresolvable shadow areas are surveyed using a roving Global Positioning System (GPS) unit and the point data are added to the 3-D model. Analyses of repeated scans over a regular time interval can accurately determine the rate of recession, the nature of landslide processes and any other morphological changes in the cliff face and beach.

In addition, laser measurements of targets are carried out at some sites in order to track movements of particular landslide features. The key factor in the successful use of long-range laser scanning is the accurate horizontal and vertical position of the instrument and at least one other point (any positional errors are magnified with distance). In most cases, this is achieved with a high quality GPS, which is essential if the 3-D model produced, is to be oriented to national grid co-ordinates and when coastal changes are to be monitored. The laser scanner is not effective where the subject is moving (e.g. water, vegetation), or where the laser is reflected by heavy rain. However, low light level does not present a problem to laser scanning, as it does with photography.

TERRESTRIAL PHOTOGRAMMETRY

Stereo-vertical aerial photography, oblique aerial photography and terrestrial photography have been obtained for geological and geomorphological study and to record individual landslide events more accurately than is possible from topographic maps alone. Such terrestrial photogrammetry is used to back-up the laser scan and to fill-in geomorphological detail if scanning is not possible. The methodology involves overlapping several photographs of the cliff from different aspects and combining them in software to produce 3-D models, panoramic images, and reference images to help interpret the scanning. Calibrated terrestrial and aerial photographs may also be used to ‘drape’ the 3-D model obtained from laser scanning. A metric digital camera mounted

Table 1. The Slope Dynamics Project locations, geology and physiology.

Location	**Geology**	**Physiology**
Happisburgh, Norfolk [TG 38703070]	Till, clays, sands and gravel	Sand beach, rapid erosion rate (formerly defended)
Sidestrand, Norfolk [TG 26603970]	Till, clays, sands and gravel	Large landslide complex, sand beach (undefended)
Weybourne, Norfolk [TG 11204360]	Clays, sands and chalk	Cobble beach, low recession rates, (undefended)
Warden Point, Isle of Sheppey, Kent [TR 01907250]	London Clay	Landslide complex, clay platform (undefended)
Folkestone Warren, Kent [TR 25803840]	Chalk, Gault Clay	Large landslide complex, researching part of the backscarp (partially defended)
Beachy Head Lighthouse, Sussex [TV 58609520]	Upper Chalk	Chalk cliffs and platform subject to undercutting and collapse, chalk debris aprons (undefended)
Aldbrough, Holderness, Yorkshire [TA 25803960]	Till	Slumps and toppling blocks, different till sheets (lithology and geotechnical properties) (undefended)
Speeton Sands, North Yorkshire [TA 14507600]	Speeton Clay, Kimmeridge Clay and till	Slumps and mudflows complex, sand beach (undefended)
Robin Hood’s Bay, North Yorkshire [NZ 95300450]	Lias, till	Slumps and mudflows and Lias platform, narrow shingle/sand beach (defences adjacent)
Black Ven, Lyme Regis, Dorset [SY 35409309]	Lias, Gault Clay, Upper Greensand	Large benched landslide complex, mudflows, slumps (undefended)
Stonebarrow Hill (Cain’s Folly), Dorset [SY 37909285]	Lias, Gault Clay, Upper Greensand	Slumps, mudflows in upper part (undefended)
Ware Cliff, Dorset [SY 32909122]	Lias, Gault Clay, Upper Greensand	Slipping along Upper Green Sand (defences adjacent)

on top of the laser permits accurate, calibrated images to be produced and draped over the 3-D image while working in the field.

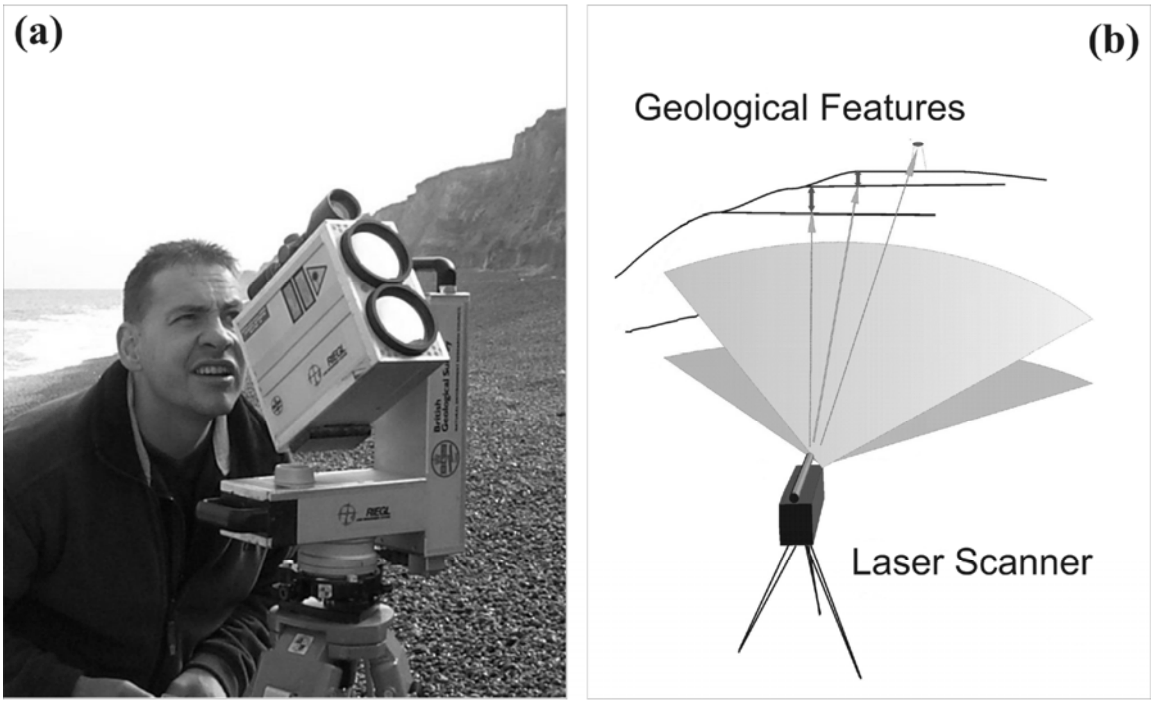

Fig. 1. (a) The Riegl LPM2 K long-range laser scanner © NERC. (b) Schematic diagram to show the laser scan with location of individual points.

ANALYSIS OF COASTAL RECESSION

On fast-retreating coasts it is important to appreciate more than just the position of the cliff face. The entire system of coastal erosion is highly complex and several aspects must be considered. These include the onshore environment, the offshore environment, the weather and climate, the strength and variability of the geological materials making up the coast and the influence of engineered structures such as groynes and sea walls.

Understanding the influence that the offshore environment has on coastal erosion is essential when attempting to accurately model future recession rates. This includes oceanographic climate, wave energy and wave direction, the distribution of sediments moved by wave action and changing sea level. One of the critical factors affecting the rate of erosion is determined by the transport of sediments away from their source – that is, from either the cliffs themselves or from the foreshore, to eventual sediment sinks. Measuring this is a particularly difficult task, especially as coarse materials, such as gravels, may remain in local beach systems, whilst finer materials, such as clays and silts, are readily transported offshore and may end-up being deposited on coasts on the other side of the North Sea (Shennan *et al.*, 2003).

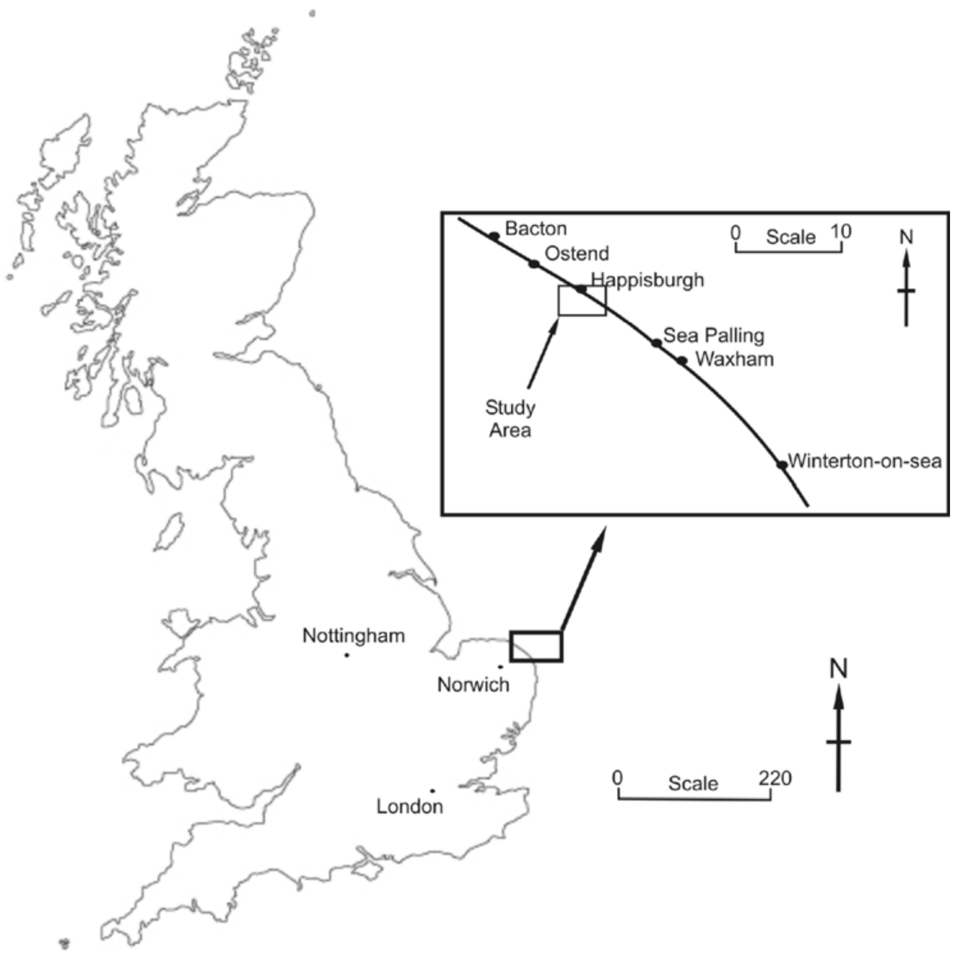

Fig. 2. The East Anglian coastline and study location.

Sea-level rise and climate change are influential factors associated with increased coastal erosion. Current estimates of the relative sea-level rise in eastern England in the 2080s, taking into account isostatic change and different fuel emission scenarios, ranges from 22 cm (assuming a 9 cm global rise with low fuel emissions) to 80 cm (assuming a 69 cm global rise with high emissions) (Hulme *et al*., 2002).

CASE STUDY – THE EROSION RATE AT HAPPISBURGH

It is likely that the Norfolk cliffs have been eroding at the present rate for the last 5000 years when sea level rose to within a metre or two of its present position (Clayton, 1989). Therefore, the future predictions of sea level rise and storm frequency due to global warming are likely to have a profound impact on coastal erosion and serious consequences for the effectiveness of coastal protection and sea defence schemes in East Anglia in the near future (Thomalla & Vincent, 2003). One of the twelve test sites of the

Slope Dynamics project includes a section of cliffs adjacent to the village of Happisburgh [NGR TG38003100] on Norfolk's North Sea coast, approximately 25 km northeast of Norwich (Fig. 2). Agriculture and tourism contribute significantly to the economy of the village and surrounding hinterland although this is threatened by the receding cliff line that, prior to the construction of a rock bund at the northern end of the survey site, has claimed at least one property per year plus significant quantities of agricultural land (Fig. 3). A section of coast further north of the study location is a designated Site of Special Scientific Interest (SSSI; Fig. 4).

THE GEOLOGY AND PALAEOENVIRONMENTAL CONTEXT OF THE SITE

The cliffs at Happisburgh range in height from 6 to 10 m and are composed of a layer-cake sequence of several tills, separated by beds of stratified silt, clay and sand (Hart, 1987; Lunkka, 1988; Hart, 1999; Lee, 2003). The basal unit within the stratigraphic succession at Happisburgh is the How Hill Member of the Wroxham Crag Formation. These deposits are typically buried beneath modern beach material but are periodically exposed following storms (Fig. 5). They consist of stratified brown sands and clays with occasional quartzose-rich gravel seams that are interpreted as inter-tidal/shallow marine in origin.

Unconformably overlying these marine deposits are a series of glacial lithologies deposited during several advances of glacier ice into the region during the Middle Pleistocene (c.780 to 430 ka BP) (Lee *et al.*, 2002; Lee *et al.*, 2004). The site investigated for the purpose of this study, is located adjacent to Beach Road (Fig. 3; NGR TG38573084) where a tripartite geological succession can be observed. The Happisburgh Till Member, crops-out at the base of the cliffs and its base is frequently obscured by modern beach material: it has a maximum thickness of 3 m. The Happisburgh Till Member is a dark grey, highly consolidated till with a matrix composed of a largely massive clayey sand with rare (<1%) pebbles of local and far-travelled material. The upper surface of the till undulates and comprises a series of ridges and troughs upon which the overlying Ostend Clay member outcrops. This unit is between 2.3 and 3.4 m thick and consists of thinly-laminated light grey silts and dark grey clays. In turn, these beds are overlain by 2 to 4 m, of weak, stratified sand (Happisburgh Sand Member) with occasional silty-clay horizons.

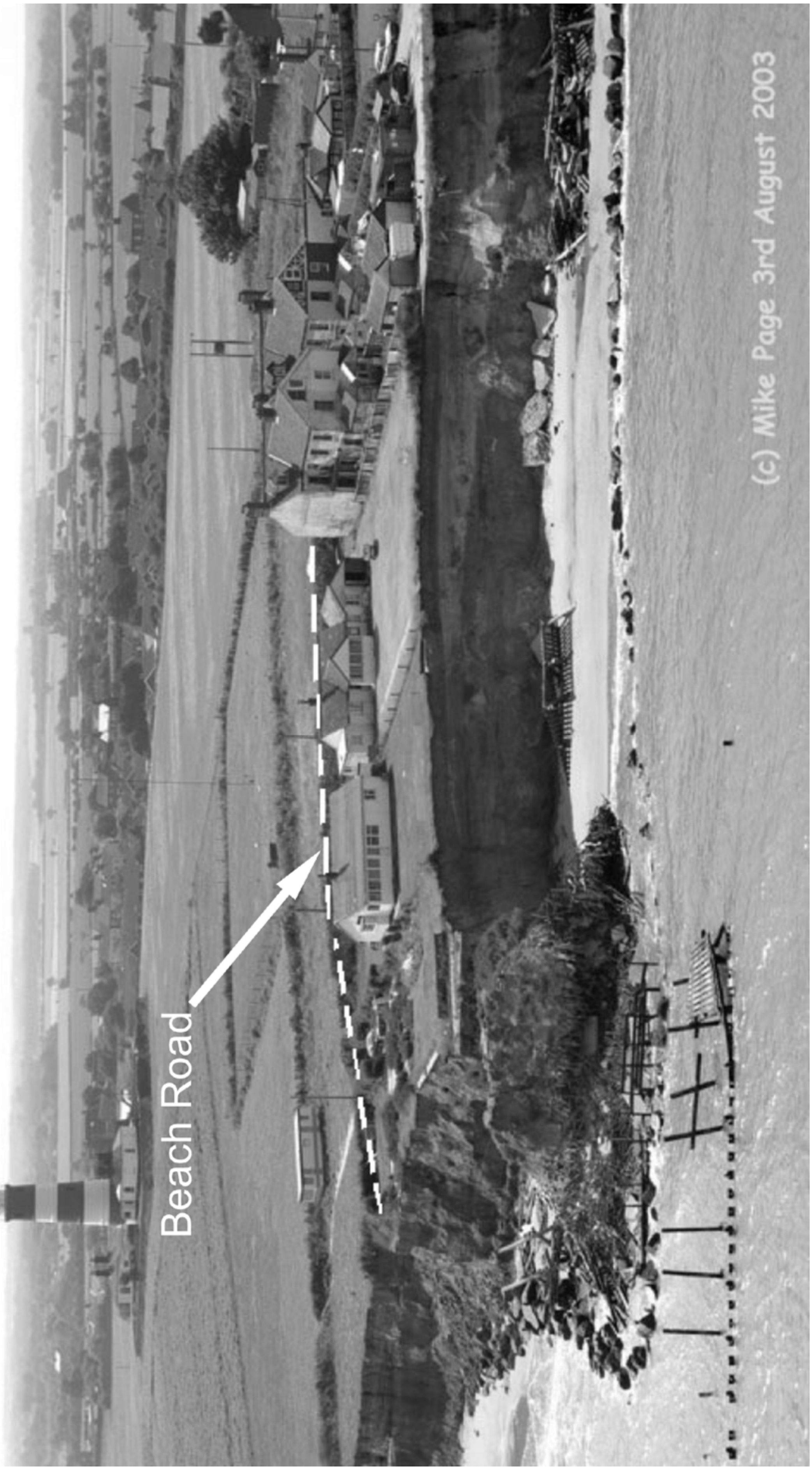

Fig. 3. Aerial view of the southern end of Happisburgh in 2003 showing the location of Beach Road, facing southwest. Photograph courtesy of Mike Page, Skyview.

Fig. 4. Aerial photograph at Happisburgh taken in 2003, facing north, showing the point where the sea defences have failed and been removed. This sea defence line was once continuous. Also marked is the "Happisburgh Cliffs SSSI" and the study area. Photograph courtesy of Mike Page, Skyview.

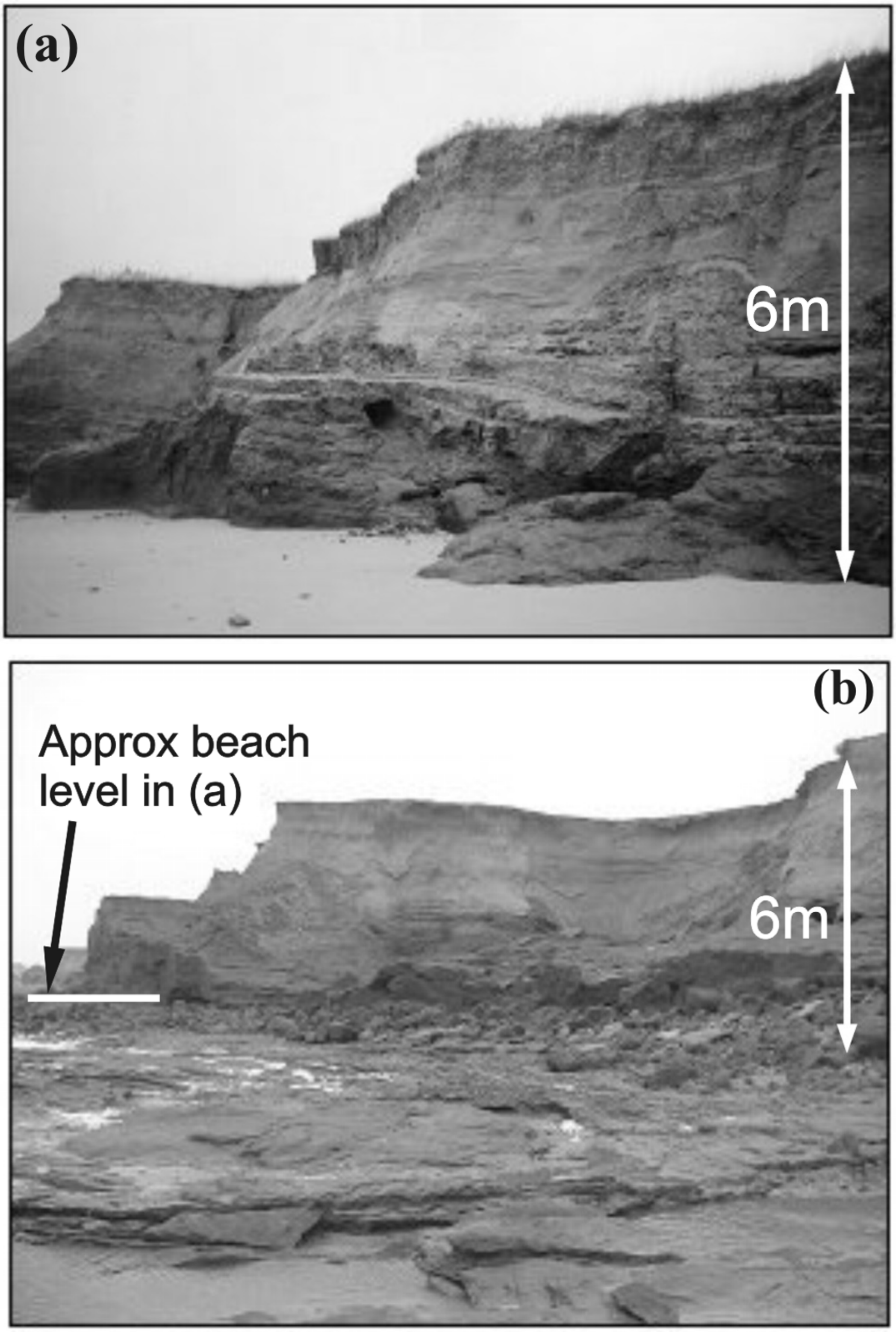

Fig. 5. (a) Cliffs at Happisburgh in September 2003. P. Hobbs © NERC. (b) Cliffs at Happisburgh after a storm event in December 2003 illustrating the drop in beach level and exposure of the Wroxham Crag Formation and the lower horizons of the Happisburgh Till. Beach lowering can also expose the Wroxham Crag (see also Fig. 9.). J. R. Lee © NERC.

COASTAL EROSION AND SEDIMENT TRANSPORT

The rate at which the Norfolk cliffs are eroding has attracted considerable research. Estimates vary from 0.30 to 0.75 m a^{-1} (a = annum or years) in North Norfolk with an average of 0.9 m a^{-1} for the entire Norfolk coast from 1880 to 1967 (Cambers, 1976; HR Wallingford, 2001, 2002; Thomalla & Vincent, 2003). The Norfolk coast has retreated landward approximately, 1 to 2 km over the past 900 years records, and records such as the Domesday Book (1086) and other historical accounts, demonstrate the presence of villages that have since been lost to the sea (Clayton, 1989).

At Happisburgh, coastal erosion has been an issue for many years. In 1845, rapid coastal retreat was recognised as a threat to St Mary's Church "having an under stratum of sand and gravel, is so continuously wasted by the agitation of the tides and storms, that it is calculated the church will be engulphed in the ocean before the close of the ensuing century, the sea having encroached upwards of 170 yards during the last sixty years" (White, 1845).

This section of coast is relatively linear and faces northeast. As a result, the coastline is exposed to a wide range of wave directions (approximately 300ºN to 90ºN but predominantly 0ºN to 70ºN) and is particularly vulnerable to storms from the north due to the virtually unlimited fetch in this direction (Ohl *et al*., 2003; Thomalla & Vincent, 2003). Various attempts to numerically model the sediment transport regime along the Norfolk coast have shown that the largest waves arrive from approximately 030ºN, the most frequent wave directions come from the northwest (330ºN) and the largest winds are associated with winds from the northwest and the north; therefore, the most erosive and damaging effects are broadly controlled by the sea conditions in the north (Ohl *et al*., 2003).

The active cliff erosive processes in the Happisburgh area involve a repeated cycle of the following three stages (based on Ohl *et al*., 2003):

1. basal undercutting of the intact toe by wave action, leading to steepening of the cliff profile and a reduction in slope stability;
2. cliff failure, involving small-scale shallow slides;
3. deposition of debris at the base of the cliff, protecting the cliff toe;
4. removal of debris from the foreshore by wave action, leading to the onset of basal undercutting (stage 1 above).

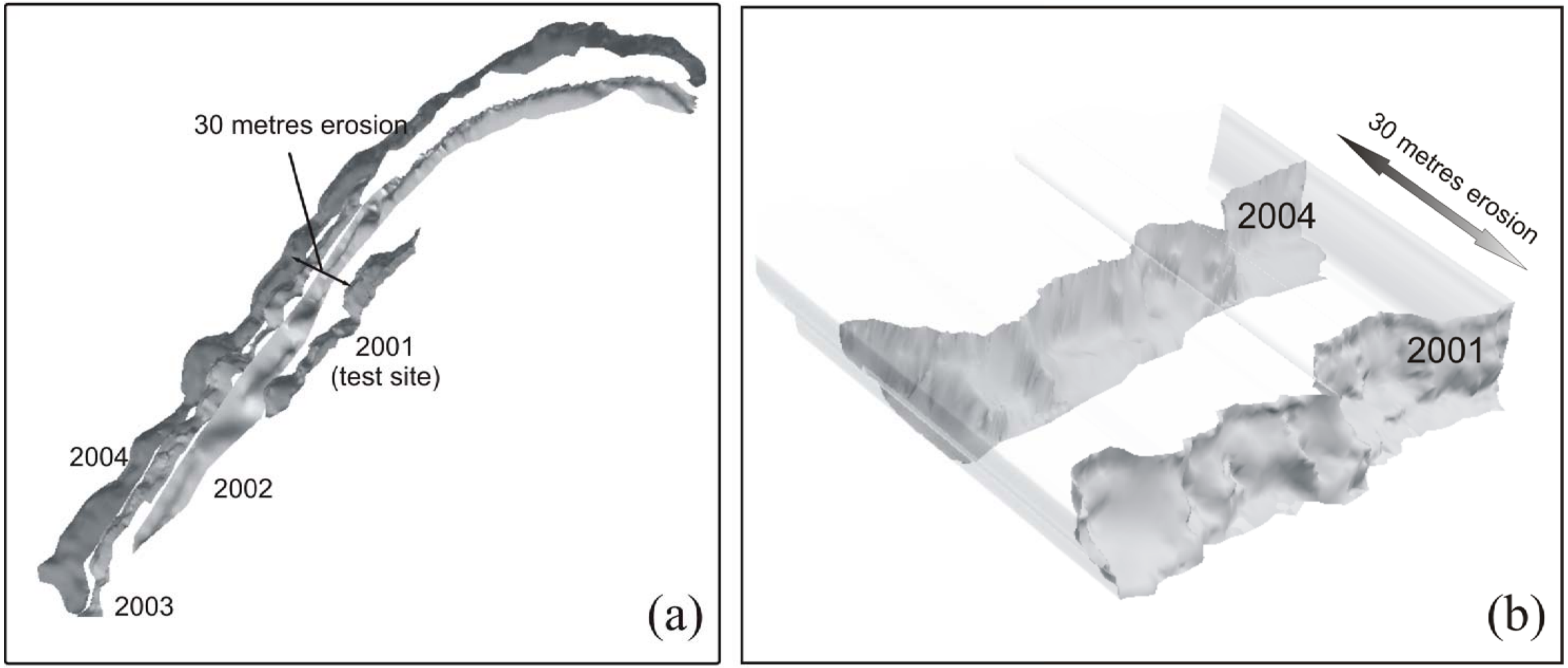

Fig. 6. (a) Four cliff surfaces as recorded by the laser. (b) Diagram showing detail of cliff scans in 2001 and 2004

The process of mechanical erosion of the cliff face by wave action releasing cliff material has also been observed. Ohl *et al*. (2003) highlight the fact that there have been substantial short-term variations in the predicted erosion rates in response to varying weather conditions, variations in glacigenic cliff material, frequency of wave attack on the cliff base and the removal of coastal defences.

The beach levels vary significantly in this area - by up to 2 m in a single storm event (Fig. 5). A study carried out by Halcrow in 1991 identified that the cause of this was due to the oblique incidence of the waves at the coast (Thomalla & Vincent, 2003). Leggett (1993) estimated that over 140,000 m^3 of sediment was lost from the beach and more than 400,000 m^3 were lost from the near-shore area to 500 m offshore between Happisburgh and Winterton between July 1992 and March 1993 (Thomalla *et al*., 2001).

Sediment derived from the erosion of the cliffs between Weybourne and Happisburgh is transported to the northwest and southeast along the beaches by longshore drift, with the dominant transport to the east (Cameron *et al*., 1992). A coarsening of sand grain-size on the beaches in the direction of transport is due the removal of finer-grained sand from the beaches by wave action, followed by the transport into the nearshore zone where the sand is removed by tidal currents (McCave, 1978). Computed net annual transport rates are about 100,000 m^3yr^{-1} to the south (Clayton *et al*., 1983).

Between Weybourne and Winterton Ness, the North Norfolk cliffs supply about 505,000 $m^3\ a^{-1}$ of sand into the littoral zone (HR Wallingford, 2001). The cliff erosion also supplies fines and gravel, the fines being transported offshore in suspension, while the sands and gravel are transported along the shore and also in the offshore area (HR Wallingford, 2002). Between Mundesley and Happisburgh the transport rate is reasonably constant to the southeast along the coastline (HR Wallingford, 2002).

At present, the rivers around the southern North Sea input very little sand. Fluvial erosion rates per unit area in East Anglia are 1–2 t $km^2\ a^{-1}$ (*t* = tonnes) (McCave, 1987); the main input is from coastal cliff erosion.

ANTHROPOGENIC EFFECTS

The construction of coastal defences along the Norfolk coast has significantly affected the rate of cliff recession. The construction and maintenance of coastal defences, mainly timber groynes and revetments, has slowed the cliff recession rates during the past few decades by trapping beach sand travelling along the coast (typically from north-west to

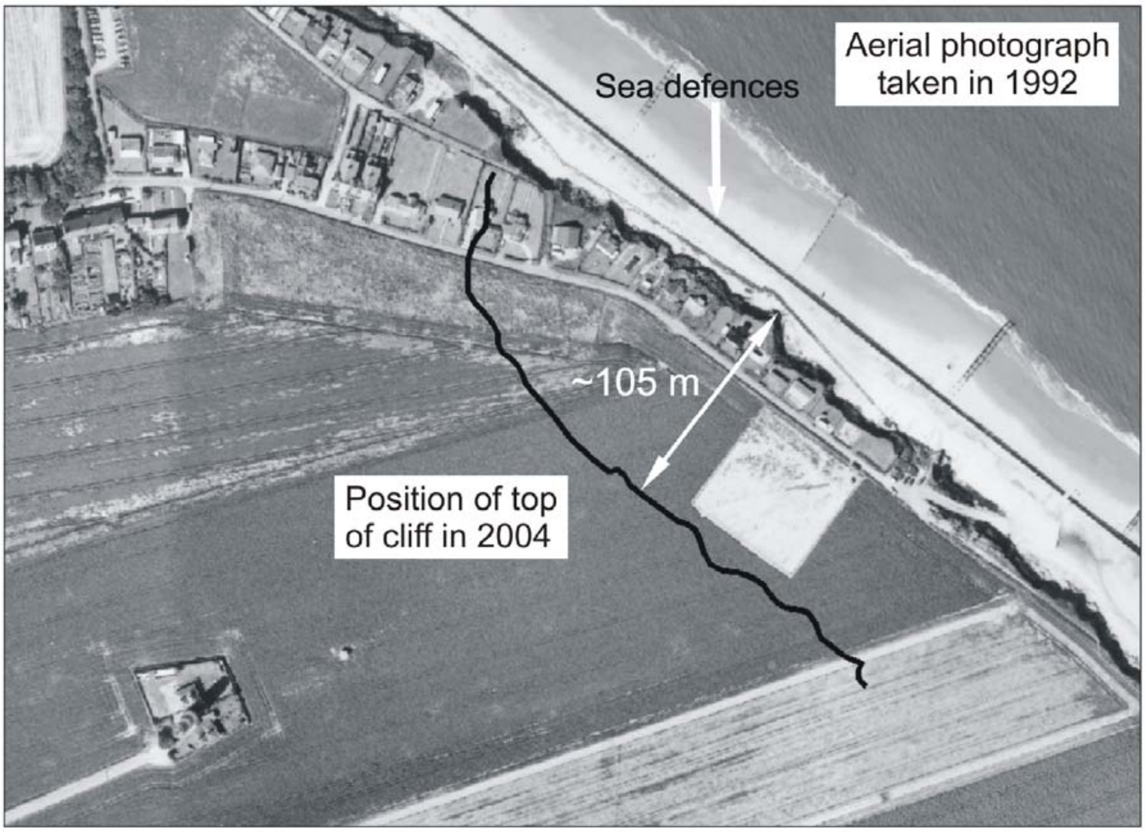

Fig. 7. A 1992 aerial photograph with line showing the location of the cliff line as measured in 2003 by BGS (photograph reproduced with kind permission of the Environment Agency, Anglian Region).

south-east) and reducing the supply of sediment arriving on the beaches down-drift of the defences (Ohl *et al*., 2003). This has, however, caused down drift starvation and a deficit in the sediment budget at undefended sections thereby increasing the cliff recession rate (HR Wallingford, 2001).

The failure and subsequent removal of a large part of the timber palisade defences at Happisburgh in the 1990s, resulted in a 50 m cliff retreat over a 3-year period from 1996 to 1999 (Ohl *et al*., 2003). Fig. 4 shows the point where the sea defences no longer exist at Happisburgh. It is clear from this image that the coastline has eroded significantly where it is no longer defended.

RESULTS OF THE SLOPE DYNAMICS PROJECT AT HAPPISBURGH

The rate of erosion at the Happisburgh test site has so far been monitored in 2001, 2002, 2003, 2004 and 2005 (2005 data yet to be processed) using the laser scan system. Fig. 6a and b show plots from the model illustrating the different surveys. The surveys have shown that where the defences have failed and been removed, and where the cliffs are

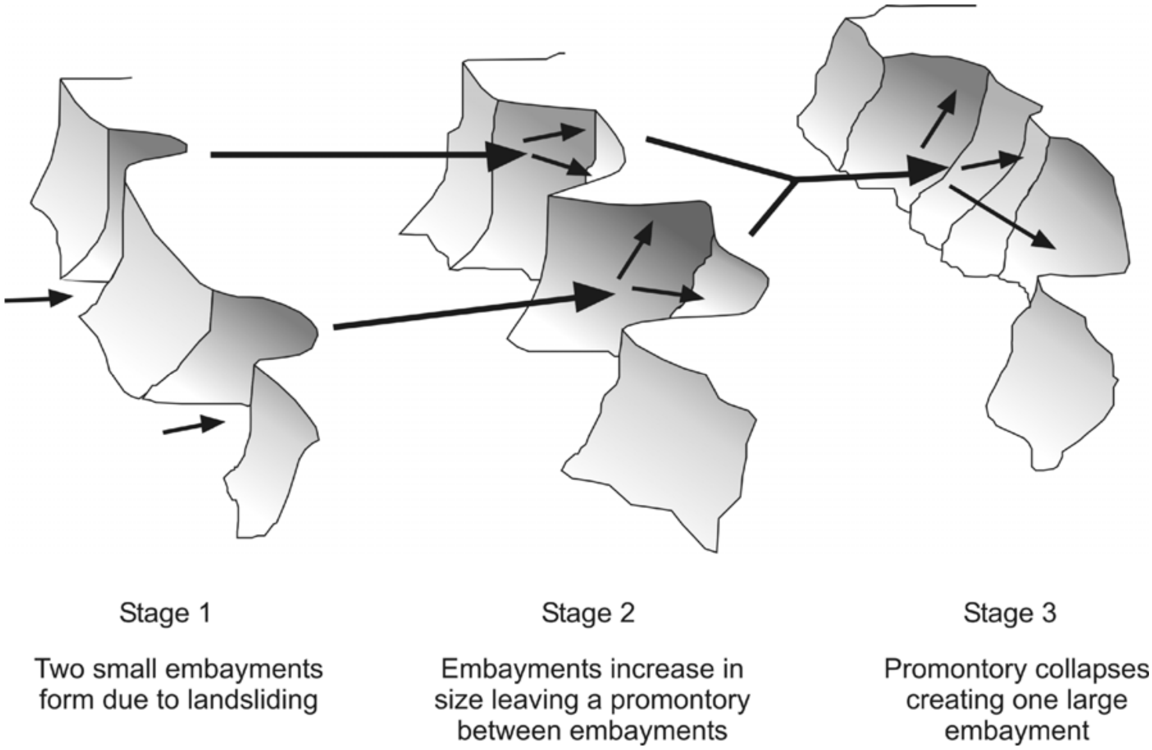

Fig. 8. Diagram to illustrate embayment formation process at Happisburgh.

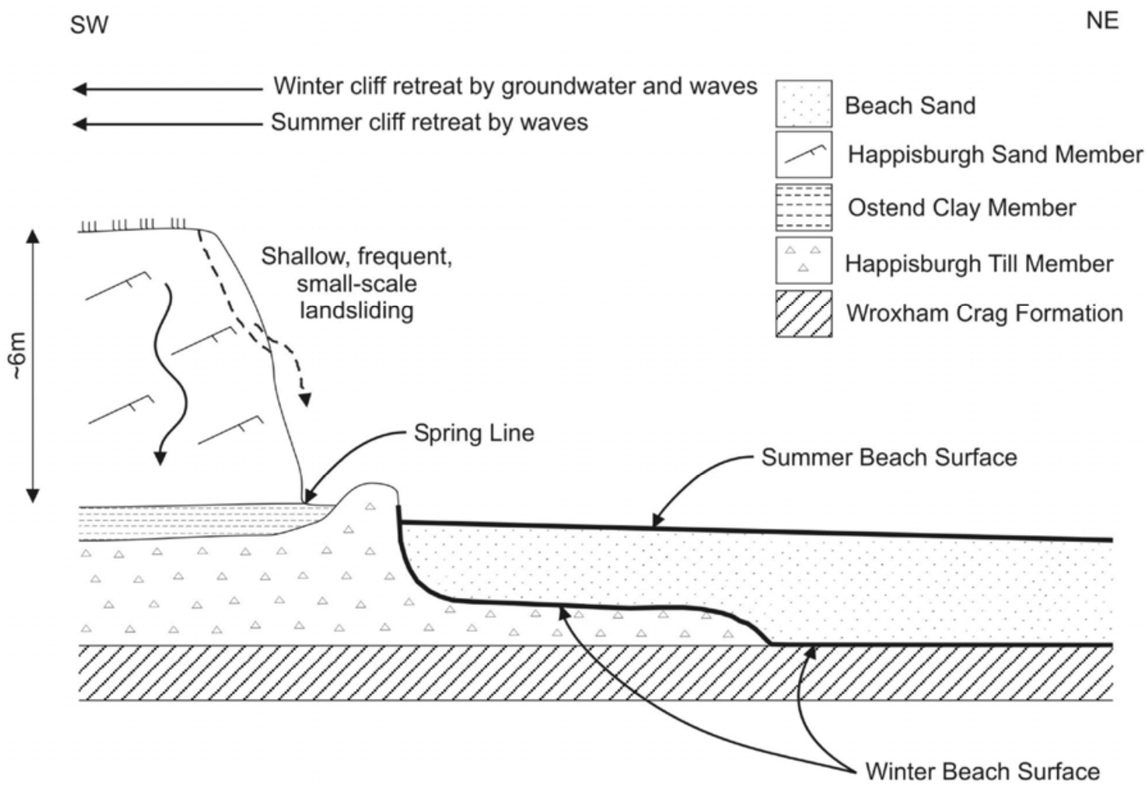

Fig. 9. Seasonal variations and erosional process model of erosion at Happisburgh

exposed (Fig. 4), erosion rates range between 8 to 10 m a^{-1}. This process has affected the properties on and adjacent to Beach Road (Fig. 3).

Early results from the surveys show that over a two-year period (September 2001 to September 2003), approximately 18,000 m^3 of sediment has been removed from a 100 m long section of cliff. This equates to approximately 36,000 t of sediment every two years.

To obtain an erosion rate over a longer time-frame, the 2004 data for the top of the cliff was drawn onto an aerial photograph from 1992 (Fig. 7). In this 12-year period the coast has retreated by approximately 105 m along a 400 m section.

The cliff surface profiles show that the erosion process is non-uniform, involving the cyclic formation of a series of embayments that continually enlarge (Fig. 4, Fig. 8). This could infer landsliding processes involving block falls, mudflows and running sand.

The aforementioned cliff recession conceptual model (Ohl *et al*., 2003) is largely correct. However, the seasonal beach-level changes at Happisburgh have a considerable effect on the erosion and landsliding process. The following conceptual model is proposed (Fig. 9):

1. In winter, erosion caused by groundwater as seen in the gullying of the cliff face, coupled with increased seasonal storminess, causes small-scale, frequent, shallow landsliding in the Happisburgh Sand Member. The Happisburgh Sand Member is easily eroded and undercutting of the cliff toe reduces slope stability and cliff failure occurs. The beach surface is low and scouring of the upper surface of the till extends the till platform.
2. In summer, the beach surface is higher and covers the ‘winter platform’. Wave attack is the dominant form of erosion accompanied by landsliding in the Happisburgh Sands.

CONCLUSION

The surveying method described is believed to be a highly accurate method to model not only rates of coastal retreat, but also detailed surface profiles of the cliff face. It enables an accurate analysis and interpretation of different failure types and mechanisms of failure and geological cross sectional mapping of the cliff face.

Detailed knowledge of the quantities of sediment input to the budget from cliff erosion has been very difficult to measure in the past. This method enables calculation of overall volume changes providing useful information for beach profiling and sediment budget studies as well as sea defence design and maintenance.

Several authors have attempted to model coastal retreat using Ordnance Survey (OS) maps but have recognised surveying errors of up to 1 m or more (Hooke & Kain, 1982; Nicholls & Webber, 1987; Gray, 1988; Cosgrove *et al*., 1998). Aerial photogrammetry, while more accurate than interpreting topographic maps, relies on accurate ground control that is not always available in such a dynamic environment. This method calibrates models and measurements made.

The advantages and benefits of terrestrial laser scanning in the coastal environment are: (1) rapid data collecting technique enabling detailed cliff surface profiles to be captured in a matter of hours such that tides are not a problem; (2) responsive methodology allowing, for example, landslide events to be scanned as soon as the team get on the site; (3) inexpensive after initial equipment purchase; (4) data requires less post-fieldwork processing than terrestrial photogrammetry; (5) 3-D cliff face surface models can be built up over time and volume loss calculations are easily and accurately obtained; (6) when used in conjunction with sub centimetre capability GPS promotes excellent spatial positional accuracy of the scans. Also, access to the cliff is not necessary as with some other survey methods.

At the beginning of 2005, BGS purchased a new laser capable of greater accuracy and resolution and the 2005 scan data is currently being processed.

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REFERENCES

CAMBERS, G. 1976. Temporal scales in coastal erosion systems. Transactions Institute British Geographers, **1**, 246-256.

CAMERON, T.D.J., CROSBY, A., BALSON, P.S., JEFFERY, D.H., LOTT, G.K., BULAT, J. & HARRISON, D.J. 1992. UK offshore regional report: The geology of the southern North Sea. British Geological Survey, Keyworth.

CLAYTON, K.M. 1989. Sediment input from the Norfolk cliffs, Eastern England - a century of coast protection and its effects. Journal of Coastal Research, **5**, 433-442.

CLAYTON, K.M., MCCAVE, I.N. & VINCENT, C.E. 1983. The establishment of a sand budget for the East Anglian coast and its implications for coastal stability. In: Shoreline Protection. Thomas Telford Ltd, University of Southampton, 91-96.

COSGROVE, A.R.P., BENNETT, M.R. & DOYLE, P. 1998. The rate and distribution of coastal cliff erosion in England: a cause for concern? In: Bennett, M.R. & Doyle, P. (Eds), Issues in Environmental Geology: A British Perspective. The Geological Society, London.

GRAY, J.M. 1988. Coastal cliff retreat at the Naze, Essex since 1874: patterns, rates and processes. Proceedings of the Geologists Association, **99**, 335-338.

HART, J.K. 1987. The genesis of the north east Norfolk Drift. Unpublished PhD thesis, University of East Anglia.

HART, J.K. 1999. Glacial sedimentology: a case study from Happisburgh, Norfolk. In: Jones, A, Tucker, M and Hart, JK (Eds), The Description and Analysis of Quaternary Stratigraphic Field Sections. Technical Guide 7, Quaternary Research Association, London, 209-234.

HIATT, M.E. 2002. Sensor Integration Aids Mapping at Ground Zero. Photogrammetric Engineering and Remote Sensing, 68, 877-879.

HOBBS, P., HUMPHREYS, B., REES, J., TRAGHEIM, D., JONES, L., GIBSON, A., ROWLANDS, K., HUNTER, G. & AIREY, R. 2002. Monitoring the role of landslides in 'soft cliff' coastal recession. In: McInnes, R.G. and Jakeways, J. (Eds), Instability Planning and Management. Thomas Telford, Isle of Wight, 589-600.

HOOKE, J.M. & KAIN, R.J.P. 1982. Historical change in the physical environment: a guide to sources and techniques. Butterworth, London.

HR WALLINGFORD. 2001. Ostend to Cart Gap Coastal Strategy Study. EX 4342. November.

HR WALLINGFORD, 2002. Southern North Sea Sediment Transport Study Phase 2: Sediment Transport Report, Report produced for Great Yarmouth Borough Council by HR Wallingford, CEFAS/UEA, Posford Haskoning and Dr Brian D'Olier, Report EX 4526.

HULME, M., JENKINS, G.J., LU, X., TURNPENNY, J.R., MITCHELL, T.D., JONES, R.G., LOWE, J., MURPHY, J.M., HASSELL, D., BOORMAN, P., McDONALD, R. & HILL, S. 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research. School of Environmental Sciences, University of East Anglia, Norwich, UK, 120pp.

HUNTER, G., PINKERTON, H., AIREY, R. & CALVARI, S. 2003. The application of a long-range laser scanner for monitoring volcanic activity on Mount Etna. Journal of Volcanology and Geothermal Research, 123, 203-210.

LEE, J.R. 2003. Early and Middle Pleistocene lithostratigraphy and palaeoenvironments in northern East Anglia, UK. (Unpublished). Ph.D., University of London.

LEE, J.R., ROSE, J., HAMBLIN, R.J.O. & MOORLOCK, B.S.P. 2004. Dating the earliest lowland glaciation of eastern England: a pre-M1512 early Middle Pleistocene Happisburgh Glaciation. Quaternary Science Reviews.

LEE, J.R., ROSE, J., RIDING, J.B., HAMBLIN, R.J.O. & MOORLOCK, B.S.P. 2002. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. Boreas, **31**, 345-355.

LEE, M. & CLARK, A. 2002. Investigation and management of soft rock cliffs. Thomas Telford.

LEGGETT, D. (1993), Happisburgh to Winterton: changes in beach levels July 1992 to March 1993, Environment Agency Internal report.

LUNKKA, J.P. 1988. Sedimentation and deformation of the North Sea Drift Formation in the Happisburgh area, North Norfolk. In: Croot, D. (Ed.), Glaciotectonics: Forms and Processes. Balkema, Rotterdam, 109-122.

McCAVE, I.N. 1978. Grain-size trends and transport along beaches: examples from Eastern England. Marine Geology, **28**, M43-M51.

McCAVE, I.N. 1987. Fine sediment sources and sinks around the East Anglian coast (UK). Journal of the Geological Society of London, **144**, 149-152.

NICHOLLS, R.J. & WEBBER, B. 1987. Coastal erosion in the eastern half of Christchurch Bay. In: Bell, MG, Cripps, FG and O'Hara, M (Eds), Planning and

Engineering Geology. Engineering Group Special Publications, **4**, Geological Society, London, 549-554.

OHL, C., FREW, P., SAYERS, P., WATSON, G., LAWTON, P., FARROW, B., WALKDEN, M. & HALL, J. 2003. North Norfolk - a regional approach to coastal erosion management and sustainability practice. In: McInnes, R.G. (Ed.), International Conference on Coastal Management 2003. Thomas Telford, Brighton, 226-240.

PAUL, F. & IWAN, P. 2001. Data Collection at Major Incident Scenes using Three Dimensional Laser Scanning Techniques. In: The Institute of Traffic Accident Investigators: 5th International Conference held at York. New York.

ROWLANDS, K., JONES, L. & WHITWORTH, M. 2003. Photographic Feature: Landslide Laser scanning: a new look at an old problem. Quarterly Journal of Engineering Geology, **36**, 155-158.

SHENNAN, I., COULTHARD, T., FLATHER, R., HORTON, B., MACKLIN, M., REES, J. & WRIGHT, M. 2003. Integration of shelf evolution and river basin models to simulate Holocene sediment dynamics of the Humber Estuary during periods of sea-level change and variation in catchment sediment supply. The Science of the Total Environment, **314-316**, 737-754.

THOMALLA, F. & VINCENT, C.E. 2003. Beach Response to Shore-Parallel Breakwaters at Sea Palling, Norfolk, UK. Estuarine, Coastal and Shelf Science, **56**, 203-212.

THOMALLA, F., VINCENT, C.E. & BLACK, K. 2001. The effects of the segmented shore-parallel breakwaters at Sea Palling on the longshore transport of sand: lessons for the future. In: Proceedings of the 36th MAFF Annual Conference of River and Coastal Engineers. Keele University, 07.4.1-07.4.12.

WHITE, W. 1845. History, Gazeteer, and Directory of Norfolk 1845.