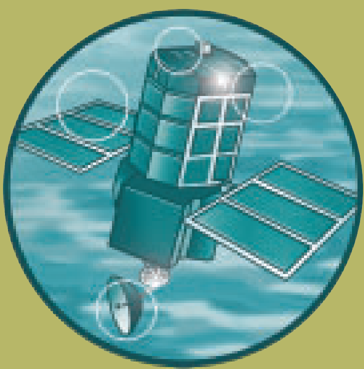
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Understanding and predicting beach morphological change processes associated with the erosion of cohesive foreshores - scoping report

R&D Technical Report FD1915/TR



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Understanding and predicting beach morphological change processes associated with the erosion of cohesive foreshores – scoping report

R&D Technical Report FD1915/TR

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Statement of use
This document is a scoping study, to current best practice, of the processes of weathering and erosion of cohesive shore platforms and their interactions with adjoining beaches (and cliffs). The study identifies R&D needs and recommendations to address gaps in understanding of these types of shoreline.

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Executive summary

There are significant stretches of cohesive shore platform in the United Kingdom where variable amounts of sand and gravel overlie cohesive clay materials (such as Holocene mud, glacial till and London Clay). Many stretches lie along the most rapidly eroding shorelines in the country (Holderness, Essex and north Kent) and pose significant problems for management. The process of downcutting of the shore platform and the interaction between the cohesive and non-cohesive components is not well understood.

The coastal community needs to be better able to manage cohesive platforms because of their value as habitats and their importance in controlling the functioning of the wider coastal system, including beach form and sediment budgets. This importance is not limited to areas in which platforms are normally visible; in other locations they may rarely be revealed but still have a significant geomorphological role, particularly in regulating recession rates. In 2001, the Defra Coastal Concerted Action recommended a scoping study to assist coastal authorities in the management of cohesive shorelines.

Objectives

The objectives of this study are to:

- Undertake a scoping study (to current best practice) of the processes associated with the erosion of cohesive shore platforms and interactions with the sediment budget in order to identify the research and development needs;
- Define a research project that will address the gaps in our understanding and provide detailed guidance to best practice regarding the management of these coastlines (provided separately as a CSG7);
- Provide preliminary advice regarding the management of these coastlines.

This scoping report provides a detailed appraisal of previous research in the field of cohesive shore platform weathering and erosion. It examines how these processes may affect the sustainability of the adjoining beaches, the evolution of any backing cliffs, and their influence on sediment budgets. The investigation of processes has not been restricted to the foreshore alone (as the project title suggests), but has also covered the subtidal zone (shoreface). This is because processes operational across the whole of the littoral zone make a significant contribution to the changing geomorphology of the shore platform, either directly or indirectly.

Weathering and Erosion Processes

It is now generally accepted that the rate of vertical lowering of the platform is the key control in the long-term recession of cohesive shorelines over periods of decades. In turn, this is probably dependent on its geology, strength of the cohesive material (and any strength changes due to weathering), rate of sea-level rise, wave climate, tidal regime and the effect of beach sediment cover.

These parameters control the magnitude of the complex variety of weathering and erosion processes operating on the platform.

This scoping study describes eight dominant processes relevant to the United Kingdom coast:

- Abrasion by mobile, non-cohesive surface sediment;
- Mechanical wave erosion;
- Biological processes;
- Softening of the fabric due to removal of overburden;
- Softening of the fabric due to pressure fluctuations induced by waves;
- Desiccation and wetting;
- Physico-chemical effects;
- Freeze-thaw (frost).

Weathering processes such as desiccation and wetting and physico-chemical effects (e.g. salt weathering), play a significant role in weakening the cohesive material prior to its erosion by marine processes, which include abrasion by mobile non-cohesive surface sediment and mechanical erosion by breaking and shoaling waves. The relative magnitude of all these processes is poorly understood and has been a matter of debate for many years. Even more poorly understood is the role of biological activity, both in erosive and protective capacities, on and within the cohesive clay surface.

Further Research

This scoping study shows that although the processes that weather and erode cohesive platforms have been identified, the rates at which they operate have not. It is therefore recommended that further research needs to be targeted at providing a better understanding of the fundamental underlying principles that control the rate of cohesive shore platform erosion, providing a baseline starting point for better strategic management. The research needs to examine and improve the technical understanding of the roles of the different parameters and processes that contribute to the downcutting of cohesive shore platforms. Four research areas are recommended for further investigation:

- The specifics of the weathering and erosion processes, particularly the effect on downcutting rates of abrasion related to sediment size and thickness of surface sediments (beach) and the importance of biological processes;
- The relationship between platform and beach geomorphology and the platform weathering and erosion processes in a range of space and time scales;
- The relative influence of material strength in the rate at which weathering and erosion processes proceed;
- The need to test models of platform development at different sites.

With this improved scientific understanding, consultants and operating authorities can make better decisions regarding options for the future management of these types of coastlines. Management capability should also be enhanced by the translation of the science into best practice guidance and tools that enable the prediction of response to changes, whether climatic, or anthropomorphic, to the platforms themselves or to the system of which they are a part.

Glossary

Abrasion - the erosion (qv) caused by material carried by wind and water.

Armoured mudball – rolled masses of mud, the surfaces of which are covered with a protective layer of sand and/or gravel.

Backshore – area above high water but which can be affected by coastal processes.

Barton Clay - a geological formation of clays and silts exposed on the Hampshire and Isle of Wight coasts.

Beach - a deposit of non-cohesive material (e.g. sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) which results from the action of present-day hydrodynamic processes (i.e. waves, tides and currents) and sometimes of winds. Extends from the low water mark to the effective landward limit of storm waves.

Bedforms - topographic sedimentary features (e.g. sand waves, ripples) resulting from the movement of fluid over a non-cohesive substrate.

Bivalve - an aquatic animal living on or within the sediment with two protective calcareous shells (valves); relative of the snail.

Chalk - a geological formation of fine-grained calcareous limestone exposed as sea cliffs in southern and eastern England.

Clay - a fine-grained sediment with a typical particle size of less than 0.002 mm.

Cohesive sediment - sediment containing a significant proportion of clays, the electromagnetic properties of which causes the particles to bind together.

Consolidated - compacted by overburden to reduce pore space and increase density; applied to fine-grained sediment.

Cross-shore transport - the movement of sediment approximately perpendicular to the shoreline.

Diagenesis - the process of alteration of a sediment which take place after its deposition.

Diatom - microscopic single-celled plant.

Dynamic equilibrium - a state of balance between environmental forces acting on a landscape and the resisting earth material which fluctuates around an average that is itself gradually changing.

Episodic - composed of a series of discrete events rather than as a continual process.

Eocene - a period of geological time between 54 and 33 million years ago; during which time the London Clay and Barton Clay (qv) were deposited.

Erosion - the process of removal of material from the land or sea bed by the action of natural forces.

Flocculation - the aggregation of clay particles in suspension to form larger composite grains (flocs).

Foreshore - a morphological term for the part of the shore between mean low water and the landward limit of normal wave action.

Glacio-lacustrine - descriptive of lakes at the borders of glacial ice sheets.

GPS - Global Positioning System - an accurate navigational and positioning system by which the location of a position on or above the earth can be determined by interpreting signals received from a constellation of satellites.

Gravel (Pebbles) - loose, fragments of rock larger than sand but smaller than cobbles. Particles larger than 4 mm but less than 64 mm.

Holocene - a period encompassing the last 10,000 years of earth history.

Hydrodynamic - the process and science associated with the flow and motion in water produced by applied forces.

Impermeable - not allowing the passage of fluids.

Lag deposit - a deposit of coarser sediment left behind after the removal of finer material by water or wind transport.

Lithology - the general description of the material of a sediment or sedimentary rock.

London Clay - a geological formation of silts and clays found in southeast England and exposed along the coasts of Essex, Kent, Sussex, Hampshire and the Isle of Wight. Deposited during the Eocene period (qv).

Longshore bar - an elongate ridge of sediment, occurring on the lower beach or shoreface parallel or sub-parallel to the shoreline.

Longshore transport - the movement of sediment approximately parallel to the shoreline predominantly as a result of wave action.

Mercia Mudstone - a geological formation of mudstones (qv) exposed along the coasts of Devon, Somerset and South Wales.

Mineral - a naturally occurring inorganic crystalline solid that has a definite chemical composition and possesses characteristic physical properties.

Mud - sediment with particles finer than sand (0.063mm). A term which encompasses both clay and silt.

Mudstone – a lithological term descriptive of consolidated or lithified mud (qv).

Nearshore – the zone which extends from the surf zone to the position marking the start of the offshore zone.

Numerical modelling - the analysis of coastal processes using computational models.

Overconsolidated - a clay that has been compacted under overburden pressure greater than that existing at the present time. Implies that overburden has been removed at some time in the past.

Overtopping - the process where water is carried over the top of an existing defence due to wave action.

Pleistocene - an epoch of the Quaternary Period characterised by several glacial ages commencing approximately 1.6 million years ago.

Pore water - the fluid found in the interstitial spaces between sediment grains.

Sand - sediment particles, with a diameter of between 0.063 mm and 2 mm. Sand is generally classified as fine, medium or coarse.

Sea-level rise - the general term given to the upward trend in mean sea level resulting from a combination of local or regional geological movements and global climate change.

Shear strength - the maximum shear stress that can be applied in a particular direction. When exceeded the material can be said to have ‘failed’.

Shear stress - the horizontal stress that results from a fluid passing over a sediment surface.

Shore platform - a platform of exposed bedrock exposed within the intertidal and subtidal zones.

Silt - sediment particles with a grain size between 0.002 mm and 0.063 mm, i.e. coarser than clay but finer than sand.

Sodium adsorption ratio - a relation between soluble sodium and soluble divalent cations, which can be used to predict the exchangeable sodium fraction of soil, equilibrated with a given solution.

Stratigraphy - the study of stratified rocks especially their sequence in time.

Subaerial - the portion of the environment above the water surface; subaerial processes due to atmospheric conditions (e.g. rainfall, temperature, pressure, etc.).

Surf zone - the zone within which waves break as they approach the shore.

Suspended sediment - fine-grained sediment transported in suspension.

Tertiary - a period of geological time between the untimely demise of Dinosaurs and the Pleistocene (qv).

Till - poorly-sorted sediments deposited by a glacier.

Triassic - a period of geological time between 250 and 205 million years ago; during which time the Mercia Mudstone (qv) was deposited.

Unconsolidated - sediment particles packed in a loose arrangement. Relatively uncompacted cf overconsolidated.

Undermining - erosion at the base, e.g. of a seawall or cliff, so that the feature above becomes unstable and is vulnerable to collapse.

Weathering - the process by which rocks are broken down and decomposed by the action of external agencies such as wind, rain, temperature changes, plants and bacteria.

1. Introduction

1.1 Aims of this scoping report

Beaches are fast responding and mobile geomorphic systems that are highly sensitive to environmental change and forcing, and susceptible to episodes of erosion and growth. Their stability depends on the equilibrium established between sediment supply and loss; this being driven by tidal and wave energy and constrained and influenced by the geology and morphology of the underlying and adjacent shore platform.

If beach management techniques to prevent erosion or flooding along the shoreline are to be sustainable then a better understanding of the mechanisms by which sediments are lost and gained from beaches is needed. One of the main concerns relates to the dynamic and morphological responses of a beach system to erosion of the adjacent cohesive clay platform. Previous projects have touched upon the issues, which are considered to be:

- The long term lowering of beaches as the irreversible process of erosion of the platform continues;
- The yield of sediment from platform erosion affecting sediment budget calculations;
- The downcutting of the platform acting as a regulator of cliff recession;
- The impact of rising sea levels and increased storminess as a consequence of climate change.

The focus of this scoping report is to provide a review of the processes of weathering and erosion of cohesive platforms. These processes are then placed in the context of the wider coastal system, by examining their relationship to change in beach form and how this may affect the stability of any backing cliffs. The report provides an assessment of previous research on these types of shore, with studies described from both the United Kingdom and worldwide, to provide an exhaustive review of the current state-of-the-art. Using this research as a guide, the scoping re-evaluates where there is a need for further work and establishes the critical areas where knowledge is insufficient.

1.2 Definition of a consolidated cohesive shore platform

Cohesive shore platforms are developed in relatively non-resistant, consolidated or partially consolidated cohesive sediments, such as Holocene mud, glacial till, glacio-lacustrine deposits and soft mudrock. A platform is cohesive when the cohesive sediment layer has a dominant role in changing the shoreline shape, through erosion. Platforms are commonly gently sloping in a seaward direction and control the shore’s response to waves, storms, and water level changes. They may be bare of overlying sediment or covered by a thin discontinuous veneer of sand and gravel (Figures 1.1 and 1.2). In some locations a substantial beach, several metres in thickness, overlies the landward margins of the platform.

Figure 1.1 Cohesive shore platform at The Naze, Essex, demonstrating the discontinuous nature of overlying non-cohesive sediment

Figure 1.2 Cohesive shore platform at Sidestrand, north-east Norfolk, demonstrating the discontinuous nature of overlying non-cohesive sediment

Commonly, an eroding cliff backs the platform (Figure 1.3), but this may not always be the case, particularly on low coasts or where the platform is composed of Holocene mud (Figure 1.4). Essentially, the cliff is the portion of the profile above the cliff toe and the platform is the profile from the cliff toe into deeper water. The platform is therefore lithologically and geotechnically closely related to the lower layers of the cliff (Figure 1.5). Holocene muds are exposed as a platform through erosion of the overlying and backing recent sediments.

Figure 1.3 Example of a cohesive shore platform backed by a cliff – glacial till at Happisburgh, north-east Norfolk

Figure 1.4 Example of a cohesive shore platform backed by a sea wall with no cliff – Holocene mud at Sea Palling, north-east Norfolk

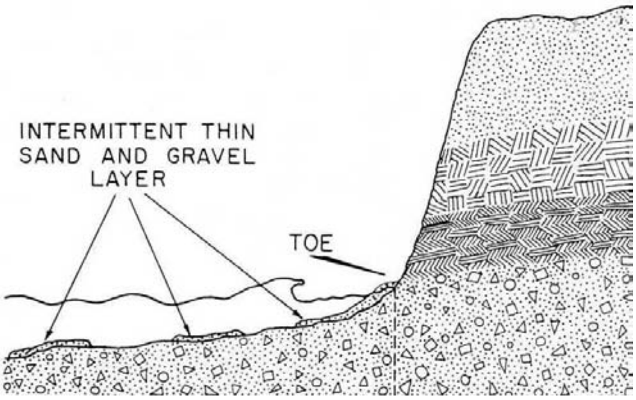

Figure 1.5 Cross-section through a cohesive profile comprising a shore platform and cliff (from Kamphuis, 1987)

Both subaerial weathering and marine erosion processes contribute to the downcutting of a cohesive platform. Weathering processes may be directly responsible for the actual break up of the cohesive material (or contribute to its weakening), which is then eroded by marine processes. An important feature of a cohesive shore platform is that erosion of the cohesive sediment is irreversible. This is because, once eroded, the cohesive sediment cannot be replaced in its consolidated form. The eroded muds are carried away in suspension and deposited in calmer water, whereas the sand or other coarser fractions tend to remain in the littoral zone. However, erosion generally produces insufficient debris to form a protective beach.

The consolidated cohesive sediment forming the platform may be predominantly mud or clay (e.g. London Clay) or consist of clay admixed with coarser sediment (such as glacial till). The hardness of the cohesive sediment may also vary and for the purposes of this scoping study, harder materials (e.g. mudstone) are included if the processes associated with their erosion are relevant to the understanding of the processes that apply to cohesive shore platforms formed of softer material.

In the United Kingdom, cohesive shore platforms occur along many stretches of the east and south coasts. Examples include the Pleistocene till shores of Holderness and North-East Norfolk, the Tertiary shores of Essex/north Kent (London Clay Formation) and West Sussex/Hampshire/Isle of Wight (Bracklesham and Barton Groups), and the Holocene exposures of the East Anglian, Lincolnshire and Lancashire coasts and the Thames Estuary.

They are also recognised along other mid-latitude (e.g. southern Baltic Sea) and high latitude (e.g. southern Beaufort Sea) shores. They form a large part of the perimeters of the Great Lakes, comprising over 40% of the shoreline of the lower lakes (Lake Ontario, Lake Erie, southern Lake Huron and southern Lake Michigan).

2. Processes of weathering and erosion

Platform erosion is the detachment of sediment particles from the platform surface and their transportation away. The processes depend on a variety of factors, which control the erodibility of the materials and the power of the assailing forces to erode. In contrast to cliff recession, the processes occur at the near-particle scale across a very thin surface layer, and they are probably near continuous rather than episodic.

2.1 Erodibility of cohesive sediments

The resistance to erosion of consolidated cohesive sediments (i.e. the strength of the bonds between the cohesive particles) is related to their geotechnical properties and chemistry. As water flows over the cohesive sediment as either steady flow or oscillatory flow under waves and tides, it exerts a shear stress on the bed due to viscosity and turbulence. When the shear stress becomes greater than gravity, friction and cohesion, then a formerly stationary particle leaves the bed and begins to move. This is known as the critical shear stress for erosion or critical erosion threshold (τ_c) and is a function of the shear strength, clay content (particle size distribution and sand to mud ratio), water content, mineralogy and other geotechnical and chemical (exchangeable Ca-Na ratio, electrolyte concentration, pH, temperature) properties of the cohesive material (Raudkivi and Hutchison, 1974; Arulanandan *et al*., 1975; Croad, 1981; Kamphuis and Hall, 1983; Dade *et al*., 1992; Mitchener and Torfs, 1996; Panagiotopoulos *et al*., 1997; Lick and McNeil, 2001). The form of the function is poorly understood and is likely to be non-linear.

Laboratory studies suggest that the links between particles within the structure of natural cohesive clays are strong enough to resist fairly high shear stresses, and erosion at an individual particle level is rarely achieved (Kamphuis and Hall, 1983; Bishop *et al*., 1993; Skafel and Bishop, 1994). Therefore, when the critical shear stress for erosion is reached, the sediment that is released is more likely to be a floc made up of several particles held together by cohesion. These results suggest that a more important parameter in the erodibility of cohesive sediment is weakness associated with discontinuities in the clay matrix such as fissures, fractures and seams of non-cohesive sediment (Lefebvre and Rohan, 1986; Hutchinson, 1986). These structures are uniquely defined by the environmental conditions during the original deposition and the subsequent diagenesis and weathering of the sediment.

2.1.1 Influence of stratigraphy and structure

The large-scale geological characteristics of cohesive platform sediments are determined by stratigraphic and lithological variability across and along the platform (US Army Corps of Engineers, 2002). Factors such as bed dip, jointing, thickness, and other structural and lithological factors may be responsible for considerable variation in the morphology of platforms composed of soft mudrock. Along many cohesive platforms comprising glacial deposits the stratigraphy is complex in both lateral and vertical directions. This complexity generally relates to the conditions under which the deposits were formed (e.g. tills, glacio-lacustrine deposits). Bell (2002) studied tills from around the United Kingdom and showed that they vary greatly in composition and consequently their geological and geotechnical properties. Within the till, properties also vary along any particular shoreline, with implications for erodibility on local scales.

In the short-term (1-10 year time scales), cohesive platforms are likely to experience differential lowering rates, with erosion at any given time concentrated in a number of locations, possibly promoted by minor geological details. For example, fissures may erode differentially to produce a step or furrow (Figure 2.1), which further concentrate the hydrodynamic and mechanic effects of waves and currents. Pebbles or cobbles within the clay matrix may concentrate erosion, due to increased turbulence and shear stresses around these larger components. Crescentic scour troughs may develop and pedestals may form supporting the objects (Figure 2.2).

Figure 2.1 The cohesive shore platform on the Isle of Sheppey, north Kent, showing development of a fissure in the platform surface

Figure 2.2 **Part of the cohesive shore platform at Holderness showing a rock capped pedestal of cohesive sediment, about 10 cm high, developed through erosion of the adjacent platform (from US Army Corps of Engineers, 2002)**

This short-term differential erosion generates an irregular platform surface, with localised variations in relative relief of tens of centimetres. Over the long term (>10 years), the localised variations in lowering rate will tend to be smoothed out to give a near uniform lowering rate across the whole platform. Areas of rapid lowering become sand-filled depressions, whereas areas of slower erosion gradually become local “highs” and subject to higher relative wave induced stresses and abrasion (Sections 2.3.1 and 2.3.2) than the surrounding areas. In this way platform lowering is self-regulating, creating a planar surface over time, despite the short-term variability in erosion rates.

The geology of a cohesive shore is a dominant control of the morphology of the cross-shore profile. Profiles can broadly be divided into two types: concave and convex (US Army Corps of Engineers, 2002) (Figure 2.3). Concave profiles develop in cohesive platforms comprised of sediment with a relatively uniform erosion resistance from the closure depth to the top of the foreshore. They have a generally exponential form and sand cover is variable. Convex profiles develop where potential lag deposits (pebbles and cobbles) exist within the eroding material. These may be left behind after the clays have been removed, to form protective armour against further erosion, producing a shallower and flatter profile, characterised by a nearshore shelf (Davidson-Arnott, 1986b). The particle size of the lag deposits, the wave climate, and the range of water level fluctuations determine the depth of the shelf. The lag deposits act to dissipate wave energy and reduce or even prevent cliff erosion. This may lead, in turn, to the development of a more stable beach.

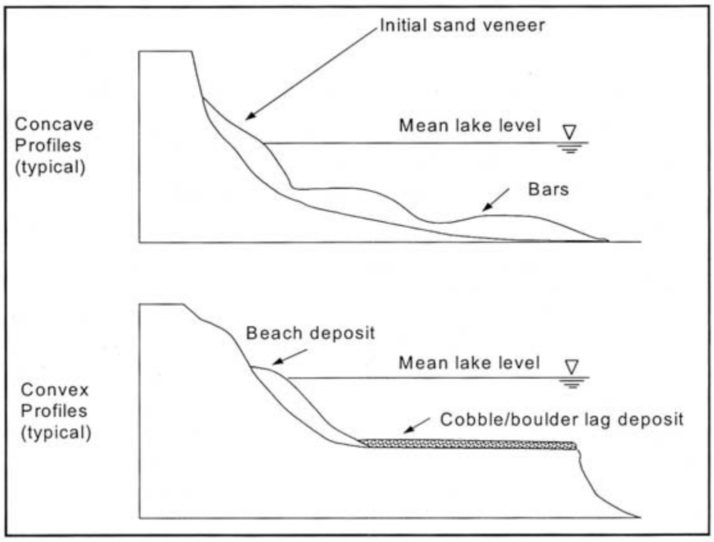

Figure 2.3 Distinction between concave and convex shore profiles as described for the Great Lakes (from US Army Corps of Engineers, 2002)

2.1.2 Influence of geotechnical properties

The form and rate of development of platforms in both cohesive and non-cohesive materials, and those that comprise a mixture of the two, is largely controlled by their geotechnical properties. It is argued that shore platforms only develop when the erosive force of waves exceeds the resisting force of the platform material. The resisting force is largely the result of the geotechnical properties of the platform material, which are influential at macro-, meso- and micro-scales. At a meso- to macro-scale important factors include geological structure (e.g. faults, folds and cleavage), bed thickness and orientation relative to the direction of wave attack, and the occurrence and pattern of discontinuities (see previous section). At a micro-scale, geochemical and geophysical properties such as mineralogy and porosity are important controls on material strength (Moses, 2002).

Physical, chemical and biological processes may alter the geotechnical properties of platform materials. Laboratory studies indicate that strength may be reduced simply by saturation and that materials with different physico-chemical properties have markedly different response patterns to the same physical weathering processes (Moses, 2002) (Section 2.3.7). The repeated stresses exerted on the platform by oscillatory motions of the water may induce fatigue that leaves the material more susceptible to erosion (Section 2.3.5). Material strength may also be reduced by the activities of marine organisms (Section 2.3.3). For example, grazing molluscs and boring organisms including algae, sponges, barnacles, bivalves and echinoids can increase the percentage of void space thus reducing material strength.

There are few comprehensive studies of the impact of weathering processes on the geotechnical properties of platform materials. Stephenson and Kirk (2000a, b) identified platform "swelling" that could not be fully explained. They highlighted the importance, but lack of understanding, of the interaction of weathering and erosion processes. In certain cases, weathering may enhance material strength. For example, evaporation may draw solutions to the surface, cementing pore spaces and increasing resistance to erosion. Similarly, some organisms secrete polysaccharides that cement particles together.

2.2 Power of energy inputs to erode

The assailing forces are primarily those associated with wave orbits, wave breaking, and with abrasion resulting from the movement of sand and gravel over the platform surface. The topography of the platform and beach, and sea (tide) level effectively control the way in which wave energy is distributed across the shore. A steeply sloping platform will tend to cause waves to plunge as they break. Plunging breakers tend to cause high water velocities and pressures and so are effective at removing material. Since they will have more effect at higher elevations than lower levels they will result in the formation of a more gently sloping platform. Low gradient shore profiles force waves to break at a relatively long distance offshore, and the coarse material on beaches absorbs most of the wave energy reaching the shoreline after the breaking of the waves.

2.3 Processes of platform weathering and erosion

Presently, there is no definitive description of cohesive platform weathering and erosion because the roles of the different processes have not been exhaustively studied. The roles of subaerial and marine processes are not fully understood and it has not been clearly demonstrated that either process is principally the cause of platform downcutting. The main difficulty lies in separating the effects of each process. The following questions arise:

- Does weathering reduce the shear strength of the cohesive sediment to a point where waves can cause erosion so that in the absence of weathering no erosion can occur?
- If so, is platform erosion mainly controlled by marine or subaerial processes?

It may be argued that both processes are effective agents in downcutting the platform, and the development of the platform is a convergent response, regardless of which process dominates in a particular location and time. All processes probably operate simultaneously at different rates across different parts of the platform. It also seems likely that lowering of a certain part of the platform by one process will inevitably lead to subsequent further lowering by a different process. The predominant process will depend on the geological, physical and climatic conditions of the site. So, further questions arise:

- Can the resolution of the marine versus subaerial erosion debate be considered an erroneous problem?
- Is the complex interaction among the different processes more important than the effect of any single process?

This scoping study identifies eight dominant processes relevant to the weathering and erosion of cohesive platforms along the United Kingdom coast:

- Abrasion by mobile, non-cohesive surface sediment;
- Mechanical wave erosion;
- Biological processes;
- Softening of the fabric due to removal of overburden;
- Softening of the fabric due to pressure fluctuations induced by waves;
- Desiccation and wetting;
- Physico-chemical effects;
- Freeze-thaw (frost).

2.3.1 Abrasion by mobile non-cohesive surface sediment

Erosion of cohesive platforms may occur by abrasion as a result of the movement of sand and gravel by waves and currents across its surface (Davidson-Arnott and Askin, 1980; Kamphuis and Hall, 1983; Coakley *et al*., 1986; Bishop *et al*., 1993; Skafel and Bishop, 1994; Davidson-Arnott and Ollerhead, 1995). In general, coarser sediment acts as an abrasive agent to accelerate erosion rather than modifying the fundamental mechanism of turbulence under wave attack. Kamphuis and Hall (1983) and Kamphuis (1983, 1987, 1990) found that even a small amount of sediment in the eroding fluid substantially lowered the critical shear stress for erosion of cohesive clay. Kamphuis (1990) found that erosion rate increased by a factor of between three and eight when sand was present in the flow. Erosion in the presence of sand takes place by a general planing down of the surface as well as by formation of gulleys in the direction of flow which tend to coalesce and result in general lowering of the surface (Kamphuis, 1987, 1990). Long-term erosion rates with sand measured inside the surf zone peak at the zone of wave breaking, and decrease in an offshore direction (Bishop *et al*., 1993; Skafel and Bishop, 1994).

Available wave energy and the hardness of the abrading sediment relative to the platform surface largely control the amount of abrasion. Kamphuis (1987) suggested a very strong relationship between cliff recession rate and wave height, such that a 3 m high wave is more than 500 times more erosive than a 0.5 m high wave. Paradoxically, Trenhaile (1987) argued that extremely severe storms probably cause less abrasion than minor storms since the higher energy levels suspend or saltate most of the particles rather than dragging them across the platform surface.

For abrasion to occur, overlying sand or gravel in contact with the platform has to be moved over the surface by wave action. There is a critical thickness, that varies with the sediment size and wave energy, above which the sediment in contact with the surface can no longer be moved under wave action, and abrasion ceases (Davidson-Arnott and Ollerhead, 1995). Using a laboratory flume, Bishop *et al*. (1993) and Skafel and Bishop (1994) found that the continuous presence of a sand (particle size 0.51 mm in their experiments) layer 10 mm or more in thickness was sufficient to provide protection against erosion of the underlying till, for the wave conditions used. A number of predictive models have attempted to evaluate the depth of the layer of sediment mobilised by waves but a definitive model has proved elusive. Sunamura and Kraus (1985) argued that mixing depth increases in an approximately linear fashion with the wave height, for breaking waves up to 1.5 m high. For greater wave heights, the rate of increase in the mixing depth decreases with increasing wave height. They also found that mixing depth is strongly related to wave period in the larger wave height region. Ferreira *et al*. (2000) defined the thickness of sand required to limit wave disturbance of the platform as exceeding one-fifth of the wave height.

The mobility of surface sediment is important, because if a beach is frequently changing position and thickness, the underlying cohesive sediments will be exposed to erosive situations more often. This can occur due to the migration of bedforms or the onshore offshore movement of sediment in nearshore bars and on the beach (Pringle, 1981, 1985) (Figure 2.4). The presence of longshore bars can protect the underlying cohesive sediment from exposure and subsequent downcutting. As these bars migrate with changing wave and water level conditions, different areas of the underlying cohesive profile become exposed in the troughs between the bars (Pringle, 1981, 1985; Davidson-Arnott *et al*., 1999; Perez Alberti *et al*., 2002). Thus, over a period of years, all of the profile will be exposed to erosion. Where overlying sand or gravel forms a beach on the landward margin of a platform, evidence from soft, non-cohesive sediments such as chalk suggests that abrasion is concentrated in a zone on the seaward margin of the beach where there is an intermittent thin cover. O’Brien *et al*. (2000) described a situation in the Severn Estuary where modern intertidal mudflat sediments overlie older consolidated Holocene muds. The thickness of modern sediment varies on a seasonal basis and erosion of the underlying Holocene material takes place when the mudflat has been removed by erosion. It was suggested that winter storm wave activity aided by freeze-thaw and ice scour were the main erosive agents.

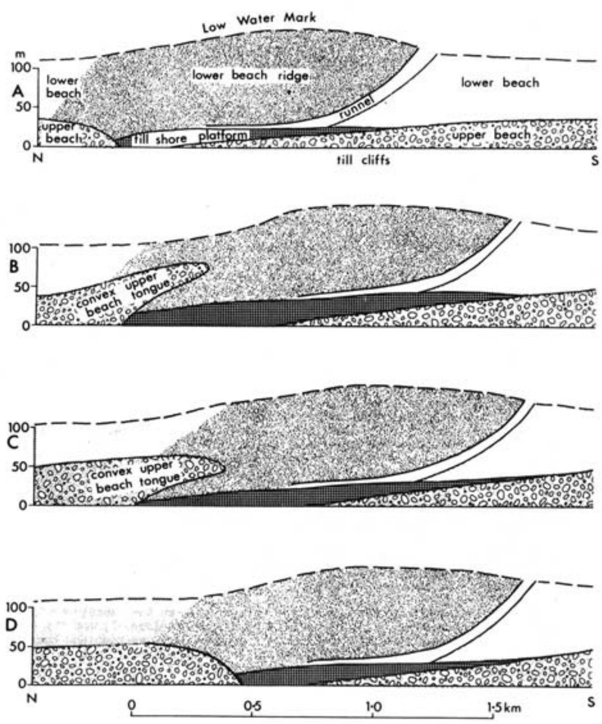

Figure 2.4 Example of beach and beach ridge movement along the Holderness coast, illustrating how the exposure of the shore platform can vary (from Pringle, 1981). A – morphology after absence of northerly storms. B – morphology during northerly storm. C – morphology immediately after northerly storm. D – morphology a few weeks later

In summary, most studies acknowledge the importance of abrasion by the movement of coarser sediment across the surface of the cohesive material, but they have not provided a definitive means of predicting this. Little is known about the relationship between the thickness of the surface layer and the degree of protection provided, nor is there much information on the typical thickness and mobility of sediment on actual cohesive shorelines.

2.3.2 Mechanical wave erosion

Particles may be eroded from the platform by the shear stresses associated with breaking and shoaling waves (Croad, 1981; Philpott, 1984). Erosion occurs with the formation of a pattern of fine cracks, created by pressure fluctuations at the boundary under turbulent flow. Detached particles are then prised from the surface (quarrying or plucking) and entrained in the flow, leaving a pitted surface. The spacing, orientation, aperture and persistence of discontinuities (e.g. joints and fractures) in the platform surface control its susceptibility to wave plucking processes and control the size of blocks removed by erosion processes. Erosion of the platform will continue due to wave action in an offshore direction until the closure depth is reached.

Philpott (1984), Nairn *et al*. (1986) and Kamphuis (1987) argued that the rate of platform lowering is strongly influenced by the rate of wave energy dissipation in the surf zone. They found rapid erosion rates where depth changes quickly and where reflected waves (from backing cliffs or seawalls) concentrate turbulent energy dissipation in shallow water. Skafel and Bishop (1994) suggested that where plunging breakers occur and the turbulence is able to penetrate to the cohesive surface, erosion rates in clear water (no sand) could be comparable to or even higher than those with sand outside the surf zone. Davidson-Arnott and Ollerhead (1995) and Amin and Davidson-Arnott (1997) showed that average annual total wave energy at the shoreline correlates positively with shoreline recession and is a good indicator of it. They argued that the significance of total wave energy as a predictor is greatest where beaches are narrow and there is limited protection from nearshore sediments.

In conclusion, although mechanical wave erosion may be accomplished by a number of processes, few direct measurements have been made. The relative importance of these processes has usually been inferred from morphological evidence, which may be ambiguous.

2.3.3 Biological processes

Most of the previous work on the effects of organisms has been carried out on active intertidal mudflats (e.g. Widdows *et al.*, 1998b) or hard rock platforms (e.g. Fornós, 2002a, b, c, d), but not on cohesive platforms. There is clear evidence, however, that boring organisms make a significant contribution to the erosion of cohesive platforms (Figures 2.5 and 2.6), though not in every location. Bioerosion may be negligible on rapidly eroding platforms, where there is little time for colonisation, whereas it may be important on slow eroding platforms where damaging organisms have time to colonise. The distribution of the biological cover is also regulated by tides, which govern the duration of submersion and exposure of the platform, and hence the absolute abundance of the flora and fauna. This factor may cause significant variations in cross-shore erosion thresholds due to biological factors.

Figure 2.5 Example of bioerosion on the cohesive platform on the Isle of Sheppey, north Kent

Figure 2.6 Example of bioerosion on the cohesive platform on the Isle of Sheppey, north Kent

Biological weathering processes, such as burrowing, are influential in weakening the platform surface, thus paving the way for larger-scale mechanical erosion. Hutchinson (1986) provided an indication of the intensity of bioerosion on a cohesive platform. He found crustaceans living in the top 9 mm of the platform with a density of around 10,000 individuals per square metre, in burrows up to 1 mm in diameter. He also identified boring bivalves, which were up to about 120 mm long with burrows 10-30 mm in diameter. Widdows *et al*. (1998b) found a significant correlation between mudflat erodibility and the abundance of cockles (*Cerastoderma* sp). They suggested that the burrowing activity of this bivalve may provide a significant contribution to sediment erosion. Andrews and Williams (2000) found that on some chalk platforms, limpets may be responsible for as much as 12% of the downcutting in the areas that they frequent.

A major burrowing organism in some clays and mudstones is the bristleworm (*Polydora ciliata)*. This worm forms u-shaped burrows only a few millimetres deep, but in densities that can exceed 20,000 per square metre, greatly reducing the surface strength of the rocks that they colonise. They can thrive even on the upper shore provided abrasion rates are fairly low. By contrast, the bivalve molluscs known as piddocks (particularly *Pholas dactylus* and *Hiatella arctica*) can bore quite deeply into clay and other soft rocks. *Pholas* burrows, up to 15 cm long, and *Hiatella* densities of over 700 individuals per square metre, have been recorded (Irving, 1998). Piddocks are most frequent on the lower shore and in the shallow subtidal zone.

Not all organisms are destructive. Some can reduce rates of platform erosion by protecting the platform surface. For example, the growth of seaweed into dense mats during summer months may blanket a cohesive platform, significantly reducing erosion. In winter, as the seaweed cover diminishes, erosion may increase. However, seaweed does not always have a protective role. Some of the larger seaweeds, such as the wracks (*Fucus* spp.), have relatively tough fronds, which may be repeatedly swept backwards and forwards by the waves, eroding the surrounding platform surfaces. Kelps (*Laminaria* spp.) anchor themselves to rock surfaces with many branched holdfasts. During storms entire plants are often torn up, with the holdfasts removing fragments of the platform, as they become detached.

Often there are complex interactions between animals and plants that control the erosion processes. This is the case on some intertidal mudflats, where the erosion threshold of the uppermost sediment layers is mainly controlled by the relationship between algal biomass (diatoms) and the abundance of deposit feeders, such as the mud snail (*Hydrobia ulvae*) (Austen *et al*., 1999). The diatoms are effective at stabilising the mudflat surface (Paterson, 1989) but *Hydrobia* is a predator of diatoms, and therefore can limit the biostabilisation process by reducing the algal biomass. In addition, *Hydrobia* produces faecal pellets, which tend to reduce the cohesive properties of the sediment with which they are aggregated. *Hydrobia* also move through the sediment resulting in a lower density surface layer which may increase the erodibility of the sediment. A continuum therefore exists between easily eroded areas with high numbers of *Hydrobia* and more resistant areas dominated by benthic diatoms (Austen *et al*., 1999).

In summary, the influence of organisms on the erosion dynamics of cohesive platforms has received little attention. Research is required to understand the contribution of biological erosion relative to marine and subaerial processes, and the relative importance of the erosive and protective effects of the organisms themselves (Stephenson, 2000). Further study is also required into the possibility that the erosion of cohesive platforms may release extra nutrients into the water, stimulating the growth of protective or erosive organisms.

2.3.4 Softening of the fabric due to removal of overburden

As the backing cliff retreats, the emerging platform experiences the effects of unloading. This causes a reduction in pore-water pressure to values below those associated with mean sea level. A process of swelling therefore takes place (particularly in overconsolidated materials) in which the pore-water pressures within the platform recover slowly to their long-term, fully equilibrated values. This reduces the strength of the platform material, as effective stresses diminish and water content increases. The magnitude of the strength reduction will depend upon clay content, mineralogy, degree of cohesion, and stress history of the platform.

Differential swelling will cause further weakening due to localised straining and the opening of fissures and joints. Parallel furrows may form, running normal to the cliff, typically around 0.1-0.2 m in width and depth (Hutchinson, 1986). Many of these features are likely to be eroded stress relief joints whereas others may be exposed shear surfaces.

Except for the work of Bromhead and Dixon (1984) and Hutchinson (1986), little attention has been paid to the depression of pore-water pressures on cohesive platforms. No accurate analyses of this phenomenon, linking the changes of geometry, and stress and strain with the generation and dissipation of depressed pore water pressures, have yet been made.

2.3.5 Softening of the fabric due to pressure fluctuations induced by waves

The strength of cohesive sediment, may be reduced by softening of the surface layers caused by cyclic loading and unloading (pressure fluctuations) related to the passage of waves (Davidson-Arnott and Askin, 1980; Davidson-Arnott, 1986a, b; Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott *et al*., 1999; Davidson-Arnott and Langham, 2000). The softening is manifested as the entry of water into the substrate pore system, leading to generation of positive pore water pressures, decreasing strength close to the surface. Lee and Focht (1976) tested clays under laboratory conditions, and found development of significant cyclic strains under pulsating stresses, and the strength after cyclic loading was less than the normal static undrained strength. Even if the passage of waves does not cause immediate erosion, it is capable of fatiguing the platform material leaving it more susceptible to erosion processes.

The softening process occurs in the top few centimetres of the cohesive sediment (Davidson-Arnott and Ollerhead, 1995; Davidson-Arnott and Langham, 2000) and can take place over a period of months (Skafel and Bishop, 1994). An increase in shear strength occurs with depth in the sediment indicating that softening proceeds from the surface downward. The process leads to the progressive development of soft patches reducing the shear strength to the point where direct erosion by fluid forces is feasible, particularly in deeper water where the cohesive sediment is exposed. As the process probably occurs at different rates across the platform, lowering could be highly variable in the short term, depending on the degree of softening at any given point.

Davidson-Arnott and Langham (2000) found that the shear strength of the exposed cohesive substrate decreased during periods of low wave activity, whereas periods of high wave activity resulted in removal of a layer of softened material, thus exposing harder underlying cohesive sediment. They suggested that erosion during a storm may be related to the thickness of the softened layer that develops during non-storm periods. The softening process may be supported by field studies which have shown that significant erosion of a cohesive substrate can occur in water depths where wave-induced shear stresses are well below the critical shear stress for erosion, and where there is little coarse sediment available for abrasion (Coakley *et al*., 1986; Davidson-Arnott, 1986a, b).

Initial results on the process of softening in glacial till subject to erosion have been published (Davidson-Arnott and Langham, 2000). Further work is required to quantify the rate at which the softening process occurs, to ascertain the thickness of the layer involved in the process, to isolate the effects of softening from those of abrasion and to determine the relative significance of softening in platform downcutting.

2.3.6 Desiccation and wetting

Alternating phases of desiccation and wetting result in the thin upper layers of the cohesive sediment being cracked into polygons (10s of millimetres across, Figures 2.7 and 2.8). The surface of these polygons may then be removed as flakes by the sea. This process is probably confined to the intertidal zone, is probably most active in well-drained areas and greater in summer than in winter. Wetting and drying can also occur as a result of rainfall episodes, although the erosive effect will be different to that caused by tidal cycles since there is an absence of salts.

Figure 2.7 Polygons on the surface of the cohesive shore platform on the Isle of Sheppey, north Kent

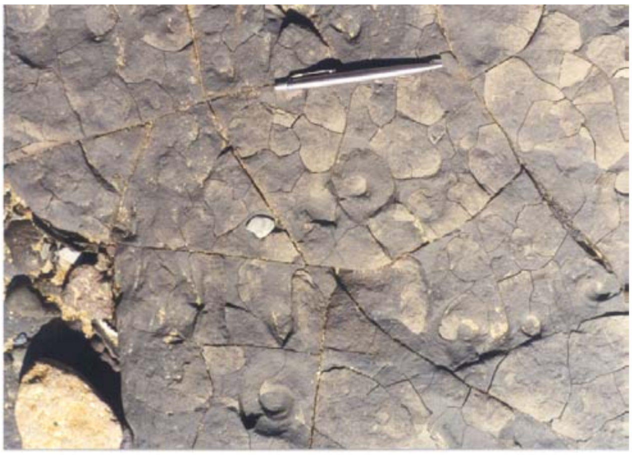

Figure 2.8 Polygons on the surface of the cohesive shore platform at The Naze, Essex

A linear relationship between elevation and the number of wetting and drying cycles does not exist, because of the influence of rainfall, tides and of algal growth during the winter months. Rainfall can reduce the number of wetting and drying cycles if it persists for longer than a tidal cycle, thus preventing the surface from drying (Stephenson and Kirk, 2000a). Also, rainfall must be followed by a sufficient time to allow drying of the platform surface.

The three most commonly described weathering processes on shore platforms related to desiccation and wetting, are salt weathering, water layer weathering and slaking (Stephenson and Kirk, 2000a). Salt weathering operates through a variety of processes including pressures exerted by crystals as they grow from solution, pressures exerted by expanding salt crystals due to heating and pressures from volume changes induced by hydration. The effectiveness of salt weathering is controlled by the nature of the salts and their solutions, the properties of the affected materials (porosity, capacity to absorb water, strength) and the environment in which the salts may cause the materials to disintegrate. Salt weathering occurs wherever pools of water are left after the tide has ebbed and evaporation can occur. It also occurs on areas of the platform that are affected by wave splash and spray. Stephenson and Kirk (2000a) observed flaked and pitted surfaces where salt growth occurred and mechanical salt weathering was argued to be the cause of the surface textures. In coastal environments salt weathering commonly occurs in combination with biological weathering, and the interaction of the two processes is under-researched.

Water layer weathering occurs when shallow depressions on the platform (few centimetres to metres in diameter) contain pools of water several centimetres deep after the tide exposes the platform. Between the depressions small ridges of cohesive sediment that remain upstanding become dry between periods of wetting and show superficial disintegration. The process of water layer weathering remains to be fully explained but salt weathering, wetting and drying, chemical weathering and the movement of solutions through fissures in the platform are thought to be important. Cohesive clay platforms are particularly susceptible because the clay minerals in them expand on wetting and shrink on drying. Seasonal variations are likely to be important in temperate conditions.

Slaking is a weathering process that results from repeated wetting and drying but produces a different morphology from water layer weathering. The products appear as platy or conchoidal fragments. Water attached to clay particles by quasi-crystalline bonds exerts pressures and repeated wetting and drying causes expansion and contraction, resulting in tensional fatigue and fracturing (Figures 2.7 and 2.8).

2.3.7 Physico-chemical effects

Physico-chemical processes strongly influence the properties of the surface layers of cohesive platforms. Arulanandan *et al*. (1975) and Hutchinson (1986) argued that an increase in salt concentration in surface pore water from the intrusion of sea water may increase the net attractive forces between clay particles, increasing the degree of flocculation and hence improving the resistance of the clay to erosion. The degree to which this effect will occur will depend on the clay content and the chemical properties of the cohesive sediment. Hutchinson (1986) concluded that the opposite effect may occur along freshwater shores, where the intrusion of freshwater may dilute the salt or cation content, thus decreasing the net attractive forces between clay particles, and increasing the susceptibility to erosion. This suggests that the clay shores of freshwater bodies (such as the Great Lakes) are likely to be more susceptible to a given degree of erosive wave attack than the shores of seas.

Arulanandan *et al*. (1975) showed that the effect of salt concentration on critical shear stress is more pronounced at low values of sodium adsorption ratio, and that the critical shear stress for erosion decreased as the sodium adsorption ratio increased. At high values of sodium adsorption ratio, repulsive forces between particles predominate and produce significant swelling. This causes a decrease in the interparticle bonding force and thus the critical shear stress required to promote surface erosion is reduced. At low values of sodium adsorption ratio, critical shear stress decreased significantly exhibiting a large decrease for a small increase in sodium adsorption ratio. For higher values of sodium adsorption ratio, the decrease of critical shear stress with increasing sodium adsorption ratio is relatively small.

In summary, the mechanisms by which fresh or salt water enters the pores of cohesive platform sediments are complex (e.g. seepage and diffusion) and no specific work has been carried out.

2.3.8 Freeze-thaw (frost)

Frost weathering has been recognised as an important factor in the development of shore platforms in environments that are colder than the United Kingdom (Trenhaile and Rudakas, 1981; Matthews *et al*., 1986) and as a process formerly active during the cold conditions of the Late Glacial (Dawson, 1980; Larsen and Holtedahl, 1985). Although the process is rare in the United Kingdom, during extreme winters there is evidence that freeze-thaw can cause severe damage to shore platforms. For example, Harris and Ralph (1980) described frost-induced lowering of the London Clay platform at Clacton by 0.3 m in a few weeks, during the hard winter of 1962/63.

Shore platforms are potentially susceptible to freeze-thaw conditions whenever air temperatures are below freezing, but the sea remains unfrozen. Each time the tide falls, the platform surface, saturated or nearly saturated with seawater, is exposed to freezing conditions. When the tide returns, submersion in seawater with its high thermal conductivity will quickly lead to thawing of any ice formed. Thus, low temperatures may only cause frost damage to shore platforms when they coincide with low-tide conditions. Rapid thawing by tidal inundation may increase the effectiveness of frost weathering. A higher number of freeze-thaw cycles will increase material fatigue.

Cycles of freeze-thaw can be important on frost heave susceptible materials, especially porous chalk. Robinson and Jerwood (1987a, b) found that chalk is very susceptible to weathering by frost, particularly when it is saturated with sea water. Chalk absorbs water rapidly when immersed. Robinson and Jerwood (1987a, b) argued that frost weathering occurred in chalk platforms along the south coast during the harsh winters of 1985 and 1986. They suggested that a combination of frost and salt, and not frost alone, is particularly destructive to shore platforms during periods of exceptionally cold weather. Frost alone is capable of causing saturated chalk breakdown but frost damage is markedly increased by the presence of salts, although the precise mechanism by which enhancement occurs requires further work (McGreevy, 1982). The influence of the combination of frost and salt weathering on cohesive sediments is unknown, but it may cause the break-up or significant softening of platform surfaces during cold winters.

Dionne and Brodeur (1988) identified the processes of frost shattering and wedging as important in the breakdown of platforms in subarctic regions. Frost wedging is the prizing apart of fragments of the platform by ice formed in open fissures. The magnitude of this process varies according to lithology. Allard *et al*. (1998) investigated a subarctic platform composed of Holocene clays and found that freeze-thaw processes controlled by the presence and thermal and hydrological behaviour of the ice foot were the principal agents of platform erosion. Thaw liquefaction and freeze-thaw weakening reduces the cohesion of the surface layers of the clays, which are then transported from the platform by waves and tidal currents.

3. The platform-beach-cliff system

If a cohesive platform is associated with a beach and cliff then its downcutting is best understood in the context of a broader geomorphological system that includes all three.

3.1 Sandy shorelines v cohesive shorelines

The processes active on cohesive shorelines are different from those on sandy shorelines. Erosion and deposition on sandy shores is directly related to the removal or addition of sand, with profile changes occurring rapidly to maintain equilibrium. Short-term erosion is often reversible (due to natural processes), while erosion on a consolidated cohesive shoreline is irreversible. Understanding of long-term erosion on a sandy shoreline requires an assessment of sediment budget on a coast-wide basis. Factors that determine sediment budget include longshore sand transport rates, interruptions to transport and bypassing, offshore and onshore movement, cliff recession rate and erosion yield.

Cohesive platforms are generally defined by an insufficient supply of non-cohesive sand and gravel, and generally no permanent and continuous beaches form as a result of cliff erosion. However, any non-cohesive sediment that rests directly on a cohesive platform can act as either a protective cover, if thick enough, or as an abrasive if the cover is thin. So, even when a beach is present, if it is underlain by cohesive sediment, it may act as a cohesive platform. The sand veneer often disguises the underlying cohesive substrate, and therefore, at many locations cohesive platforms may be incorrectly assumed to behave as sandy shores.

3.2 Cliff recession-platform downcutting relationship

It is generally agreed that the primary control on the long-term rate of cliff toe erosion is the rate of vertical lowering of the beach and platform (Davidson-Arnott and Askin, 1980; Philpott, 1984; Hutchinson, 1986; Kamphuis, 1987; Davidson-Arnott *et al*., 1999). Hutchinson (1986) suggested that cliff erosion follows at a rate that the platform erosion permits (Figure 3.1). While subaerial weathering processes may dictate when and where a slope failure will occur, the frequency of failures over the long term is strongly determined by the rate at which the platform profile is eroded.

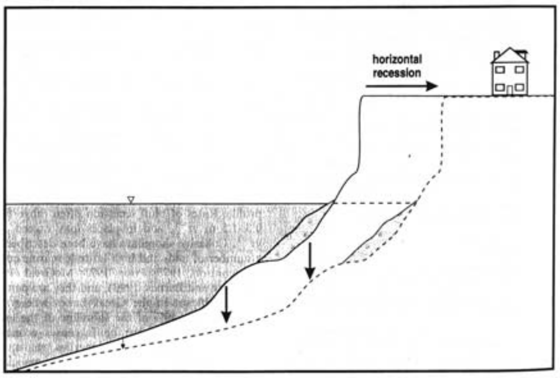

Figure 3.1 Profile of an eroding cohesive shore with backing cliff. Vertical lowering of the nearshore must accompany horizontal recession of the cliffs in order to maintain an equilibrium (from Davidson-Arnott and Ollerhead, 1995)

Where shoreline recession is rapid and longshore transport removes coarser non-cohesive sediments, the whole profile retreats uniformly, while maintaining a relatively steady shape. This necessitates an increase in platform downcutting rates towards the shore thus allowing for the preservation of the profile shape as it shifts shoreward with time. The observation that the profile tends to retain its shape as it recedes suggests that toe erosion is in dynamic equilibrium with platform lowering and a characteristic cohesive profile shape exists.

The formation of a dynamically stable profile can be illustrated by considering the likely behaviour following situations where, for some reason:

- the platform lowers excessively whilst the cliff remains temporarily static;
- the cliff toe retreats excessively whilst the platform remains temporarily static.

Following (a) it is likely that the cliff toe will rapidly retreat due to its proximity to deeper water and larger waves, leaving behind it a new, higher platform. Over time the cliff retreat rate will lower to its average rate as the platform returns to its characteristic shape. The likely cliff behaviour subsequent to (b) is that the cliff toe will retreat at a reduced rate due to the increased protection provided by its uncharacteristically wide platform. The platform will continue to erode, decreasing the level of protection to the cliff and gradually allowing the cliff retreat rate to return to normal.

The emergence of a dynamically stable profile form shows that the retreat rates of the cliff and platform tend to equalise and consequently the long-term rate of cliff retreat can be directly related to the rate of platform downcutting and the associated profile retreat, by the equation:

$$d = r.\tan\alpha$$

where d = vertical rate of platform lowering, r = corresponding horizontal rate of cliff erosion, α = platform gradient at a point.

If this equation is applied to the Holderness coast where r ~ 2 myr^{-1} and $\tan\alpha$ ~ 0.01, then a vertical platform erosion rate of about 0.02 myr^{-1} is calculated. For the long-term evolution of the shore (over centuries) this represents a reasonable approximation. However, cliff recession is measured at the scale of decades, whereas platform lowering has often been measured over a period of a few years. Since platform development is thought to occur over longer time scales (1000s of years), extrapolating short-term data may not provide a reliable estimate of rate of development. This problem is compounded by climate change, which means that future wave conditions and rates of sea level rise (and therefore recession) will be different to those acting during recent history (Section 3.4).

Cliff recession is controlled directly by wave attack at the cliff toe, which is linked to average annual wave energy flux at the break point through a series of controlling factors which reflect sea level, beach slope and sediment supply. However, over the long-term the overall rate of profile adjustment and shoreline recession is dependent on the vertical lowering of the nearshore profile, which itself is more directly linked to the average annual wave energy flux at the break point (Davidson-Arnott and Ollerhead, 1995). Thus, while wave energy at the break point is only an indirect measure of wave energy reaching the cliff toe, it does appear to provide a reasonable measure for predicting long-term recession rates (Amin and Davidson-Arnott, 1997).

The profile retreat model for cohesive shores implies that the amount that the driving forces for erosion exceed the resisting forces is inversely proportional to the water depth. The most active erosion occurs towards the shoreline. In general, it may be assumed that the erosion resistance of the cohesive sediment is consistent across the profile. Therefore, the driving force for erosion must increase in the shoreward direction.

Amin and Davidson-Arnott (1997) carried out a statistical analysis of the relationship between cliff recession and wave energy, sediment availability, potential longshore sediment transport rate and cliff height. They found that longshore variations in cliff recession are controlled primarily by variations in total wave energy reaching the shoreline and by the degree of protection by surface non-cohesive sediment. They studied cliffs with alongshore uniformity, such that material strength was regarded as a constant, thus permitting evaluation of other factors. They concluded that in areas of more complex stratigraphy it would be necessary to include some measure of the strength or resistance of the cohesive material in order to achieve the same level of explanation.

3.3 Beach-platform interaction

Any non-cohesive sediment lying on the platform must be mobilised before the underlying cohesive material can be eroded (Section 2.3.1). This does not mean that all of the sediment must be mobilised by all wave conditions and in practice it may only be moved under storm conditions. Changes to the beach produced for example by variations in the longshore sediment transport can have profound effects on the intensity of erosion of a cohesive clay shore.

If a non-cohesive beach is to provide adequate protection to a cohesive shore it must be high enough and wide enough that the cliff is beyond the reach of most extreme combinations of water level and wave action. The beach must also extend below water to the limiting depth for significant erosion of the underlying profile, which is related to water levels, incident wave power and the erosion resistance of the cohesive bed. The beach deposit must also be thick enough so that it is not fully mobilised or dynamically influenced by the impermeable cohesive material beneath. This means that there must always be enough beach material in place to fully cushion the effects of wave pressure fluctuations including those that occur under breakers in the surf zone.

Amin and Davidson-Arnott (1997) found that sediment availability for beach building has a negative correlation with shoreline recession, indicating that recession is generally lower where there is more sediment available to form a protective beach. They argued that this probably provides a better prediction of the recession rates in areas where there is sufficient sediment to provide an effective cover, and it is probably more important than wave energy in these areas.

Generally, if a beach is present at a cohesive shore it is likely to be comprised of sediment released locally or moved in by longshore transport. If the platform and cliff are good sources of non-cohesive sediment then the material released will tend to increase the size of the beach. Larger beaches are capable of providing more protection against wave erosion, so this trend will act to reduce cliff retreat. If beach material were not removed by other means it would continue to build and cliff retreat would continue to drop. In general, however, hydrodynamic processes remove beach material, deplete its volume, reduce its protective capability and so promote erosion, shore retreat and the release of more sediment. If a beach remains then this tendency to remove sediment must be balanced by the supply of sediment, and in this way the local differential in sediment transport rate can be a strong determinant in shoreline retreat.

Platforms receive less protection from intermittent sparse beaches, and in this situation the relationship between shore retreat and transport differentials is less strong, but the beach can still exert a strong influence on the profile. Kamphuis (1990) demonstrated that cohesive platform profiles with very little overlying sand were similar in shape to profiles of completely sandy beaches along the same shoreline. In other words the eroded cohesive bed closely resembles the equilibrium shape that the overlying non-cohesive sediment would take in the absence of a cohesive substrate. Where the cohesive profile is lower than the natural profile for the non-cohesive sediment, the latter will deposit out of the fluid, into these depressions. Such deposited sediment then provides localised protection to the cohesive bed. When cohesive material protrudes through a beach, the non-cohesive sediment will be mobilised over the high spots, abrading them rapidly. By this process the eroded cohesive shore profiles eventually come to resemble stable profiles for the sand sizes overlying them.

Kamphuis (1983) found that the presence of an impermeable platform beneath the beach increased beach mobility. The impermeable layer prevented the complete dissipation of pore water pressures and caused a reduction in the net strength of the sand layer and its net resistance to removal by waves. He concluded that an impermeable layer would begin to effect the sediment transport process at a water depth approximately twice the depth for significant movement of the beach material.

Powell (1990) conducted model tests on shingle beaches of varying thicknesses (up to 325 mm) and particle sizes above an impermeable layer in a laboratory wave flume. He found that the effect of an underlying impermeable layer on the resultant beach profile could be categorised according to the ratio of the beach thickness and the median particle size. Shingle beaches with a ratio of less that about 30 generally led to exposure of the impermeable layer and the beach structure broke down. For ratios between 30 and 100 the profile was distorted but the effects confined mainly to horizontal displacements, and for ratios greater than 100 the beach profile was largely unaffected.

3.4 Sea-level rise and storminess

Erosion at the base of a cliff is a critical factor in maintaining cliff instability, so the shore platform and its sediment cover ultimately control cliff retreat by dissipating energy. This cliff-platform relationship will be complicated by potential future sea-level rise. Bray and Hooke (1997) recognised two different scenarios, each having a different response to sea-level rise:

- Bare platforms that regulate erosion through their geometry. Typically, they erode and widen as sea-level rises;
- Platforms covered by protective sediments that can accumulate to form beaches at the cliff toe. These can potentially build-up to preserve the profile morphology with rising sea level.

As a cliff retreats the platform widens so that wave dissipation increases. At the same time the platform is being downcut and is gradually inundated by rising sea levels. For shores that mature to a state of dynamic equilibrium the wave dissipation and rate of sea-level rise produce a distribution of erosion that tends to maintain the profile shape. A change to incident wave conditions (and therefore wave dissipation) or rate of sea-level rise would be expected to produce different distributions of erosion and, consequently, different profile shapes and retreat rates.

Generally, higher rates of sea-level rise are expected to cause greater retreat rates. This is because, unless countered by enhanced sedimentation, sea-level rise should produce increasing nearshore water depths that allow waves to break further inshore. This is especially important over platforms with no beach. Higher sea levels would also reduce the return frequency of extreme sea levels produced by storm surges (i.e. increased storminess) and erosive events at the cliff toe would become more frequent. However, the role of the shore profile is not fully understood; it appears to act as a regulator to the recession rate and may mitigate effects of climate change. In addition, higher recession rates imply increased beach volumes, which will tend to reduce erosion, so the response of a shore platform to sea-level rise and increased storminess must be considered in the context of the broader geomorphic system.

4. Measurement techniques

A variety of techniques have been adopted to understand different aspects of cohesive platform erosion and beach change. These can be divided into techniques that are used to measure platform downcutting, those used to analyse beaches (or cliff recession; Lee, 2002) that have a bearing on broad-scale platform evolution and those used to measure material properties in the laboratory and *in situ*. Remote sensing techniques can be applied to look at broader scale changes both to the beach, shore platform and any backing cliffs.

4.1 Techniques to measure platform downcutting

4.1.1 Micro-erosion meter

The micro-erosion meter was initially developed by High and Hannah (1970) since when, it has been modified for a variety of purposes including analysis of erosion of cohesive platforms (Askin and Davidson-Arnott, 1981) (Figure 4.1). In essence, it consists of an equilateral triangular base on which is mounted a vertical pointer which can be rotated to the centre of each side and allowed to drop to the bed. The pointer is connected to an engineer's dial gauge so that the distance to the bed can be measured with a high degree of precision. At each measuring station three pins are fixed in holes drilled into the cohesive substrate and the meter can be relocated precisely for successive measurements. Measurements are made at the mid-point of each side, away from possible disturbance caused by emplacement of the pins.

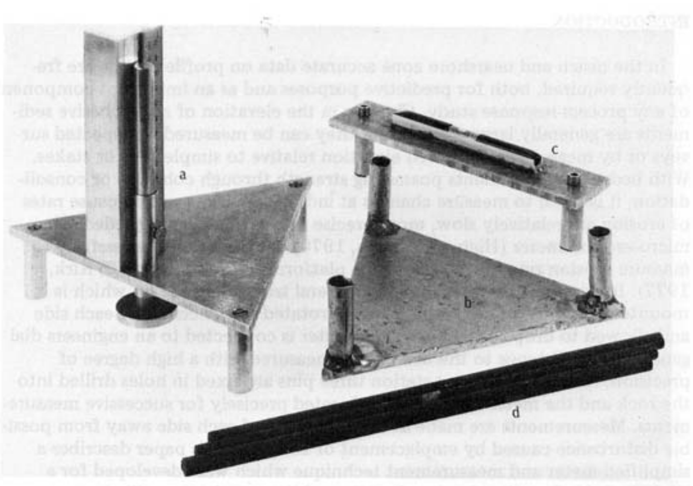

Figure 4.1 A micro-erosion meter and ancillary equipment. a) micro erosion meter; b) template used as a guide during installation of pins; c) levelling bar; d) steel pins (from Askin and Davidson-Arnott, 1981)

Although the micro-erosion meter facilitates the measurement of platform erosion rates, the responsible processes must still be inferred from the erosion data (Smith *et al.*, 1995; Moses *et al.*, 1995). The technique is also incapable of considering the quarrying of large rock fragments, and shares with other techniques the difficulty of assessing the role of high magnitude, low frequency erosive events. Abrasion of softer cohesive substrates by the pointer may reduce the accuracy of measurements compared to use of the instrument on harder rock surfaces.

4.1.2 Underwater abrasion table

Schrottke (2001), Schrottke *et al.* (2003) and Schwarzer *et al.* (2003) reported the abrasion of the submarine platform in front of cliffs in the Baltic Sea measured over a period of three years. Platform and cliff are made of glacial till and thus similar to parts of the United Kingdom coast. However, a major difference occurs in that the platform along the Baltic Sea coast is constantly covered by water due to the lack of tides. This meant that the abrasion table had to be operated by divers.

The abrasion table is a three-legged square table made of Perspex and the principle of placing it over the platform surface is the same as for the micro-erosion meter. The table has 36 measurement positions (arranged in a 6 x 6 grid covering an area of ~70 x 70 cm) through which a gauging rod is pushed to touch the platform surface. The gauging rod has a millimetre scale and the divers conducted measurements to an accuracy of ±1-2 mm. The principles behind the measurements are similar to those of the micro-erosion meter, as are some of the limitations. However, it can be operated under water by divers and covers a larger area than the micro-erosion meter.

4.1.3 Micro-scale laser mapping

Recently, micro-mapping of platform surfaces by use of a state-of-the-art laser suspended from a portable aluminium frame and driven by computer controlled stepping motors has been shown to produce accurate measurements of the rates and patterns and of surface downcutting and change (Williams *et al*., 2000). Accurate to 0.025 mm, the instrument is capable of taking one measurement each square millimetre covering an area 0.4 x 0.4 m in 2 hours, i.e. 160,000 individual measurements. Overlying images taken over intervals of time enables downcutting rates as low as 1 $mmyr^{-1}$ to be measured. The instrument is robust, but can only be used on dry platform surfaces, which limits its use to the higher parts of the platform that dry out between tides.

4.2 Techniques to analyse beaches and broad-scale platform morphology

Field techniques for assessing surface and sub-surface conditions and the extent of sand cover or protective lag across the cohesive profile include beach profiling, sediment sampling and analysis, macro-scale laser scanning and GPS surveys. These techniques have numerous applications with respect to broad-scale development of a cohesive shore system. For example, they allow evaluation of the elevation of the top of beach sediments at the toe of the cliff, which may be directly related to toe erosion of the cliffs. The techniques are able to map the longshore beach-top profile allowing the areas of low beach levels, where the toe of the cliff would be vulnerable to wave attack at high tide, to be located.

4.2.1 Beach profiling

A common form of measuring changes in beach dimensions is beach profiling. Beach morphology can be monitored using cross-shore profile data to assess changes in width, slope and volume, and to describe beach behaviour and its variability. These data can be used to identify trends and areas of high net change and high variability.

The frequency of profiles depends on the specific aim of the measurements. In developing a profiling strategy it is essential that the limitations of the method are recognised at the outset. Thought must be given to how and when the data are collected and over what time period. For example, because of natural variation on the coast, the true pattern of beach change may only become apparent after a long period of time. Possibly time-scales longer than five years may be required before trends can be distinguished.

Several techniques of varying sophistication are available for collecting beach survey data. The least sophisticated method (although not necessarily the least accurate) is survey using a quick set level, staff and chain. More advanced methods include using a total station with electronic distance measurement to a survey reflector prism and computer logging of data points. Geographical Positioning Systems (GPS) with centimetre accuracy can also be used to create three-dimensional maps of the beach surface that can be input directly to a Geographic Information System (GIS).

4.2.2 Sediment sampling and analysis

Beach sediment composition and distribution can be evaluated by a campaign of surface and sub-surface sampling followed by laboratory analysis. The campaign should start with a qualitative assessment of the sediments at the surface and at depth. Sample sites can then be selected based on these observations to reflect sediment variability across the area. Laboratory analysis will determine particle size and other textural parameters, which can be interpreted in the context of sedimentary processes and temporal change. Maps of the temporal and spatial variability can then be constructed.

4.2.3 Macro-scale laser scanning

High-resolution long-range (2 km) laser scanning provides a new state-of-the-art technique for generating 3-D profiles of cliffs, beaches and cohesive platforms at low tide (Hobbs *et al*., 2002). The laser scanning apparatus effectively operates as a terrestrial LiDAR device (Section 4.3.2). Scans provide digital data and repeat surveys can be carried out for monitoring purposes.

The laser reflects off most natural and man-made surfaces and is capable of being used in automatic “scanning” or manual “backsight” modes. This enables a random sweep of the subject to be combined with individual points selected using the telescope sight; these latter can be points of geological interest or survey points to help orient the scan within a grid reference system.

The resolution of the laser is 25 mm under ideal conditions, although the accuracy of a scan is dependent on the following factors:

- the accuracy of location of the device, and backsights;
- the geometric configuration of the scan and subject;
- the levelness and steadiness of the scanning platform.

The device gives a poor (or nill) return from vegetation and water. This is because the laser cannot resolve moving objects, and bounces off water. This may present a problem when scanning a smooth sandy beach with standing water, but should not present a major problem in the case of an irregular cohesive platform scanned at low tide. The most likely method for scanning a beach and cohesive platform would be to set up the instrument on the cliff top, i.e. the reverse of cliff scanning. In the absence of a cliff, or other vantagepoint, the scan would have to be made from the platform itself.

4.2.4 GPS surveys

GPS surveys offer an alternative tool for beach profiling. The surveys can be carried out in shorter times than traditional beach profiling, allowing a dense spacing of the profiles and thus provide the necessary data density to feed into digital terrain modelling. Real time kinematic GPS can be used to survey large areas with a vertical error in the order of ±3 cm using a wheel attached to the antenna pole, or about ±6 cm using an antenna mounted on a buggy or vehicle (Sallenger *et al*., 2003). The density of points collected along the survey path can be as high as 5 points per metre.

To provide higher level accuracy, static GPS can be used to survey individual points with a vertical accuracy of a few millimetres by occupying a point for ~10 seconds. The high accuracy of static surveys makes it possible to relocate points previously surveyed without marking them on the ground. Results can then be produced that are almost comparable with micro-erosion meter measurements, although the “point” to be surveyed would cover a few square centimetres rather than the “pin-point” used by micro-erosion meters. On smooth surfaces this would not pose a problem and the speed of data collection combined with the fact that no fixed points are required on the surface to be measured, might counterbalance shortcomings in the vertical accuracy.

4.3 Remote sensing

In view of the costs and practical difficulties of regular measurement of large areas of coast for elevation change by *in situ* methods, there is an increasing role for remote sensing techniques from aircraft or satellite. Remote sensing has the potential for large spatial coverage with high resolution, which would not be practicable with *in situ* methods. For example, experience is being gained with technologies for measuring elevation, such as airborne Laser Induced Direction and Range (LiDAR). Surveys repeated every 6 months would provide digital data to indicate broad-scale changes in elevation (and cliff recession) through time.

4.3.1 Satellite imagery and aerial photographs

Satellite images provide a snapshot of a large area providing a broad scale impression of the shore. However, the limitation of satellite imagery is that it has only become available over the last 25 years or so and therefore it has limited historical significance. Satellite images also lack the ability to extract height information and usually have a ground resolution of at least several metres. As such, it is important to refer to information available from traditional aerial photography. Yearly vertical aerial surveys of a shoreline can provide quantitative data on large-scale changes of the coast, such as the retreat of cliffs and changes in beach position and extent (Figure 4.2).

Figure 4.2 Aerial photograph of the cliffs, beach and shore platform at The Naze, Essex

4.3.2 LiDAR

Airborne laser scanning (LiDAR) is a remote sensing technique for the collection of topographic data. It uses laser technology to “scan” the ground surface, taking up to 10,000 observations per square kilometre. These observations are then converted to the local co-ordinate and elevation datum by the use of differential GPS.

The system routinely achieves vertical accuracies of ±11-25 cm (Sallenger *et al.*, 2003) and plan accuracy of ±45 cm, with a very rapid speed of data capture (up to 50 km^2 per hour). This rapid data capture, coupled with the relatively automatic processing system can result in quick delivery of results. The system can operate both day and night, and with light cloud cover, although it is affected by rain. It can operate on beaches and shore platforms but care needs to be taken in areas of standing water as with the normal settings the laser beam is absorbed by water rather than reflected.

4.4 Techniques to measure material properties in the laboratory

The most common approach to quantifying the relationship between erodibility and shear stress applied under given flow conditions is to conduct laboratory experiments. Testing is performed on samples extracted from the field to provide an indirect assessment of erodibility. Lefebvre and Rohan (1986) showed that the shear stress required to initiate erosion for remoulded samples was much less than that of undisturbed samples, indicating that the acquisition of undisturbed samples for testing is an important requirement. They showed that resistance to erosion of undisturbed samples is at least an order of magnitude greater than that of remoulded or reconstituted samples.

Samples extracted in the field for laboratory testing can be removed intact to preserve the natural structure of the cohesive sediment, using several techniques. These include coring, box coring and cutting (chainsaw or trenching chain). Borehole information may be valuable for assessing variations in stratigraphy both above and below water level.

Several laboratory techniques for assessing erodibility can be used. These include:

- Flow and wave flumes
- Rotating cylinder
- Pinhole test

4.4.1 Flow and wave flumes

Erodibility in a laboratory setting can be assessed by creating a nearshore profile in a wave flume or basin (Kamphuis, 1990; Bishop *et al.*, 1993; Skafel and Bishop, 1994; Skafel, 1995). Intact samples are exposed to different flow conditions and the erosion of the sample surface is surveyed intermittently to determine erosion rates for the different conditions. These tests are typically performed for both clear-water and sand-in-flow conditions to elucidate the importance of sand as an abrasive agent. The tests include an assessment of the relationship between wave properties (wave height, orbital velocity, type and fraction of broken waves) and local erosion rate, and the relationship between sand cover and erosion rates.

The main difficulty of using physical models on cohesive shores is scaling the cohesive material. At present, it is not possible to accurately scale cohesive sediment with respect to its erosion resistance properties. Therefore, model tests must be interpreted qualitatively, or full-scale tests must be conducted using low wave energy conditions. Nevertheless, the tests have been extremely valuable in advancing the understanding of cohesive shore erosion processes both inside and outside the surf zone.

4.4.2 Rotating cylinder

Laboratory erodibility tests can be carried out using a rotating cylinder apparatus (Arulanandan *et al*., 1975; Zeman, 1986). A long cylindrical sample is mounted inside a larger transparent cell. The cell is filled with water and rotated at pre-set speeds, with the sample held stationary. During rotation the torque transmitted to the inside stationary cylinder is measured to quantify the shear stress applied to the sample. Erosion rates are determined by the loss in mass of the sample (after 60 seconds of erosion). The torque and mass loss can be recorded at 50 rpm increments. The test is terminated when major degradation of the sample takes place or when the rotation speed reaches 1800 rpm. Zeman (1986) defined the critical shear stress as the lowest stress applied to the sediment surface at which erosion was quantitatively detected.

This method is advantageous because the procedure is relatively rapid, the shear stress applied can be directly computed from torque and does not have to be derived from flow velocity, and significantly higher shear stresses can be generated than in flume tests. However, the method does not allow the introduction of sand to the flow to assess abrasion, it does not permit testing of samples that are too soft or have low cohesion, and it cannot test samples under oscillatory flow conditions.

4.4.3 Pinhole test

Laboratory erodibility tests can be carried out using an adaptation of the standard pinhole test (Rohan *et al*., 1986; Lefebvre and Rohan, 1986). Distilled water is circulated through a hole drilled through the axis of a cylindrical sample. The head loss caused by friction in the sample is measured using differential manometers in order to assess the shear stress applied to the sample by the flow. The head is generated by gravity and controlled by a flowmeter. The flow velocity is increased by 0.5 ms^{-1} every 15 minutes. At the end of each increment, the eroded sediment in the circulating water that has been deposited in a sedimentation basin at the exit of the sample is dried and weighed to determine erosion rate. Lefebvre and Rohan (1986) defined the critical shear stress as the lowest stress applied to the sediment surface at which erosion was quantitatively detected. Depending on the size of the hole bored in the sample, it is possible that this technique could be adapted to assess the influence on erosion of sand in the flow.

4.5 Techniques to measure material properties *in situ*

4.5.1 *In situ* measurement of shear strength

Undrained shear strength in the field can be determined using a cone penetrometer or vane shear apparatus. Ultra-lightweight devices are available that enable a cone penetration test to be carried out to depths of 5 m in soft sediments by a single operator, without the use of an engine. Whilst the test is not strictly a cone penetration test, in that the force is not applied continuously by hydraulic pressure, the geometry of the cone and the principle of operation are the same.

Unlike most types of cone penetrometer test or probe it measures the force applied by a hammer using an accelerometer, rather than a weight dropping a fixed distance or some other motorised power source. This means that considerable saving in weight is made, and the device does not have to be used in the vertical position. This gives it much greater flexibility as a geotechnical investigation tool, and allows it to be smaller, lighter, and more portable than other types. Data logging is digital, and a detailed profile of cone resistance versus depth can be obtained in most soft-cohesive or loose materials.

There are two 60^{o} cones available; a small (2 cm^2) re-usable cone which is retrieved, and a large (4 cm^2) cone, which is not. These enable most test conditions to be dealt with, without the rods becoming jammed. The device is capable of detecting quite subtle lithological and geotechnical changes in the profile, and is ideal for use on cohesive platforms.

4.5.2 *In situ* measurement of erosion resistance

Most research on the engineering properties of cohesive sediments has been carried out using laboratory testing. Whilst these improve understanding of the processes, the test conditions vary significantly from the field. The sediment will have changed due to the effects of transport and storage, and the environmental conditions may be rather difficult to simulate in the laboratory. For this reason, *in situ* measurements are invaluable. Numerous types of flume have been developed to measure the erosive resistance of cohesive sediment (Young, 1977; Amos *et al*., 1992a, b; Williamson and Ockenden, 1996; Widdows *et al*., 1998a, b; Houwing, 1999; Tolhurst *et al*., 1999). The flume generates the conditions of a shear force imposed on the mud surface by a flow of water. Several of the recently developed flumes are described here.

Houwing (1999) measured the shear strength of an intertidal mudflat using an *in situ* erosion flume (Figure 4.3). The apparatus is designed to exert a controlled shear stress on the bed. The flume is a circulating flow system where the flow of water is generated by a propeller, which can rotate at various speeds. The flow velocity in the horizontal section at the bed is measured by an electromagnetic flow meter, to an accuracy of 0.01 ms^{-1}. The suspended sediment concentration is measured using an optical sensor. The bed shear stress is determined from the measured velocity profile assuming a logarithmic distribution in the vertical direction.

Current velocity is increased in discrete steps until erosion of the bed starts (as observed by an increase in suspended sediment concentration). The length of each step lasts from when erosion started to when it stops. The current velocity is then again increased until erosion is once more observed. Critical erosion stress is calculated from scattergrams of suspended sediment concentration plotted against applied bed shear stress.

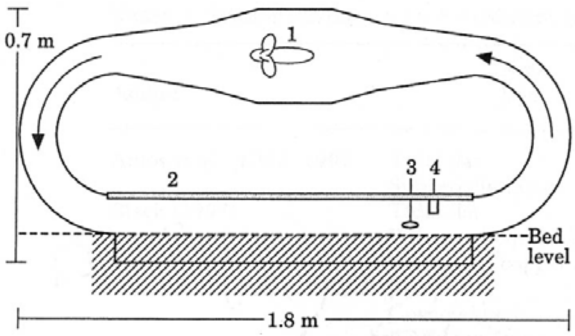

Figure 4.3 Schematic layout of the *in situ* erosion flume (ISEF), 1) propeller; 2) perspex cover plate; 3) elecromagnetic flow meter; 4) optical turbidity sensor (from Houwing, 1999)

Williamson and Ockenden (1996) developed an instrument for measuring shear stress for erosion *in situ* on mudflats (Figure 4.4). The instrument is constructed around a bell-shaped funnel, which rests just above the bed. Water is drawn up through its centre by smooth pumping and replaced by water drawn down the sides. The bell head is shaped so that water flow across the bed is laminar and flows radially towards the bell centre, exerting an approximately even shear stress across the whole of the bed. Turbidity is measured using a nephelometer. Turbidity, flow and the gap between bed and bell are measured during the test, and shear stresses are applied to the bed at time intervals. The point of surface erosion is recorded as an increase in turbidity relating to significant removal of material from the bed surface. Erosion shear stress is defined as the minimum applied bed shear stress required to initiate erosion and to remove sediment from the bed surface.

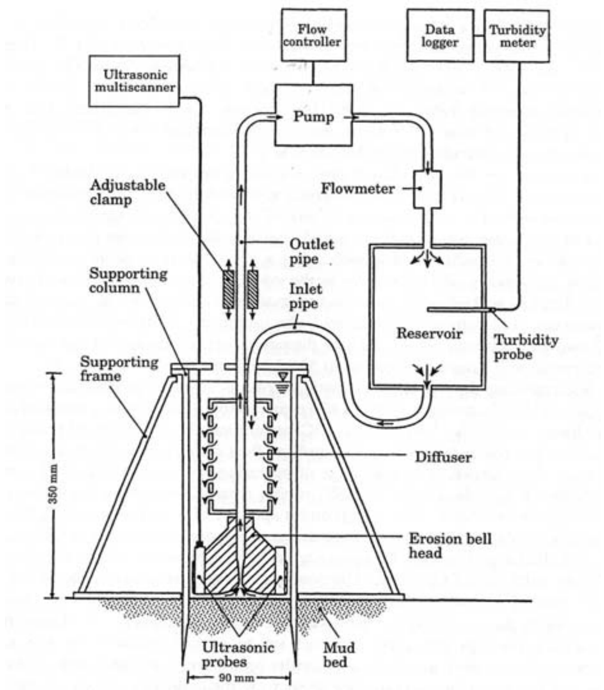

Figure 4.4 Schematic diagram of ISIS (instrument to measure erosion shear stress *in situ*) showing the major components of the system for a field deployment (from Williamson and Ockenden, 1996)

Widdows *et al*. (1998a, b) used an *in situ* annular flume to measure the erosion potential of intertidal mudflat sediments (Figure 4.5). A rotating annular drive plate creates flows in the annulus generating bed shear stresses. Suspended particulate matter is measured using an optical backscatter sensor. Sediment resuspension and sediment erosion rates are measured in response to a stepwise increase in current velocity. Calculation of shear stress is based on a log profile of current velocity within 1 cm above the bed.

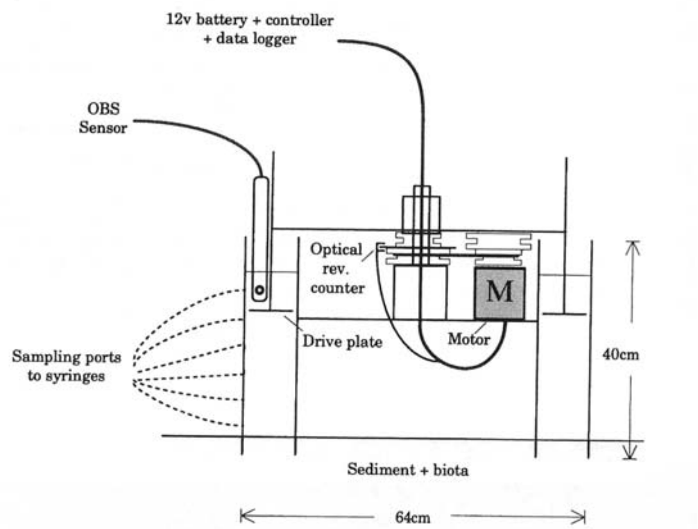

Figure 4.5 Schematic diagram showing *in situ* annular flume (from Widdows *et al*., 1998b)

Tolhurst *et al*., (1999) described their cohesive strength meter designed to determine the critical erosion stress of intertidal and marsh sediments in a semi-quantitative way. The equipment employs the eroding stress of a perpendicular jet of water fired at the sediment surface in short pulses. By sequentially increasing the force of the jet, the point of incipient scour can be identified. This is determined by the reduction of light transmission across the test chamber as the bed fails.

For each run, the lowest value of transmission during the first 1.2 seconds for each pressure step was determined and plotted to produce and erosion profile. The erosion profile has three parts. First an initial horizontal profile, where the transmission values are near or at 100%. Second, a slope representing the drop in transmission of light across the chamber as erosion occurs. Third, an asymptotic region where transmission values approach zero as pulse pressure increases. The profiles vary depending on the properties of the sediment. The critical erosion threshold is defined as the pressure step at which transmission falls below 90%.

4.6 Numerical modelling

The development and application of numerical models for describing erosion processes on cohesive shorelines is not far advanced owing to the complexity of the processes involved and the range of scales over which they act. Essentially a numerical model of the erosion of cohesive shores must represent the erosive potential of waves (F_w), the capability of the *in situ* material to resist (F_R) and the influence of mobile sediments that may enhance, reduce or prevent erosion (Section 2.3.1). The foreshore profile shape is also very important because it can concentrate or distribute F_w. Universal agreement is still to be reached on the hydrodynamic and geotechnical properties that F_w and F_R should represent, although there has been specific attention on hydrodynamic shear forces and material shear strength (Kamphuis, 1990; Skafel and Bishop, 1994). The geotechnical term is the least supported by the available literature, consequently both the models described below use empirical coefficients to represent material resistance.

Nairn *et al*. (1986) developed a numerical model to simulate the processes on a cohesive shore profile. The model empirically relates downcutting to two processes. First, the shear stresses on the bed, due to wave orbital velocities. Second, the intensity of wave breaking (as indicated by the local gradients in wave energy dissipation across the surf zone) and associated turbulence and jets (due to plunging breakers) impinging on the bottom. The former is dominant outside the surf zone while the latter is dominant in the surf zone. These concepts are in agreement with the observation that the degree of downcutting increases towards the shore, a result that cannot be sustained by a model based only on shear due to orbital velocity. Two empirical coefficients are used to relate the downcutting to these processes. This model forms part of the shore profile model COSMOS (Nairn and Southgate, 1993).

COSMOS describes a two-dimensional shore profile, but includes longshore transport, so it can be used to represent quasi-three dimensional morphodynamics. Tidal variation in water surface elevation is represented and the effect of tidal currents on sediment transport is included. COSMOS deals with storm waves so can only predict over storm durations and cannot represent beach building during calm periods.

Walkden and Hall (2002) developed a process-based shore platform and cliff erosion model called cliffSCAPE. A cross-shore erosion distribution is calculated for each tide using the wave power in the breaking zone, the energy contained in each breaking wave, the rate of energy dissipation, local surface slope, tidal water level variation and a semi-empirical distribution of erosion under a breaking wave field. The protective capability of beach material is accounted for in a simple manner. This model describes processes at a larger scale than COSMOS, consequently cross-shore sediment transport and erosion are calculated with less precision. Because run times are shorter and longshore sediment transport is represented, larger areas can be modelled over longer periods, and so broad-scale feedback can be captured, for example between foreshore retreat, cliff erosion and beach volume. This means that cliffSCAPE can be used for strategic as well as local studies. The shoreline and platform shapes emerge from the model and can be used to assess model performance.

5. Case examples

There are relatively few detailed studies of the weathering and erosion processes on United Kingdom shore platforms. Studies have tended to focus on broader coastal issues in which the platform has formed a small part of the investigation. More detailed research has been carried out on the processes operational on the cohesive shores of the Great Lakes. However, these shorelines differ from the United Kingdom shoreline in that they are non-tidal, freshwater and regularly freeze over in winter.

5.1 United Kingdom

5.1.1 Triassic Mercia mudstone group of the Severn Estuary

The Triassic Mercia Mudstone Group is composed mainly of mudstones and siltstones. Substantial deposits of halite occur, and sulphate deposits (gypsum and anhydrite) and sandstone beds are common at some stratigraphical levels. The coastal outcrop of the Mercia Mudstone Group in Southwest England and Wales extends northwards from Devon through Somerset and on to both sides of the Severn Estuary. Although platforms of mudstone are exposed along the shores of the estuary, no specific research has been found that was directed at understanding processes of erosion.

5.1.2 Eocene London clay formation of Essex

The cliff and platform at The Naze are composed of relatively uniform, stiff, fissured Eocene London Clay overlain by Crag (Figures 5.1 and 5.2). A sandy beach intermittently covers the platform and is occasionally thick enough to protect it. Erosion of the platform occurs through a variety of processes (Walkden and Hall, 2002). The presence of sand and a reasonably energetic wave climate implies abrasion by sand particles moving across the surface or carried within turbulent water. The bedding planes in the platform appear to be approximately horizontal and there is evidence of small thin sheets of clay being lifted out of the platform. This might be caused by high wave impact pressures within fissures at the bedding planes, or low pressures induced within breaking wave turbulence. The platform close to the cliff toe shows evidence of the removal of small lens-shaped chips, apparently plucked out by plunging waves.

Figure 5.1 View alongshore of the shore platform at The Naze, Essex

Figure 5.2 Close-up of the shore platform at The Naze, Essex

Harris and Ralph (1980) described the London Clay cliffs and platform at Clacton-on-Sea. The platform is around 30-40 m wide and covered by a thin layer of sand. Claystone layers within the London Clay are exposed on the platform and are present in the cliff. The platform has had a long history of erosion, documented back to the late 19^{th} century, necessitating different types of coast protection measures, of varying success. For example, concrete groynes constructed in 1952, resulted in the accumulation of large quantities of sediment on the updrift side. This led to erosion on the downdrift side and exposure of London Clay on the platform, which contributed to failure of the adjacent walls and cliff. Posford Duvivier (2001) compared current clay levels (using trial pits) with those recorded in 1962 (beach surveys prior to groyne construction) to assess platform downcutting rates. The results showed that between 0.4 m and 0.8 m of clay had been lost over 40 years (1-2 $cmyr^{-1}$). During the severe winter of 1962/63, Harris and Ralph (1980) reported that, between tides, frost disintegrated the surface of the platform clay, and that 0.3 m had been removed in a few weeks.

5.1.3 Eocene London Clay formation of north Kent

The cliffs of the northern coast of the Isle of Sheppey comprise London Clay. The intertidal zone comprises a variable coarse-grained beach above a wide (100-500 m), low gradient (0.5^o-2^o) shore platform also cut into London Clay (Nicholls *et al*., 2000) (Figure 5.3). The shore platform is actively eroding under present conditions. Seaward of low water is a wide shallow platform covered by sand.

Figure 5.3 Shoreward view the London Clay cliffs, beach and shore platform on the Isle of Sheppey, north Kent

The cliffs have receded at around 1 myr^{-1} between 1897 and 1998 (Nicholls *et al*., 2000) producing large quantities of fine-grained sediment and small amounts of sand and gravel. The base of the cliff has retreated landward at a similar rate to the cliff top showing that the broad cliff form has been conserved over time. However, mean low water moved 150 m shoreward between 1897 and 1966, suggesting a steepening of the shore platform.

Nicholls *et al*. (2000), suggested that most of the sediment eroded from the Isle of Sheppey coast comes from the subaerial cliff. This they contrast with the Holderness coast where the eroding platform supplies significant quantities of sediment (Balson *et al*., 1998). Hutchinson (1986) described examples of swelling in the London Clay platforms of the Isle of Sheppey (see also Bromhead and Dixon, 1984). He found very high water contents in the surface few millimetres of the platforms.

5.1.4 Eocene Barton Clay formation of Hampshire

Barton (1973) investigated stability and degradation of defended cliffs composed of Barton Clay Formation sediments in Hampshire. They are composed of fissured overconsolidated (sandy) silty clay, which is prone to various types of mass movement. The composition and processes on the platform fronting these cliffs was not investigated.

Coast protection works at Lee-on-the-Solent have had a substantial effect on the morphology of the adjacent Barton Clay shore platform (Figure 5.4). Kemp (1999) described protection of the cliffs with construction of a sea wall and wooden groynes in the 1960s. During subsequent years beach levels were reduced (mainly by storms) leading to exposure of the underlying clay platform. Erosion of the platform was accelerated causing undercutting of the groynes (Figure 5.5). By 1991, the reduced beach levels and concentrated erosion necessitated remedial buttress work along the base of part of the sea wall. Another short section of the sea wall completely failed (Figure 5.6). Kemp (1999) estimated continued losses of beach sediment of more than 0.5 m between 1990 and 1996, and hence continued exposure of the shore platform.

Figure 5.4 Cohesive shore platform comprised of Barton Clay Formation at Lee-on-the-Solent, Hampshire (from Kemp, 1999)

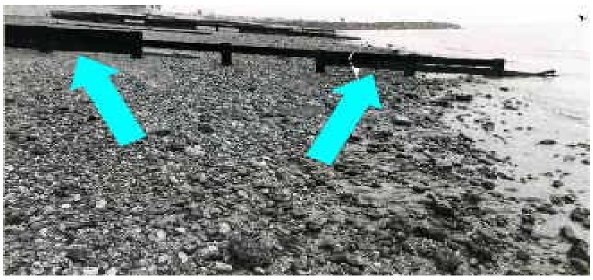

Figure 5.5 Beach slope and toe erosion at Lee-on-the-Solent showing exposure of the shore platform and undercutting of wooden groynes (from Kemp, 1999)

Figure 5.6 Sea wall failure at Lee-on-the-Solent (from Kemp, 1999)

In 1997, a major coastal protection initiative was completed, comprising construction of rock groynes, and recharging the beach (Figure 5.7) using sediment dredged from Southampton Water. The platform was buried beneath more than 2 m of gravel. Kemp (1999) suggested that the adopted scheme has not fully recognised the significance of the site as an important geological SSSI for the Barton Clay (fossil birds and fishes). The full impact of the scheme at Lee-on-the-Solent has yet to be assessed.

Figure 5.7 Beach recharge at Lee-on-the-Solent 1997 (from Kemp, 1999)

5.1.5 Pleistocene Till of Holderness

Holderness is an eroding cohesive shore with intermittent sand cover. The cliffs and platform are composed predominantly of glacial tills of differing ages and character (Bell, 2002). The thickness of the tills varies both alongshore and cross-shore, with the result that erosion exposes a slightly different sequence at any one time. In many cases the beaches of Holderness are extremely thin, being in many cases a veneer of sand less than 5-10 cm thick overlying the till platform (Figure 5.8). This is especially so during stormy periods when beach sediments are transported seawards and form a nearshore bar, often leaving the upper shore completely bare of sand.

Figure 5.8 Shore platform along Holderness

Cliff erosion along the Holderness coast is due to a combination of subaerial weathering and toe erosion by waves, which causes instability and results in frequent small slumps of a few tens of metres in width. Retreat of the cliffs is matched by the landward erosion of the platform which slopes at 0.5-0.75^o down to a depth of about 11-16 m below OD where a break of slope marks a change to a more gently sloping 0.05-0.2^o offshore platform. The latter profile is effectively flat and the vertical erosion rate is low, whereas the former is actively eroding. This erosion causes a permanent lowering of the platform with persistent beach erosion and a tendency towards a convex profile. The detailed form of the platform appears to vary considerably according to changes in sand storage.

Around 3-4 x 10^6 m^3 of sediment enters the nearshore zone of Holderness each year (Balson *et al*., 1998). This figure includes cliff retreat and erosion of the shore platform in the intertidal and subtidal zones. Mud makes up around 75-80% of the sediment with around 20-25% sand or coarser. The mud is lost from the shoreline in suspension whereas, over the long-term, the net movement of sand along the shore is to the south.

Pringle (1985) suggested that erosion of the Holderness platform is partly controlled by features within the till. Closely spaced gullying at right angles to the shoreline and to a depth of 0.5 m is commonly found in the middle of the intertidal zone. Where gullies are absent the till surface may be smooth or irregularly undulating. During the summer, desiccation cracking may affect parts of the till surface which then breaks up into small flakes of till, which themselves form into short-lived till "pebbles". Armoured mudballs often lie on the exposed till surface (Pringle, 1981) and a concentration of them indicates locations of rapid erosion at a particular time (Figure 5.9). They derive mainly from cliff falls but also from erosion of the till platform. They are rounded by wave action and are generally destroyed within a week.

Figure 5.9 Shore platform and cliff along Holderness, illustrating presence of armoured mudballs

Pringle (1981, 1985) argued for the presence of large coast oblique depressions called ords, which allow increased wave energy to reach the cliff toe where the beach level is low. They have an important role in exposing the underlying till to erosion. Southward migration of the ords (around 500 myr^{-1}) allows the locus of scour to move along the shore locally increasing erosion and resulting in temporally variable recession rates at any given point.

Pringle (1985) showed that the reduction in beach level at the cliff toe associated with an ord was up to 3.9 m allowing high water neaps to reach the cliff toe as compared to only some high water spring tides along the inter-ord beach. The lowering of the beach exposed the till platform to erosion. The volume of cliff material eroded amounted to 72 m^3m^{-1} with an ord present compared to 9 m^3m^{-1} along the inter-ord coast.

5.1.6 Pleistocene Till of North-East Norfolk

The till cliffs of north-east Norfolk extend from Weybourne to Happisburgh, although they are underpinned by chalk between Weybourne and Overstrand, so the platform for this area is chalk. The chalk disappears south of Overstrand, with the till platform variably exposed on the foreshore until Happisburgh (Figures 5.10 and 5.11). A mixed sand and gravel beach cover varies seasonally across and along the shore, with the beach surface to platform depth not much more than 1 m anywhere on the shoreline. At Happisburgh, the cohesive platform is partially exposed at low tide.

Figure 5.10 Cohesive shore platform at Sidestrand, Northeast Norfolk

Figure 5.11 Cohesive shore platform at Sidestrand, Northeast Norfolk

The tills and overlying clays and sands are lithologically and structurally complex. Boundaries are often severely undulating and micro-faulting is common. The tills are deformational and lodgement in type. Large intact rafts, tens of metres in size, of both solid and brecciated chalk are found within the tills. These often provide buttresses in the cliff as this material is more resistant than the till matrix to erosion and landsliding.

In its natural state this coast retreated at rates of the order of 1 myr^{-1}, although current revetments, groynes and sea walls protect much of the region. Most of the sand released by the erosion of this coast moves south passed Happisburgh. In 1959 and 1960 groynes were constructed at Happisburgh to increase the depth of the beach, and so protect the underlying platform. At the same time revetments were installed to protect the upper foreshore and lower cliff. Due to undermining and deterioration these structures were removed in 1991 and 1996.

The subsequent shore retreat has been remarkably rapid and is resulting in the formation of a bay. The retreat rate at the widest part of the bay is around 9 myr^{-1} (1994–2003), whereas the rate prior to the installation of the structures was less than 1 myr^{-1}. The current cliff position at the widest part of the bay is further inland than would have been predicted by extrapolation of historic rates when the structures were installed. Three potential causes of these high rates are:

- insufficient beach protection;
- depressed foreshore levels;
- increased wave loading due to climate change.

For more than a century the rate of sediment release from the cliffs and foreshores north of Happisburgh has fallen as measures have been taken to reduce cliff retreat. The current beach depths over the Happisburgh platform are therefore probably lower than they were before the coast was engineered. A thinner beach is less able to protect the platform, which is therefore more likely to erode and retreat.

Whilst the Happisburgh groynes were in place they boosted beach thicknesses. They were intended to retain deeper beaches than would have existed when the coast was retreating in its natural state of dynamic equilibrium. Given the reduction of sediment supply this may not have been capable of achieving this, in which case the platform would have continued to erode. In any case the platform seaward of the groynes would have lowered, leading to coastal steepening.

In addition, sea levels have continued to increase the water depths, and therefore wave heights, over the platform. Ultimately platform lowering leads to revetment undermining (Figure 5.12), and increased wave attack as higher waves are able to reach the structures. Once they had been destroyed or removed, the higher waves can then attack the upper platform and the lower cliff. This may partly explain the high cliff retreat rates recently observed. Increased storminess since 1990 may also have contributed to the high recession rate. Figures 5.12 and 5.13 show structures at Happisburgh as they were in the summer of 2003. The state of these structures indicates lowering of the platform.

Figure 5.12 Timber revetments at Happisburgh


Figure 5.13 Remains of groynes at Happisburgh

5.1.7 Pleistocene Till of Kilkeel, Northern Ireland

McGreal (1979) studied a till shoreline near Kilkeel in Northern Ireland. The shore comprises tills of various compositions fronted by a cohesive till platform (mean slope 1-1.5^{o}), up to 100 m wide with a superficial cover of cobbles and boulders. The cliffs erode at rates of 0.3-0.4 myr^{-1}, whereas the platform is subject to little short-term change. The shore is low-energy being fairly sheltered from high waves.

McGreal (1979) showed that the frequency of erosion of the cliffs was low along this shore, due to the relationship between platform geology, beach height and wave-energy conditions. The cobble-boulder lag on the platform acts to dissipate wave energy and the protective role of the beach is mainly responsible for the low incidence of wave attack at the cliff toe. He suggested that large tidal ranges and high-energy conditions or removal of the beach with a lowering of the platform were necessary for erosion of the cliff to occur.

5.1.8 Holocene mud of South West Lancashire

Parker (1975) described erosion of Holocene mud deposits exposed as a platform north of Formby Point in south-west Lancashire. The platform is exposed in the runnels of the beach system or at the seaward edge of the intertidal area. Parker (1975) suggested that deficits in the sand supply to parts of this shore allow the Holocene sediments to be exposed between beach ridges. The exposed platform is eroded by two mechanisms; formation of large pits or retreat of small cliffs formed in the platform. The whole of the foreshore is being eroded and retreating landward.

Parker (1975) suggested that it is necessary to define the depth below the sediment surface to which erosion is effective, to determine the transition from a stable to an eroding platform. This is likely to be as significant as the behaviour of the sediment surface, and may indicate the degrees of change to be considered in the design of any protective engineering works.

5.2 Great Lakes

5.2.1 Pleistocene Till of Lake Ontario

Research along the shores of Lake Ontario has been generally confined to the till platforms between Hamilton and St Catherines along the south-west corner of the lake. This area comprises cliffs of till generally up to 5 m high with a narrow shore platform overlain by a thin (<30 cm) sand and gravel beach. The till outcrops over the whole nearshore area to a water depth of at least 10 m, although it is frequently obscured by patches of lag cobbles and boulders, and by the occurrence of a veneer of sand out to a depth of 1-2 m (Davidson-Arnott and Askin, 1980). The till is overconsolidated and extremely dense with mud making up 60-90%. Rates of cliff recession average around 1myr^{-1} although higher rates occur locally. The beach and nearshore profile is typically steep and concave.

Coakley *et al*. (1986) suggested that wave-induced shear stress is the dominant factor in lowering submerged (7 m of water) till platforms at Stoney Creek. They noted that high energy waves created sufficient shear stress to erode the till and account for all the recorded lowering rates (rates of around 2 cmyr^{-1}). Supplementary processes such as sand abrasion do not appear to be necessary, at least in water depths of 7 m or more, where coarse materials are rare.

Davidson-Arnott (1986a, b) measured vertical erosion rates of the till profile east of Fifty Mile Point. He found an increase in vertical erosion, from 1.5 cmyr^{-1} in 6 m water depths, to 3.5 cmyr^{-1} in 2.3 m of water, to over 7 cmyr^{-1} in depths shallower than 1 m. This results in a characteristic concave-upwards cross-shore profile, and an increase in the effectiveness of the erosion mechanism close to the step. This in turn is probably related to the rapid increase in wave orbital velocities near the beach as the waves shoal and break, with turbulence due to breaking and backwash, and abrasion from the movement of surface sand and gravel close to the beach.

Davidson-Arnott and Ollerhead (1995) measured the vertical erosion of the nearshore till profile west of Port Dalhousie. They estimated vertical erosion rates of around 5-6 cmyr^{-1}, based on measured cumulative erosion rate of 3-4 cm between May and October 1992. This they extrapolated to an annual horizontal erosion rate for the bluffs of 0.7-0.8 myr^{-1} based on the assumption of an equilibrium profile.

5.2.2 Pleistocene Till of Lake Erie

Research along the shores of Lake Erie have been concentrated on the till platforms between Port Glasgow and Clear Creek on the north central shore. This shore is composed of 10-40 m high cliffs of interlayered tills and glacio-lacustrine sediments. The sediments are predominantly 84-96% mud and 4-16% sand and gravel (Rukavina and Zeman, 1987) and erode at an average long-term rate of 1.6 myr^{-1}. Permanent beaches are restricted to the vicinity of harbours at Ports Stanley, Bruce and Burwell. Elsewhere the shore has small ephemeral beaches. A narrow zone of modern sediments grades into a broad shelf of exposed glacial sediments in water depths of 15-20 m.

Philpott (1984) showed that the till platform (in areas away from the harbours) erodes to a maximum water depth of 12 m. Average rates of downcutting range from 0.7 to 1.2 $cmyr^{-1}$ with a maximum rate of 4.7 $cmyr^{-1}$ (waterlain till). These figures equate to a mud yield of around 350,000 m^3yr^{-1}, and a sand and gravel yield of around 140,000 m^3yr^{-1} from the till exposed in the 96 km long nearshore zone between Port Glasgow and Clear Creek (Rukavina and Zeman, 1987). In total, this represents about 11% of the associated cliff erosion volumes (3,200,000 m^3yr^{-1} mud and 1,000,000 m^3yr^{-1} sand and gravel).

Computation of the sediment budget shows that only about 1% of the sediment yield from the cliffs and nearshore remains in the study area, with the balance lost to longshore transport to the east and to the offshore (Rukavina and Zeman, 1987). A comparison of harbour and non-harbour reaches showed that harbour structures might be responsible for about 40% of the sediment accumulation within the study area. However, their effect on the sediment budget is minimal because of the high supply and transport rates (Rukavina and Zeman, 1987).

Philpott (1984) suggested that cohesive shores along the north central shore of Lake Erie seldom have, and probably never had, enough sand to halt the downcutting of the underlying till. Consequently, the shoreline was eroding prior to construction of any harbours. Updrift of Burwell Harbour, the deposition of large quantities of sand eventually halted the nearshore profile downcutting and the cliff position was stabilised. On the downdrift side, erosion continued as it had in the past prior to construction of the jetty.

5.3 Other areas

5.3.1 Pleistocene Till of Schleswig-Holstein

Schrottke *et al*. (2003) studied the eroding till cliff coast of Schleswig-Holstein to understand the submarine abrasion processes with respect to short-term wave and water level fluctuations. Annual submarine erosion rates of 1.2-4.6 $cmyr^{-1}$ were recorded in a more-or-less non-tidal environment (no intertidal factors), with higher erosion rates associated with higher wave energy input. The highest erosion rates were not always measured at the most landward stations, reflecting spatial variations in the main wave energy dissipation zone. The erosion rate is strongly influenced by the mechanical resistance of the till.

Schwarzer *et al*. (2003) suggested that in areas of long-term erosion, the entire morphology of the coastal profile (nearshore slope, bar-trough system, beach, beach ridge, dune or cliff) retreats due to hydrodynamic impact. Substantial changes in the succession of geomorphological features do not occur, and for active cliff sections this is expressed as the “constancy of the retreating profile”. Schwarzer *et al*. (2003) found that the controlling processes for the evolution of the cliffed southern Baltic Sea coast are located offshore and not at the cliff itself. They suggested that the lowering of the seabed and cliff retreat are slightly discontinuous processes primarily controlled by storm events combined with water level fluctuations. The importance of different parameters for erosion processes depends on the timescale considered.

5.3.2 Pleistocene Till of the Southern Canadian Beaufort Sea

Hequette and Barnes (1990) studied a coastal section along the southern Beaufort Sea, where coastal erosion rates exceed 1 myr^{-1}. This they considered unusual because, although the Beaufort Sea is ice-free for 3 months of the year, wave energy is restricted by the pack ice offshore. They therefore considered the retreat rates to be high compared to mid latitude coasts of a similar character where the erosive action of waves occurs throughout the year. Their results indicated that shoreline recession is not completely explained by subaerial processes nor combined wave-induced and subaerial processes, and other mechanisms are needed to explain the erosion.

A comparison of bathymetric transects indicated 1 m of erosion of the sea bed in 12-15 m of water over a 21 year period. Hequette and Barnes (1990) suggested the erosion was caused by ice gouging, predominantly in winter. They suggested that this erosion is important because to maintain an equilibrium profile, the upper shoreface also erodes. The sea-ice induced erosion of the lower shoreface increases the water depths seaward of 12 m, and so contributes to the erosion of the profile inshore of 5 m as wave energy is expended further up the submarine slope. Rapid coastal retreat without erosion of the lower shoreface would lead, in contrast, to decreasing wave energy inshore as the shoreface slope becomes flatter and would ultimately result in decreasing erosion at the coast and nearshore. Hence, the upper shoreface erosion is a continuous adjustment of an equilibrium subaqueous profile related to sea-ice erosion at water depths greater than 12 m. The lower shoreface erosion is driving coastal erosion by affecting the whole submarine profile.

6. Preliminary management advice

The ultimate aim of further research is to provide guidance on best practice management of cohesive shorelines, in line with Defra/Environment Agency objectives. The management guidance should help the users (be they conservation body, coastal defence manager, navigator or local authority) to identify what their objectives are in seeking to manage cohesive platforms and their associated beaches. The present scientific understanding of cohesive shore platforms is insufficient to provide detailed guidance at this scoping stage and so preliminary management advice is given here. This advice is based on limited available information relating to strategic management practices that have been implemented as a direct result of cohesive shore platform lowering.

6.1 Management issues

There are numerous issues relating to cohesive shore platforms that management needs to address. These include:

- loss of habitat (intertidal and subtidal);
- loss of land mass through cliff recession;
- weakening of coastal defences and flood protection works;
- sediment supply (its interruption and influence on near-field and far-field sites);
- permanent lowering and possible loss of beaches;
- increased recession due to accelerated sea-level rise, wave and storms (climate change);
- loss of geological and geomorphological designated sites;
- archaeological implications.

This list indicates that a sound knowledge of the dynamic and morphological responses of a beach system to changes in the adjacent cohesive platform is important for resolving management issues. Indeed, many estimates of sediment yield from shoreline erosion ignore the important contribution made by the platform. The erosion of the platform proceeds at a rate dependent upon the erosion processes (Section 2) and will produce fine and coarse sediment into the coastal system. The coarser sediment moves along the shoreline by wave and tidal action influencing other areas as they pass and finer sediment is removed offshore in suspension. Changes to erosion and transport processes will impact on the sediment budgets, which in turn will have long term impacts on the areas where sediment is usually deposited.

In addition to being an important influence on the beach, the platform also acts as a regulator of cliff erosion. Over time, in a natural state, the rates of downcutting of the platform and retreat of the cliff tend to reach a state of equilibrium as the platform regulates the wave energy impinging on the cliff toe (Section 3). This quasi-steady state has made the recession of unprotected sites relatively predictable. However, wave characteristics are changing and sea level rise is expected to accelerate. It is not known how cohesive shores will respond, therefore future recession of unprotected cliffs is uncertain. Improved knowledge of the processes is needed to make cliff recession predictable, and tools based on this knowledge are required to make these predictions.

Maximum observed rates of platform lowering can be surprisingly high, especially on shorelines developed in glacial tills or clays. This can become an important consideration in the long-term performance of coastal defence structures, especially as these structures have their foundations in the same formations. The water depth in front of structures such as sea walls can increase significantly over their design life, affecting the overtopping performance and standard of protection as well as increasing the risk of undermining and failure. Rates of cliff retreat and platform lowering can also be severely affected by defensive structures erected on adjacent stretches of coastline that interfere with sediment movement and wave activity.

6.2 Management options

6.2.1 Do nothing

One potential management view is that no attempts should be made to prevent cohesive platform erosion. The likelihood of this option being adopted is increased by its minimal initial cost. "Do nothing" may be the preferred option in areas that are currently unprotected. However, it should be noted that, due to climate change, future rates of cliff retreat might be higher than they have been in the past. The consequences of do nothing may, therefore, be an increase in shore retreat rate.

If a decision is made to not maintain existing defences and to allow them to fail, then the state of equilibrium of the foreshore should be considered before the likely response of the shore can be predicted. Structures may protect the upper foreshore but allow the lower foreshore to erode. Following the removal of the structure a period of accelerated retreat might be expected as the shore profile reverts to an equilibrium form. Similarly alongshore balances may have been disturbed by the protective structures. If the foreshore at a site has been protected through engineering intervention it may begin to emerge as an anthropogenic headland, if neighbouring areas are unprotected. If such structures are allowed to fail then the headland may be rapidly removed because of a tendency for beaches to be stripped from it, exposing the platform.

6.2.2 Reduce platform downcutting by beach recharge

The failure of many coastal structures may result from undermining through continuing erosion of the cohesive platform seaward of the structures. In order to reduce cohesive shoreline recession it may be necessary to prevent downcutting across the whole profile. One of the main methods of reducing erosion of a cohesive profile is to artificially create a substantial beach. A healthy beach is probably the most effective form of coastal defence since it has the ability to adapt its shape naturally to changing wave and tidal conditions and dissipates wave energy. However, it must be noted that this technique often has limited or no effect on erosion of the subtidal shoreface. There are two main ways of artificially creating a beach:

- Provide a barrier to induce “natural” development through the interception of longshore sediment transport;
- Construct retaining structures and artificially fill with an appropriate beach material.

There are numerous design principles that need to be taken into consideration before beach recharge is implemented, including:

- Determining recharge volume
- Selecting sediment texture
- Environmental considerations

Determining recharge volume
In determining the volume of beach sediment required to protect the cohesive profile, consideration must be given to the seasonal and storm-induced variations in the beach. There must be sufficient volume of sediment present to allow for the formation of both winter and summer beach profiles, and still provide adequate coverage to both the nearshore bed and the backshore. Similarly, there must be enough sediment present to allow for the shift in beach plan due to storms from oblique directions without causing inadequate protection along some other part of the beach. Allowance, therefore, needs to be made for losses due to longshore sediment transport and cross-shore transport, and a balance has to be struck between the amount of sediment initially placed and future maintenance commitments.

In practice, the minimum beach cross section required to protect a cohesive profile with natural sediment will tend to be site specific. This may be identified in local areas where beaches already exist, and the backshore or cliff is vegetated with no signs of wave erosion at the toe of the slope.

Selecting material texture
Selecting the appropriate sediment texture is the most important aspect of design, as it will influence beach stability, dynamics and durability. By appropriate selection of the particle size of the beach filling material, the range of beach movement and therefore the total volume of sediment required, may be reduced. For example, it may be feasible to construct an artificial beach out of large gravel where the wave energy is too high for a sand beach to be stable. Also, by building the backshore to a higher elevation than would be reached by interrupting the longshore sediment transport, the width of the backshore required to provide sufficient protection could be greatly reduced.

Environmental considerations

Environmental considerations require an assessment of a variety of potentially adverse, as well as beneficial, impacts on the environment, including physical, natural and human factors. The main impact on the physical environment is the alteration of coastal processes. Increased or reduced movement of sediment in a longshore direction may potentially affect the natural or human assets elsewhere along the coast. For example, lengths of coast that once had sufficient sand cover to protect the cohesive substrate from downcutting may start to erode if the sediment supply is reduced through anthropogenic effects to protect the platform elsewhere.

Impacts on the natural environment include potential smothering of flora, invertebrates, birds and fish. The human environmental considerations are varied and include impacts on recreation, access, safety, landscape, commercial activities, archaeology, navigation and infrastructure.

6.2.3 Design better structures

The rapid erosion of cohesive platforms increases the difficulty of establishing a purely structural solution. In a study of shore protection structures along a 10 km stretch of the Lake Ontario cohesive shoreline, Davidson-Arnott and Keizer (1982) found that 71% of structures were damaged or destroyed within 10 years of construction and 87% within 20 years. They argued that the low durability reflected poor design and construction in relation to the stresses imposed by the physical environment.

The structures described by Davidson-Arnott and Keizer (1982) were built in an area subject to high storm activity. This coupled with a scarcity of beach sediments led to rapid erosion. Beaches at the sites were extremely narrow and the effectiveness of groynes in building a protective beach was severely restricted. The highly erodible nature of the cohesive material also made it difficult to provide stable foundations. Thus, one of the most common failures of sea walls was inadequate toe protection leading to scour and collapse. Failure of groynes usually occurred through scour at their bases, especially on their downdrift sides.

6.2.4 Managed realignment

Even when a cliff toe is protected with structures, vertical erosion of the platform will continue leading to a steepening of the profile, allowing increased wave energy to reach the beach or protective structure. As shore platforms at protected sites continue to lower, water depth increases and the protective structures are undermined and become more expensive to maintain, realignment will increasingly be considered as a possible management option.

A cautious approach needs to be adopted if managed realignment is implemented. This is because there is a danger that medium to long term coast protection may have allowed the local shoreline to develop into a state of imbalance so that if the coast protection were to be removed then a period of accelerated erosion might follow. This danger arises partly from feedback between the profile slope and erosion processes. Waves have a tendency to plunge as they break on steeply sloping platforms. This, in turn, causes relatively high water velocities and pressures, which are more effective at eroding the substrate. Since they have more effect at higher elevations they will result in the formation of a more gently sloping platform. As the platform slope becomes gentler the breakers become less aggressive and the retreat rate reduces.

Considering the cliff retreat to platform downcutting relationship (Section 3), if the platform has been "artificially" steepened as a result of construction of coast protection measures, then periods of accelerated cliff retreat might follow, as the platform adjusts towards a more natural slope, once the protection is removed. Consequently the intention to protect cliffs from erosion has in some areas only delayed it (and possibly enhanced it under some circumstances). The unprecedented cliff erosion rates observed at Happisburgh on the north Norfolk coast following the removal of 30 year old revetments may be evidence of this (Section 5.1.6).

In summary, preliminary advice on managed realignment is:

- Inspection of the shape of the platform is necessary to develop an understanding of the likely shore recession following the removal or failure of structures;
- To predict the behaviour of one part of the cross-shore profile, such as the cliff toe, it is necessary to understand its interaction with other parts, such as the platform shape and beach thickness;
- The behaviour of a local area may be controlled by larger scale coastal behaviour. To predict the likely behaviour of a local cliff it is necessary to understand its dependence on the broader geomorphic system.

7. Research needs and recommendations

Strategies for the management of cohesive shore platforms require an understanding of the controls on shoreline evolution. However, weathering and erosion on a cohesive shoreline are complex, involving a wide range of controlling factors and processes. This scoping study shows that the main processes have been identified, but that little research specifically addressing the rates at which these processes erode the platform has been undertaken. It is recommended that further research should be targeted at trying to answer the more fundamental questions about rates of cohesive platform weathering and erosion, providing a starting point for better strategic management of these shorelines. Qualitative and semi-quantitative assessments of the processes have been carried out, but there is still work to be done in four main areas:

- The specifics of the weathering and erosion processes, particularly the effect on downcutting rates of abrasion related to sediment size and thickness of surface sediments and the importance of biological processes;
- The relationship between platform morphology, geology and the weathering and erosion processes in a range of space and time scales;
- The relative influence of material strength in the rate at which weathering and erosion processes proceed;
- The need to test models of platform development at different sites.

The tasks outlined below should communicate with and benefit with other work being done under the Defra/Environment Agency Fluvial, Estuarine and Coastal Processes Research Theme. This research includes project FD1916 – Beach Lowering in Front of Coastal Structures, being led by HR Wallingford (Sutherland *et al*., 2003). The research would also benefit by fostering links with related ongoing studies outside the processes theme. These include the development of a Regional Coastal Simulator being prepared by the Tyndall Centre for Climate Change Research and *in situ* and laboratory investigation of biological erosion being carried out at the University of Southampton. The work should also tie into currently operational monitoring programmes being undertaken by local authorities.

7.1 Weathering and erosion processes

This scoping study has highlighted gaps in the understanding of the main processes that control the rate at which cohesive platforms weather and erode. Little is known about the effectiveness of each individual process as a weathering or erosive agent and previous platform studies have suffered generally from a lack of rigorous quantitative investigation. Previous research has also failed to explore the relationships and interactions between the individual processes, which rarely operate in isolation. Estimations of the relative rates at which individual processes act, (they could be as high as tens of centimetres over a tide) are still in their infancy. It has also been difficult to distinguish between processes, which may be very different, but have the same effect on platform morphology. A lack of data and a clear understanding of the erosion processes have also handicapped numerical model development.

The first recommended research initiative is therefore to investigate the weathering and erosion processes to elucidate the roles of each, and their interactions, in controlling the rate of platform downcutting. This type of research would ideally be carried out through an intensive investigation at a few sample sites around the United Kingdom coast. The research could focus on (in order of priority with respect to improving coastal management):

- A better understanding of abrasion rates and the depth of reactivation of beach sediments during periods of both low and high wave conditions to determine how thick the beach needs to be before it becomes protective as opposed to abrasive;
- The relationship between erosion rates and incident wave energy over periods of days or weeks (by *in situ* experimentation);
- The contribution of biological mechanisms compared to other processes, and the importance of protection afforded by organisms;
- The quantification of weathering in subtidal areas to determine the thickness of the layer involved in the process and to isolate these effects from those of abrasion.

7.2 Relationship between platform morphology and physical environment

Cohesive shore recession rate relates to the constant adjustment of the platform form through a broad range of processes. However, clear relationships between platform morphology and the process environment have yet to be established. Short to medium-term rates of development requires further investigation to help resolve the problems of prediction over the long term.

The second recommended research initiative is therefore to look at the relationship between morphology of the platform (slope, width, micro-morphology) and the broad-scale physical environment. Research could focus on acquiring more quantitative information on the rates of platform lowering in different United Kingdom coastal environments. This could involve investigations of platforms with a similar geological make-up, but in different places with different conditions, such as degree of shelter, amount of subaerial exposure, length and timing of exposure, wave climate, tidal range and non-cohesive sediment cover.

The research could include (in order of priority):

- Monitoring of the cohesive clay substrate level and the top of the non-cohesive surface sediment, and comparison of the morphological changes with broad-scale process data;

- Assessment of how the morphology of the nearshore profile affects the amount of energy reaching the toe of the cliff and the limits (if any) imposed on shoreline erosion by an increasing platform width;
- Development of conceptual morphological models of broad-scale coastal systems with emphasis placed on climate change and the current disequilibrium of many protected areas;
- Determination of the shape and characteristic features of the subtidal profile in an area undergoing rapid recession (influence of platform erosion on offshore transport of sand);
- Elucidation of whether pre-Pleistocene platforms are in equilibrium with modern processes and that they are not inherited from a previous interglacial sea level.

7.3 Relationship between geotechnical parameters and sediment erodibility

There is little available information on what measure of strength can be used to predict resistance to erosion by wave-induced forces, abrasion by surficial sediments, and the effects of softening or weathering of the cohesive sediment. Critical to understanding the strength and geotechnical properties of materials is their measurement *in situ*. Presently, there is a dearth of such measurements. So, in order to advance present understanding of how micro-scale spatial and temporal variations in geotechnical properties control erosion of platforms a comprehensive programme of field measurements needs to be conducted.

The third recommended research initiative is therefore to study the geotechnical properties of cohesive sediments of different types and relate these properties to its erodibility. This research could involve mainly *in situ* measurements (with some complementary laboratory studies) on different types of cohesive material from platforms around the United Kingdom. The main research needs are:

- to accurately measure *in situ* the geotechnical properties of cohesive shore platforms
- to determine the form of the relationships between critical shear stress for erosion (τ_c) and shear strength, clay content (particle size distribution), water content, and other geotechnical and chemical properties
- to quantify the impact of physical, chemical and biological weathering processes on the geotechnical properties of platform materials (how they alter material strength and susceptibility to marine erosion).

7.4 Numerical models

New modelling tools are needed to represent the development of cohesive foreshores. These should be process-based so that they can represent foreshore response to changed wave climates and rate of sea level rise. They should be suitable for investigating shore response to management scenarios, so should be capable of representing the installation of structures, and their removal from currently protected areas. Since decisions regarding the management of cohesive shores will, in many cases, affect neighbouring sections of coast the modelling tool should be capable of functioning at a reasonably large scale, to capture such interaction. In addition the tools should be capable of representing uncertainty in processes, parameters and future loading conditions. Model development should be integrated with the other research aspects areas identified in sections 7.1 to 7.3 to facilitate rapid uptake of findings.

The fourth recommended research initiative is therefore to test existing numerical models at different sites. The research could include:

- uncertainty in modeling;
- response rate of systems to future climate change (e.g. sea-level rise and increased storminess);
- response rate of systems to anthropogenic influences (sea walls, revetments, groynes etc).

7.5 CSG7 research proposal

The higher priority research needs identified in sections 7.1-7.4 have been translated into a proposal for further research, submitted separately on a Defra CSG7 form (Application for a Research Contract with Defra).

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Appendix A

Consultation report

1. Introduction

Posford Haskoning has been commissioned under the Defra/Environment Agency Combined R&D Programme for Flood and Coastal Defence to undertake a project entitled *Understanding and Predicting Beach Morphological Change Processes Associated with the Erosion of Cohesive Foreshores*. Posford Haskoning is leading the work in consortium with British Geological Survey, University of Sussex and University of Bristol. This 7-month project is a scoping study aimed at investigating the relationship between cohesive foreshore erosion and the supplies and losses of sediment to the adjacent beaches. The project will lead to the definition of a larger stage 2 research project aimed at furthering scientific understanding of the subject in the United Kingdom and working towards the resolution of some of the issues raised in the initial scoping study.

As part of the scoping study, Posford Haskoning has undertaken a targeted consultation exercise. This report provides details of the consultation exercise and its results. Specifically, the contents of the report are as follows:

- Section 2 details the aims of the consultation exercise, the consultees contacted, the questions they were asked and the responses received.
- Section 3 provides a discussion of how the results of the consultation feed into the findings of the overall scoping study and the definition of the stage 2 research project.

2. The consultation exercise

2.1 Aims of consultation

The overall aim of the consultation exercise was to identify and define some of the key user-defined problems and issues related to the erosion of cohesive foreshores and their relationship to beach morphology. The consultation responses will be used to assist in the definition of the Stage 2 Research Project.

2.2 Consultees

The list of consultees was compiled to represent those who are potentially affected by the erosion of cohesive foreshores and therefore who would:

- have an interest in the research and
- have knowledge and previous experience of the subject.

The list was produced based on knowledge of the locations of eroding cohesive foreshores, from a meeting with the Project Officer and through the experience of the project team. Individuals were selected from the following areas (Table1):

- Local authorities
- Environment Agency
- Defra
- English Nature
- EPSRC beach processes network
- Academia

Table 1 Consultees' details

Organisation	Individual	Role	Notes
Tendring District Council	John Ryan	Coastal engineer	Erosion of London Clay along the Tendring Peninsula is an important process
East Riding of Yorkshire Council	Mike Ball	Coastal engineer	The erosion of till along the Holderness coast is an important process
Environment Agency	Michael Owen	Coastal processes	Flood and coastal defence perspective
Defra	David Collins	Environmental advisor	Flood and coastal defence perspective
English Nature	Tim Collins / Chris Pater	Coastal geomorphologists	Nature conservation perspective
University of Plymouth	Andrew Chadwick	Coastal Research	EPSRC Beach Processes Network leader
University of Nottingham	Dominic Reeve	Coastal research	EPSRC beach processes Network

Independent Geologist	Hugh Payne	Coastal geology	Recommended by members of project team
St Andrews University	David Paterson	Coastal geology	Recommended by members of project team

The consultation letter sent to each of the consultees is reproduced in the following sub-section.

2.3 Consultation letter

Dear……,

Posford Haskoning is currently leading a project within the Defra/Environment Agency combined R&D programme for flood and coastal defence entitled:

"Understanding and predicting beach morphological change processes associated with the erosion of cohesive foreshores"

The work is being managed by Posford Haskoning, in consortium with British Geological Survey, University of Sussex and University of Bristol. The project is a scoping study aimed at providing a comprehensive review of the processes of erosion of cohesive foreshores and their relationship to change in beach form. The study will identify gaps in our knowledge and state-of-the-art methodologies to analyse this type of erosion. The present project will culminate in the definition of a larger Stage 2 Research Project to improve understanding in this field.

We are contacting you as part of a targeted consultation exercise we are undertaking within the scoping study. The intention of this exercise is to identify user-defined problems and issues related to the erosion of cohesive foreshores and their potential relationship to beach morphology. These issues and problems may include, by way of example: beach management; conservation; loss of archaeological sites; sediment transport.

We would therefore like to invite you to be a consultee. This will involve providing your views on the subject, as outlined in the following sections. We will collate these views, compile a consultation report and feed this information into the process of developing and defining the Stage 2 Research Project. In this way, your views can help to guide the direction of the research and ensure the work is focussed on end user issues and problems.

Technical background
Beaches are fast responding and mobile geomorphic systems that are highly sensitive to environmental change and forcing, and susceptible to episodes of erosion and growth. Their stability depends on the equilibrium established between sediment supply and loss. This equilibrium is in turn being driven by tidal and wave energy and constrained and influenced by the geology and morphology of the adjacent foreshore. Cohesive foreshores are defined as those composed of stiff clay, such as the till and London Clay foreshores along

the Holderness and Essex/Kent coasts, respectively, and the Mercia Mudstone fringe of the Severn Estuary.

The erosion of cohesive foreshores is important from a management perspective for the following reasons (amongst others):

- Erosion of the foreshore will produce a contribution to the coastal sediment budget. This contribution is likely to be at least as important as the contribution from the coastal cliffs. Many estimates of sediment yield from coastal erosion consider only the contribution from the cliffs and ignore the important contribution made by the foreshore platform, which must retreat concurrently with the cliffs. A sound knowledge of the dynamic and morphological responses of a beach system to changes in the adjacent clay foreshore is therefore important;

- Foreshore lowering by wave action is a fundamental control of beach level and cliff recession, ensuring that wave power across the foreshore remains constant. If the foreshore is not lowered then it will widen and become more effective in dissipating wave energy, waves will break further offshore and the number of waves reaching the toe of the cliff and the fronting beach will decline. Thus, the evolution of the foreshore profile ultimately controls both the beach and cliff line evolution and so the supply of sediment to the coastal system;

- Maximum observed rates of foreshore lowering can be surprisingly high, especially on coasts developed in glacial tills or clays. This can become an important consideration in the long-term performance of coastal defence structures. The water depths in front of the structure can increase significantly over its design life, affecting the overtopping performance and standard of protection as well as increasing the risk of undermining.

Your Input
Previous research on erosion of cohesive foreshores in the UK has been limited. As a result, the Stage 2 research that will be defined by this scoping study will not be able to resolve all the issues surrounding the subject. However, definition of the most critical issues to be tackled in Stage 2 will be achieved through the experience of the project team in combination with the results of this consultation exercise.

We would therefore be keen to hear your views on the subject, in particular relating to the following:

- Do you feel the erosion of cohesive foreshores has been adequately considered in previous studies either along your coast or other coasts you have been involved with?
- (This would include a consideration of the processes of erosion, the rates of erosion and the implications of the erosion, such as sediment budgets and cliff retreat / beach stability.)

- What do you feel are the management issues arising from the erosion of cohesive foreshores along the coast you are responsible for, or other coasts you have knowledge of?
- What do you feel are the key issues (technical and management) you would like to see the Stage 2 research target?
- Do you know of any previous research relevant to this topic?

Any information or views you provide will be useful to the project. If you feel that you have had no experience of the subject or are not aware of any issues relating to the subject, then please inform us of this. This may be an important comment in itself.

Should you wish to discuss any of the above, please do not hesitate to contact me. Many thanks for your time.

Yours sincerely,

David Brew
Senior Coastal Geomorphologist
for
Posford Haskoning Ltd

2.4 Consultation responses

Completed questionnaires were received from 3 consultees, providing answers to the four questions presented in the consultation letter. These responses are reproduced in the Tables 2 – 6. One further consultee replied but did not respond to the questions.

Table 2 Consultees responses: question 1

Question: Do you feel the erosion of cohesive foreshores has been adequately considered in previous studies either along your coast or other coasts you have been involved with? (This would include a consideration of the processes of erosion, the rates of erosion and the implications of the erosion, such as sediment budgets and cliff retreat / beach stability.)
Answers: Certainly not to the extent required for the level of effective planning required by SMP's and similar. I assume research on 'cohesive foreshores', has been spatially restricted to a few locations such as Holderness. A study with a national perspective would make a valuable contribution with particular reference to how different cohesive foreshores around the country will react to estimates of sea level / climate change. Cohesive foreshores in Wales are primarily within estuaries and are not subject to open coast processes. Much more detailed work has been carried out in the Severn Estuary over the past 5-6 years, but relatively little in other estuaries where problems are not seen as critical. Wales has virtually no Mercia Mudstone foreshore. However, it should not be overlooked that many beaches comprising non-cohesive sediments are often only a thin layer of such sediment over a cohesive (or predominantly so) sub-stratum. This is particularly so where glacial materials form the sub-stratum. Foreshore lowering is due to erosion of the sub-stratum.

Table 3 Consultees responses: question 2

Question: What do you feel are the management issues arising from the erosion of cohesive foreshores along the coast you are responsible for, or other coasts you have a knowledge of?
Answers: Is 'Hold the Line' a viable and realistic option. Biological interactions with sediments. In terms of nature conservation then we wish to see a coast that can function and respond to the dynamics of the environment; this includes erosion. We are working towards promoting functional shorelines in England and through the Shoreline Management Plan process we will seek to realise environmental enhancement opportunities that enable dynamic processes to occur. In the estuarine environment, management issues arise from the retreat of

mudflats and saltmarshes in front of defences, and the consequent increased exposure of the defences to wave action. There can be significant fetches in wider estuaries. Methods of combating this erosion often comprise physical protection, such as rock armour against the salt marsh “cliff” face. It would be preferable to use methods that attempt to regenerate mudflat and saltmarsh. Methods leading to and rates of retreat/erosion of glacial till sub-strata are un-researched as far as I am aware.

Table 4 Consultees responses: question 3

Question: What do you feel are the key issues (technical and management) you would like to see the Stage 2 research target?
Answers: An improved understanding of the processes governing the response of cohesive foreshores to both wave and tidal action. An improved understanding of the processes affecting the long term (decades) evolution of coastal morphology. The technical question concerns the rate of foreshore lowering on different sections of coast as linked to predictions of sea level / climate change. The management question is how we enable foreshore erosion to occur given other coastal interests (e.g. commercial, industrial, residential development). Foreshores/beaches that appear sandy, even when backed by e.g. sand dunes or shingle bars, often comprise a relatively thin layer of sand over a glacial till and/or peat sub-stratum. The mobile nature of the sand means that this thin veneer is usually present. It may be assumed that lowering of the foreshore is due to removal of sand but more frequently it is due to the erosion of the underlying cohesive sub-stratum. This presumably is due to the abrasion of the sand and shingle in the veneer during storm action. Occasionally when sand depletion from an area is greater than supply, the underlying beds are exposed. Then they are subject to direct wave action. Do they then erode as rapidly as when abraded by sand? If not, is there any relationship between sand depth, storm energy and erosion? Answers to such questions could give useful guidance to future retreat rates.

Table 5 Consultees’ responses: question 4

Question: Do you know of any previous research relevant to this topic?
Answers: Your academic team members should know but I am not aware of very much published research on this topic relevant to the UK situation. Significant research has been undertaken recently into foreshore erosion of the Gwent levels – by the Environment Agency. I know of little research into

cohesive foreshore lowering where there is a non cohesive cover. Some useful information may be available from work undertaken in Wales though, e.g. Williams A.W on the Ceredigion Coast *c*. 1985 and by Posfords (?) on Porth Neigwil Beach. There is also an amount of beach profiling available. Perhaps all beach profiling should be accompanied by augering to determine depths to cohesive materials where likely to be within 1m of the surface.

Table 6 Consultees responses: question 5

Question: Any other Comments.
Answers: I think this could be a topic suitable for a multi-funder supplied consortium (much like the EPSRC / defra/ EA / flooding consortiums.

3. Discussion of responses and conclusions

3.1 Responses

Of the 9 consultees invited to participate in the consultation exercise, 3 returned completed questionnaires. This low response is taken as an indication of the lack of awareness of the subject of erosion of cohesive foreshores and the associated issues, from both a science and a management perspective.

The responses that were received provided some interesting views and comments. All the responses indicated that consideration of the erosion of cohesive foreshores has been limited in the past in terms of both research and practical management work.

The responses regarding management issues centred on how erosional processes and eroding coastlines can be accommodated into management strategies. For example: can we enable dynamic processes to continue? Can we ‘hold the line’? This is considered to be an important point and worthy of further discussion. If, as suggested, the management issues relate to whether we seek to prevent erosion and if so how we do so, then there is a role for science in providing input into this decision making process. For such decisions to be made, an understanding is required of the likely rates and mechanisms of erosion.

In terms of the key issues that a Stage 2 research project should target, the consultees raised a number of points ranging from the mechanisms involved in the erosion of cohesive foreshore to the rates of lowering and how such lowering affects the long term evolution of coastal morphology. An important question was raised by one consultee regarding whether lowering would be as rapid when a cohesive foreshore was exposed to direct wave action compared to when a thin veneer of sand is present, i.e. what is the role of abrasion. This issue is discussed further in the Scoping Report.

Consultees highlighted very little previous research and this in itself is an important finding of the consultation exercise. Useful information was provided regarding work in Wales and a useful comment made regarding the use of augering to accompany beach profiles as a monitoring technique.

3.2 Conclusions

A number of conclusions can be drawn from the consultation exercise.

- The topic of cohesive foreshore lowering has not been the subject of a great deal of research in the past and management practice has generally not given much consideration to the process. It is the role of research to provide the understanding and tools for the management practices to incorporate. The lack of previous work and awareness of the subject is reflected by both the comments received and by the low number of responses;

- Some important points were raised by consultees regarding how we place the process of an eroding foreshore, and coastline, into a management framework. Again, this decision-making process is one in which research of the subject, improving our understanding, should feed into.
- Some useful technical issues for investigation in a research project were raised, such as the role of abrasion and the rates of lowering of foreshores.

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