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**Soft Cliffs**

**Prediction of Recession Rates and Erosion Control Techniques**

**R&D Project FD2403/1302**

## **Soft Cliffs Manual for Managers**

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The research drew together information from a review of published technical literature, a survey of and discussions with coast protection authorities, discussions with researchers and practitioners (UK and overseas), a limited number of site inspections, and the considerable experience of the team members and the Advisory Committee.

## EXECUTIVE SUMMARY

In order to manage coastal cliffs it is important to have access to accurate and reliable information on past and future cliff recession patterns and trends, the level of risk to coastal communities, and the range of management strategies and erosion control techniques that may be suitable in different cliff environments. The need for high priority research into the investigation and management of eroding coastal cliffs was identified by MAFF's Advisory Committee on Flood and Coastal Defence Research and Development in 1992 (Advisory Committee 1992). As a result, the Department for Environment, Food and Rural Affairs (DEFRA; formerly MAFF) commissioned High Point Rendel (formerly Rendel Geotechnics) in association with HR Wallingford, and supported by the Cambridge Coastal Research Unit (now Newcastle University) and the River and Coastal Environments Research Group (RACER; Portsmouth University) to undertake a broad-based study of coastal cliffs in England and Wales. The objectives of the study included:

- to develop analytical methods of predicting cliff erosion rates for the wide variety of differing situations around the coast;
- to develop a methodology for taking accurate measurements and recording actual recession rates;
- to review and evaluate methods for reducing and controlling erosion;
- to identify the factors relevant to the management of soft cliffs for conservation purposes.

The results of this study have been presented as:

- a Technical Report: Lee E M and Clark A R (2002) *The Investigation and Management of Soft Rock Cliffs*, published by Thomas Telford (ISBN 07277-3110-6);
- a Manual (this volume) which provides a non-technical summary of the Technical Report.

The results of the research set out state-of-the-art guidance for coastal engineers and planners on how eroding cliffs can best be managed. This Manual is intended to provide a synopsis of the more detailed content of the Technical Report and, hence, follows the same structure. On reading through this report there may be occasions when the Reader wishes to find a more detailed account of a particular issue - this can be found by cross referring to the same Chapter in the Technical Report.

The research has stressed the need to consider both structural and non structural solutions to cliff recession problems. Where structural solutions are appropriate a combination of toe protection and slope stabilisation will generally be necessary; such works may reduce the risks of cliff recession and coastal landsliding, but they cannot eliminate them. On protected cliffs there will be a need for an ongoing programme of monitoring and maintenance, especially where there is a risk of delayed failure.

The Manual also presents the investigation approaches, measurement and monitoring techniques and prediction methods available for obtaining the necessary cliff recession information to support different stages of the decision-making process. Above all it

stresses that each cliff will be unique because of the overwhelming influence of site conditions on the recession process. There is, therefore no one method for tackling cliff problems; investigations and management of each cliff can only be determined on the ground, drawing upon expert judgement, experience and thorough site investigation and data analysis.

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# CHAPTER 1 INTRODUCTION

## 1.1 Background

Cliff recession and coastal landsliding present significant threats to land use and development, especially on the south and east coasts of England (Table 1). Although individual failures often tend to cause only small amounts of cliff retreat, the cumulative effects can be dramatic. For example, the Holderness coast has retreated by around 2km over the last 1000 years, including at least 26 villages listed in the Domesday survey of 1086; 75Mm<sup>3</sup> of land has been lost in 100 years (Valentin, 1954; Pethick 1996). On parts of the north Norfolk coast there has been over 175m of recession since 1885 (Clayton and Coventry 1986).

Major landslide events are a feature of some clifflines, such as the till cliffs of northeast England. In 1682, for example, the village of Runswick, North Yorkshire, was destroyed by a sudden cliff failure (Jones and Lee 1994). The most recent example occurred in Scarborough during June 1993, when guests at the Holbeck Hall Hotel woke to discover that a major landslide had occurred on the 70m high coastal cliffs in front of the hotel. Over 60m of cliff was lost overnight.

Over the last 100 years or so some 860km of coast protection works have been constructed to prevent the losses associated with cliff recession (MAFF 1994; this figure includes low-lying areas prone to erosion). The problems have arisen not so much because of widespread rapid erosion (the current average annual land loss in England is probably less than 25ha i.e. 250km of cliffline eroding at less than 1m/year), but due to an inheritance of communities and developments built on eroding cliff tops.

Prior to the publication of PPG 14 (Development on Unstable Land; DoE 1990) and PPG 20 (Coastal Planning; DoE 1992) most local planning authorities did not have specific regard to problems of cliff recession either in determining planning applications or in defining planning policies in development plans (GSL 1987; Rendel Geotechnics 1995a). Examples of “set-back” policies were rare; Canterbury City Council’s cliff top “coastal protection zone”, where no permanent development is permitted, was amongst only a few exceptions. Although the recent introduction of Shoreline Management Plans (SMPs) and the consideration of coastal risks in the land-use planning process have marked a significant change in attitudes, the legacy of the past remains.

## 1.2 Current Issues

Over the last few decades there has been a shift in the focus of cliff recession priorities away from the unprotected coast towards the maintenance and improvement of both the existing defences and the protected slopes behind. It has become increasingly apparent that whilst the prevention of marine erosion at the cliff foot has reduced the potential for cliff recession and landsliding, it has not eliminated it. The internal slope processes of weathering, strain-softening, creep and the recovery of depressed pore water pressures can cause delayed failures many years later. Thus long lengths of cliff in

urban areas that are currently defended by toe protection structures will not necessarily remain stable over the design lifetime of these structures. Problems are also experienced as a result of the inevitable deterioration of toe protection structures and associated slope stabilisation works. Seawalls, for example, may have a life of 100 years or more, whilst drainage works may only have an effective life of around 20 years. Failure of protected slopes can cause severe damage to toe protection structures and may lead to renewal of cliff foot erosion if the structures subsequently fail.

Awareness has been growing of the cumulative impacts of coast protection on the environment. Eroding cliffs can be of considerable significance for their earth science and biological conservation value, and for their role as a source of sediment to littoral cells. As a result, their continued erosion is a conservation priority (e.g. English Nature 1992a, b). The soft cliff resource is, however under considerable pressure. Pye and French (1992) identified some 250km of unprotected soft cliffs in England, whereas the recent Coast Protection Survey of England (MAFF 1994) concluded that over 90km of new coast protection works were likely to be needed over the next 10 years. The potential loss of around 36% of the remaining soft cliff resource could have major implications for conservation and environmental management. For example, the protection of many clifflines has been accompanied by a reduction in the sediment supply to littoral cells. Although difficult to quantify, sediment inputs (notably sand and shingle for beaches, clays and silts for mudflats and saltmarshes) could have declined by as much as 50% over the last 100 years. This decline has probably been a factor in the degradation of beaches around many parts of the coastline.

The EC Habitats and Species Directive is likely to have a significant influence on the way in which some cliffs are managed. The Habitats Regulations (which implement the Directive in Great Britain) set out measures intended to maintain at, or restore to, a “*favourable conservation status*” those habitats and species designated as SAC/SPA. The Directive identifies “Vegetated Sea Cliff of the Atlantic and Baltic coasts” as requiring the designation of SAC. The UK coast supports a significant proportion of the EC sea cliff resource and, to date, 10 lengths of cliffline have been put forward as candidate SACs, including the cliffs of Suffolk, East Devon, West Dorset and the Isle of Wight. The Government is required to take appropriate steps to avoid the deterioration of the natural habitats and the habitats of species, as well as the significant disturbance of species, along these clifflines. A coast protection scheme that might affect the integrity of the habitats would only be approved if there were imperative reasons of overriding public interest. In such circumstances compensation measures would be required as part of the scheme e.g. the creation of replacement vegetated sea cliff habitat (e.g. Lee *et al*, 2001a).

Coast protection authorities have specific High Level Targets in relation to biodiversity. The Government has published a series of Habitat Action Plans which contain habitat creation and rehabilitation targets. When carrying out works they must aim to ensure that there is no net loss to habitats covered by biodiversity action plans (MAFF 1999a).

The Maritime Cliff and Slope Habitat Action Plan contains five targets, three of which are directly related to coast protection (UK Biodiversity Group 1999):

- to seek to maintain the existing maritime cliff resource of cliff top and slope habitat;
- to maintain wherever possible, free functioning of coastal physical processes acting on maritime cliff and slope habitats;
- to seek to retain and where possible increase the amount of maritime cliff and slope habitats unaffected by coastal defence and other engineering works.

These targets have introduced a “no net loss” policy for coastal cliff habitats, with the aspiration of achieving, over time, a “net gain”. It follows that if further new defences were to be provided there might need to be an abandonment of a matching or greater length of defences elsewhere.

From the preceding discussion, it is clear that coastal engineers and managers are faced with a range of issues on cliffed coastlines. These include:

1. Providing coastal defences to protect communities that will become vulnerable to cliff recession over the next few decades.
2. The long term maintenance and renewal of coast protection works to offset the deterioration of scheme components.
3. The protection of previously stabilised coastal slopes which have become critically unstable due to the process of weathering and other time dependent processes.
4. Ensuring that the risks to public safety on the unprotected coast are minimised through cliff management and the use of early warning systems etc.
5. Liaison with local planning authorities to ensure that further development is not placed in areas vulnerable to cliff recession and does not lead to an acceleration of recession on adjacent cliffs (e.g. through water leakage, loading etc.).
6. Recognising the strategic importance of cliff recession as a source of littoral sediment, especially for beaches and, where possible, avoiding further losses of sediment source areas.
7. Recognising the national and international conservation importance of soft rock cliffs and, where possible, avoiding further losses of this priority conservation resource.

In order to effectively manage coastal cliffs it is important that coastal engineers and planners have access to accurate and reliable information on the character of the cliffs, past and future cliff recession patterns and trends and the level of risk to coastal communities, together with the range of management strategies and erosion control techniques that might be suitable in different cliff environments.

**Table 1 A Selection of Reported Recession Rates Around the Coast of England and Wales**

Site	CBU Type	Average Erosion Rate (m/year)	Period	Source
Aberarth, Dyfed	Cm	0.12	1880 - 1970	Jones & Williams 1991
Llanon, Dyfed	Cm	0.25		Jones & Williams 1991
Morfa, Gwynedd	Cm	0.08		Jones & Williams 1991
Llantwit, S. Glamorgan	Cm	0.43		Williams et al 1991; Davies et al 1991
Ogmore-Barry, S. Glamorgan	Sf	0.07	1977 - 1985	Williams & Davies 1987
Blue Anchor Bay, Somerset	Cm	0.2		Williams et al 1991
Dowderry, Cornwall	Sl	0.11	1845 - 1966	Sims & Ternan 1988
St Marys Bay, Torbay	Cx	1.03	1946 - 1975	Derbyshire et al 1975
Bindon, E. Devon	R	0.1	1904 - 1958	Pitts 1983
Charton Bay, E. Devon	R	0.25	1905 - 1958	Pitts 1983
Black Ven	Cx	3.14	1958 - 1988	Chandler 1989; Bray 1996
Stonebarrow, Dorset	Cx	0.5	1887 - 1964	Brunsdon & Jones, 1980; Bray 1996
West Bay (W), Dorset	Cm	0.37	1887 - 1962	Jolliffe 1979; Bray 1996
West Bay (E), Dorset	Sf	0.03	1902 - 1962	Bray 1996
Purbeck, Dorset	Sf	0.3	1882 - 1962	May & Heaps 1985
White Nothe, Dorset	Sf	0.22	1882 - 1962	May, 1971
Barton-on-Sea, Hampshire	Cx	1.9	1950 - 1980	Barton & Coles 1984
Highcliffe, Hampshire	Cx	0.27	1931 - 1975	Univ. Strathclyde 1991
Undercliff, Isle of Wight	R	0.05		Hutchinson 1991
Blackgang, Isle of Wight	Cx	5		Clark et al 1995
Chale Cliff, Isle of Wight	Cx	0.41	1861 - 1980	Hutchinson et al 1981
Shanklin, Isle of Wight	Sf	0.68	1907 - 1981	Clark et al 1991
Seven Sisters, Sussex	Sf	0.51	1873 - 1962	May, 1971
Fairlight Glen, Sussex	Cx	1.43	1955 - 1983	Robinson & Williams 1984
Beachy Head, Sussex	Sf	0.9		May & Heaps 1985
Warden Point, Kent	Sl	1.5	1865 - 1963	Hutchinson 1973
Studd Hill, Kent	Sl	1.5	1872 - 1898	So 1967
Beltinge, Kent	Sl	0.83	1936 - 1966	Hutchinson 1970
North Foreland, Kent	Sf	0.19	1878 - 1962	May, 1971
Walton-on-Naze, Essex	Sl	0.52	1922 - 1955	Hutchinson 1973
Covehithe, Suffolk	Sf	5.1	1925 - 1950	Steers 1951
Southwold, Suffolk	Sf	3.3	1925 - 1950	Steers 1951
Pakefield, Suffolk	Sf	0.9	1926 - 1950	Steers 1951
Dunwich, Suffolk	Sf	1.6	1589 - 1783	So 1967
Runton, Norfolk	Sl	0.8	1880 - 1950	Cambers 1976
Trimmingham, Norfolk	Sl	1.4	1966 - 1985	Univ. Strathclyde 1991
Cromer-Mundesley, Norfolk	Sl	4.2 - 5.7	1838 - 1861	Mathews 1934
Marl Buff-Kirby Hill, Norfolk	Sl	1.1	1885 - 1927	Hutchinson 1976
Hornsea-Withernsea, Holderness	Sf/Sl	1.8	1852 - 1990	Pethick 1996

**Table 1 A Selection of Reported Recession Rates Around the Coast of England and Wales (cont...)**

<b>Site</b>	<b>CBU Type</b>	<b>Average Erosion Rate (m/year)</b>	<b>Period</b>	<b>Source</b>
Flamborough Head, N. Yorks	Sf	0.3		Mathews 1934
Robin Hoods Bay, N. Yorks	Cm	0.31	1892 - 1960	Agar 1960
Saltwick Nab, N. Yorks	Cm	0.04	1892 - 1960	Agar 1960
Whitby (W), N. Yorks	Sl	0.5		Clark & Guest 1991
Whitby (E), N. Yorks	Sf	0.19	1892 - 1960	Agar 1960
Runswick Bay, N. Yorks	Sl	0.27		Rozier & Reeves 1979
Port Mulgrave, N. Yorks	Sl	1.12	1892 - 1960	Agar 1960
Crimdon-Blackhall, Durham	Cm	0.2 - 0.3		Rendel Geotechnics 1995d
<p>Notes:            Sf - Simple cliff (falls)            Cm - Composite cliff            Sl - Simple cliff (landslide)            Cx - Complex cliff            R - Relict cliff</p> <p>See Chapter 2 for description of CBU types</p>				

### 1.3 A Strategic Approach to Cliff Management

Effective management of coastal cliffs should take account of the effects of *cliff top*, *coastal slopes* and *shoreline conditions* on the overall stability of particular coastal sections i.e. a strategic view is needed before action is taken. This type of co-ordinated approach has not been common practice around the coast, although the scale and complexity of problems in some areas (e.g. the Isle of Wight Undercliff, Canterbury City Council's London Clay cliffs, the Scarborough urban area and the coastal slopes of Lyme Regis) have been instrumental in the adoption of integrated cliff management techniques.

The long-term maintenance of previously protected and partially stabilised coastal slopes has become a priority task for many coast protection authorities. On many protected cliff lines it may be appropriate to undertake a strategic appraisal of the defences, especially where:

- large scale or long term problems are involved;
- the works involve improvements or maintenance over a long time period;
- there are process connections or interactions between adjacent CBUs;
- there are interconnected benefit areas;
- several smaller problems can be tackled in an integrated manner;
- the environmental effects of any works are likely to be widespread.

On the Scarborough coastline, the solution has been to complement the shoreline management plan. In response to the 1993 Holbeck Hall landslide, a preliminary assessment of the risk to the coastal defences from cliff instability was undertaken (Rendel Geotechnics 1994; Riby 1997; Lee 1999). This study involved:

- a review of the condition of the coastal cliffs;
- identifying the potential for cliff instability and the potential impact on the existing defences;
- assessing the financial consequences and risk of cliff instability;
- prioritising sections of the cliffs for future action;
- identification of cliff management strategies.

The preliminary risk assessment recommended the preparation of an integrated cliff and foreshore management plan; this has been developed as part of a strategic coastal defence study of the Scarborough urban frontage. This strategy involves:

- a review of the condition, performance and residual life of the existing defences;
- a quantitative risk assessment of the threat to the seawalls from landslides;
- an assessment of the consequences of seawall failure;
- assessment of wave overtopping problems;
- identification of coastal defence options for the next 60 years;
- environmental assessment of the defence options;
- the development of a prioritised and costed programme of works for monitoring, maintenance and improvements to allow progress within budget constraints.

## 1.4 Cliff Management: Key Points

This Manual is intended to provide a synopsis of the more detailed content of the Technical Report and, hence, follows the same structure. On reading through this report there may be occasions when the Reader wishes to find a more detailed account of a particular issue - this can be found by cross referring to the same Chapter in the Technical Report.

The Manual highlights a number of *key points* relevant to the investigation and management of coastal cliffs:

1. *The cliff recession process overwhelmingly reflects site conditions.* Every cliff problem will be unique because of the great range of cliff forms and processes and inherent variability of the cliff materials. It follows that measurement programmes, prediction strategies and coast protection schemes need to be designed to reflect site conditions and cannot be provided “off-the-shelf”.
2. *Cliff recession can be an episodic and uncertain process, controlled by both shoreline and slope processes.* Both the resisting (e.g. material type and strength, structural controls etc.) and destabilising factors (e.g. exposure to wave attack etc.) can vary markedly from cliff to cliff and through time giving rise to significantly different rates and modes of recession and instability even on similar material types. The uncertainty in the timing of events is due to variations of the factor of safety of a cliff over time in response to the combination of geotechnical factors (e.g. strain-softening of stiff plastic clays, pore water pressure changes etc.) and geomorphological factors (e.g. marine erosion and groundwater levels). This leads to variations in the size of triggering event that is needed to initiate failure and a degree of uncertainty in the timing and frequency of major recession events.
3. *Marine erosion is the dominant factor promoting the recession of unprotected cliffs,* involving the direct undercutting, oversteepening and erosion of the cliff face, the removal of debris from the foreshore and shore platform lowering. There are, however, significant differences in the way marine erosion controls the recession process in different cliffs. In simple cliffs and simple landslides there may be a direct and readily observable link between marine erosion and cliff recession. However, in composite complex and relic cliffs continuous sea cliff erosion through small events often leads to intermittent larger events in other parts of the cliff. Thus, in such settings cliff recession can be an irregular process and appears “detached” from the effects of marine erosion. This is not the case; marine erosion is generally the single most important factor in ensuring that the cliffs remain oversteepened and unstable.
4. *It is not possible to make completely reliable predictions about future cliff recession* partly because of the uncertainty in future weather conditions and partly because of the uncertainty about the physical properties and behaviour of the cliff. The inherent randomness in the main causal factors (e.g. wave height, rainfall etc.) dictates that future recession cannot be expected to be an accurate match with the historical records. Indeed, the pattern of past recession events is the result of a

particular and unique set of wave, weather and environmental conditions. A different set of conditions could have generated a different recession scenario.

5. *Problems arise because development has taken place in vulnerable locations.*
6. *The response to cliff recession problems should involve the consideration of both structural and non-structural solutions* i.e. there needs to be an integrated approach to cliff management, involving a combination of structural and non-structural solutions, as appropriate. Although coastal defence measures represent the traditional response to cliff recession problems, it would not be economic or desirable to protect all eroding soft cliffs. Growing awareness of the environmental benefits of cliff recession, together with a greater appreciation of the broad scale operation of coastal processes, have reinforced the need to take a more strategic and pragmatic view of the problems.
7. *Effective erosion control (coast protection) schemes are likely to involve a combination of toe protection and slope stabilisation.* As marine erosion will be fundamental to most cliff recession problems, the preferred option will typically include some form of toe protection to prevent or reduce wave attack. Secondary treatment measures, involving slope stabilisation, will often be needed to prevent the deterioration of the protected cliffs.
8. *The key to scheme selection is the identification and clear definition of the scheme objectives.* These may include:
  - to prevent or reduce cliff recession;
  - to minimise the risks associated with land instability.

The evaluation of potential options and combinations of options needs to be based on awareness of the problems within different elements of the cliff system and their interrelationships. These may include:

- foreshore lowering and beach loss;
  - cliff foot erosion;
  - active landsliding, seepage erosion and surface erosion;
  - the presence of pre-existing landslides;
  - unstable or potentially unstable rear cliff faces.
9. *The potential for landslide events does not cease when marine erosion has been prevented.* A protected slope may continue to degrade until it reaches a long term stable angle, in response to internal changes such as weathering, strain-softening and progressive failure, and the gradual recovery of depressed pore water pressures. The process of degradation generally involves small scale failures and surface creep, but can result in major deep seated movements. Under natural conditions this process may take hundreds, if not thousands, of years to complete and could involve substantial loss of cliff top land. Thus long lengths of cliff in urban areas which are currently defended by toe protection structures will not necessarily remain stable over the design lifetime of these structures.



10. *Coast protection and slope stabilisation works can have adverse consequences for the level of recession and flood risk elsewhere, and can damage the natural environment.* Eroding soft rock cliffs are a priority conservation resource. This resource is under considerable pressure from further coast protection works. The potential impacts of coast protection need to be fully appreciated before a decision is made to defend a cliff; only then can the true benefits of the “do-nothing” approach be set against the benefits of erosion control.
11. *The EC Habitats and Species Directive is likely to have a significant influence on the way in which some cliffs are managed.* The Habitats Regulations (which implement the Directive in Great Britain) set out measures intended to maintain at, or restore to, a “favourable conservation status” those habitats and species designated as SAC/SPA. The Directive identifies “Vegetated Sea Cliff of the Atlantic and Baltic coasts” as requiring the designation of SAC. The UK coast supports a significant proportion of the EC sea cliff resource and, to date, 10 lengths of cliffline have been put forward as candidate SACs, including the cliffs of Suffolk, East Devon, West Dorset and the Isle of Wight. The Government is required to take appropriate steps to avoid the deterioration of the natural habitats and the habitats of species, as well as the significant disturbance of species, along these clifflines. A coast protection scheme that might affect the integrity of the habitats would only be approved if there were imperative reasons of overriding public interest. In such circumstances compensation measures would be required as part of the scheme e.g. the creation of replacement vegetated sea cliff habitat.
12. *Coast protection authorities have specific High Level Targets in relation to biodiversity.* When carrying out works they must aim to ensure that there is no net loss to Maritime Cliff and Slope and Chalk Cliff Habitats. These targets have introduced a “no net loss” policy for coastal cliff habitats, with the aspiration of achieving, over time, a “net gain”. If further new defences were to be provided there would need to be an abandonment of a matching or greater length of defences elsewhere.

## CHAPTER 2 CLIFF RECESSSION

### 2.1 Coastal Landsliding and Cliff Recession

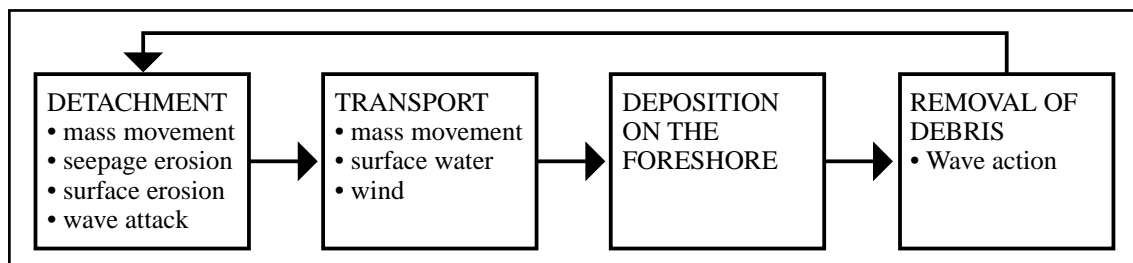
Soft cliffs are formed through the exposure of rocks that have little resistance such as clays, shales or sandstone, or unconsolidated materials such as sands. Having little resistance they generally have shallower gradients than hard cliffs, which allows for greater colonisation of vegetation. The English coastline exhibits a wide variety of such landforms. Coastal cliffs form the dominant erosional features along many parts of the Northeast, East Anglian and the South coasts. Their variety reflects the complex interactions between rock character, geological structure and inland relief on the one hand and the applied forces of both marine and non-marine processes on the other.

A number of broad categories of cliff type can be recognised, on the basis of the geology and associated landslide types (Hutchinson, 1984b, 1988; Jones and Lee 1994);

1. *Cliffs developed in weak superficial deposits;*
2. *Cliffs developed in weak superficial deposits overlying jointed rock;*
3. *Cliffs developed in stiff clay;*
4. *Cliffs developed in weak sandy strata;*
5. *Cliffs developed in sequences of stiff clays and weak sandy strata;*
6. *Cliffs developed in stiff clay with a hard cap-rock;*
7. *Cliffs developed in bedded, jointed weak rock.*

### 2.2 Cliff Recession

Cliff recession is a four-stage process involving *detachment* of particles or blocks of material, the *transport* of this material through the cliff system, its *deposition* on the foreshore and its *redistribution* or *removal* by marine action (Figure 1). Behind this simple model is considerable complexity. A variety of mechanisms result in the detachment of material, including: mass movement, seepage erosion, surface erosion (i.e. rainsplash and wind erosion) and wave attack (including abrasion and hydraulic action, and fluid shear by uprushing waves during large storms).



**Figure 1 The Cliff Recession Process**

The causes of cliff recession are extremely complex and varied although most events are promoted by a combination of wave attack, weathering and groundwater levels within the cliff (Table 2). In addition, the effects of development and human activity should never be underestimated (e.g. Jones and Lee 1994). Many cliff failures in and

around developed areas are often the result of uncontrolled discharge of surface water through soakaways and highway drains; discharge of groundwater onto the cliff face through land drains in agricultural areas; progressive deterioration and leakage of swimming pools and services such as foul sewers, water mains and service pipes. Common factors in many coastal failures also include excavations to create level plots for building, especially at the foot of a cliff; disruption of sediment supply by protecting eroding cliffs, leading to starvation of beaches down drift of the protected cliffs and accelerated erosion.

<p><b>Table 2 A Summary of the Various Factors Involved in the Coastal Landsliding Process.</b></p>
<p style="text-align: center;"><b>A FACTORS PROMOTING MASS MOVEMENT</b></p> <p style="text-align: center;"><b>External Factors</b></p> <ul style="list-style-type: none"> <li>• Undermining of the cliff by wave action (e.g. formation of a notch or cave at the cliff foot)</li> <li>• Oversteepening of the cliff by wave action</li> <li>• Unloading of the cliff (e.g. by removal of debris from the toe of a pre-existing landslide)</li> <li>• Shore platform lowering</li> <li>• Lowering of beach levels</li> </ul> <p style="text-align: center;"><b>Internal Factors</b></p> <ul style="list-style-type: none"> <li>• Weathering (e.g. frost action, salt weathering and drying)</li> <li>• Stress relief and swelling</li> <li>• Strain-softening</li> <li>• Groundwater level changes</li> <li>• Shrinkage</li> </ul> <p style="text-align: center;"><b>B FACTORS CONTROLLING THE RATE OF DEBRIS REMOVAL</b></p> <ul style="list-style-type: none"> <li>• Wave and tide climate</li> <li>• Foreshore gradient</li> <li>• Erodibility of debris</li> <li>• Sediment transport potential</li> </ul>

Cliff recession is generally an uncertain and episodic process, characterised by:

- seasonal patterns of surface erosion and seepage erosion especially on cliffs developed in weak, sandy or silty materials, which are generally associated with periods of heavy rainfall;
- repetitive sequences of landslide activity comprising first-time failure, debris removal and reactivation. The duration of this sequence is not constant, reflecting changes in climate even over the short term, and variations in the geological conditions exposed at the coast by the recession process;
- variations in time of the stability of a cliff due to a combination of geotechnical factors (e.g. strain-softening of stiff plastic clays, pore water pressure changes etc.) and geomorphological factors (e.g. marine erosion). This leads to variations in the size of triggering event that is needed to initiate failure and results in a degree of uncertainty in the timing and frequency of major recession events.

### 2.3 Cliff Behaviour Units

Cliffs are open sediment transport systems characterised by inputs, throughputs and outputs of material, i.e. they are cascading systems. The concept of a “cliff behaviour unit” (CBU) provides an important framework for cliff management (Lee 1997; Moore *et al*, 1998; Brunsten and Lee 2000). These units (CBUs) span the nearshore to the cliff top and are coupled to adjacent CBU’s within the framework provided by littoral cells/sediment cells. A range of types of cliff system can be recognised on the basis of the throughput and storage of sediment within the system (Figure 2):

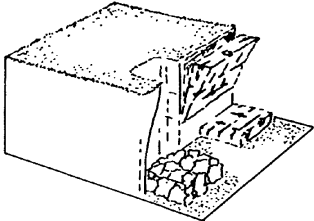
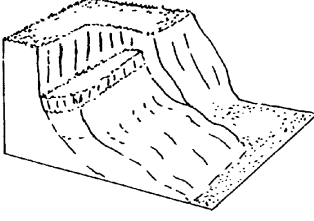
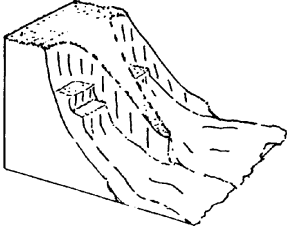
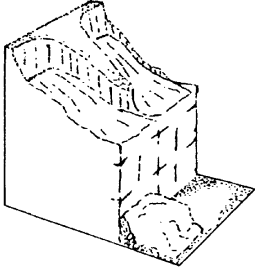
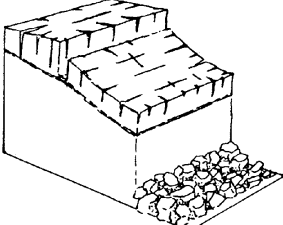
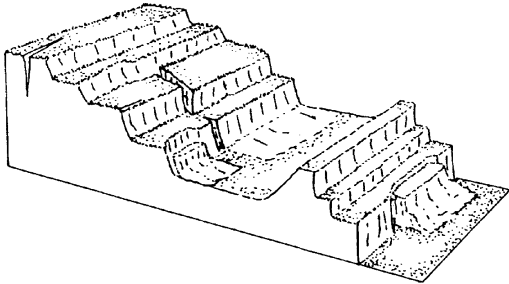
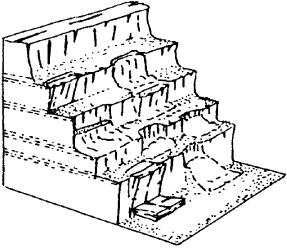
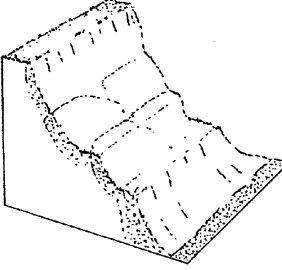
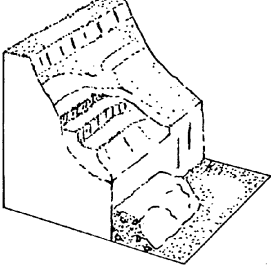
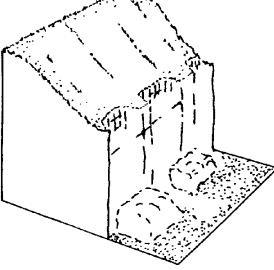
Simple cliffs	 <p>Topples and falls</p>	 <p>Rotational landslide</p>	 <p>Mudslide</p>
Composite cliffs	 <p>Rotational landslide in glacial till over hard rock</p>	 <p>Block slide in hard rock over a thin clay layer</p>	
Complex cliffs	 <p>Deep-seated landslide with failure at more than one level</p>		 <p>Seepage erosion cliff alternating sand and clay</p>
Relict cliffs	 <p>Dormant</p>	 <p>Reactivated</p>	 <p>"Slope-Over-Wall"</p>

Figure 2 The Main CBU Types

1. Simple cliff systems in hard or soft rock or superficial materials; comprising a single sequence of sediment inputs (from falls or slides) and outputs, with limited storage. A distinction can be made between cliffs prone to falls and topples and those shaped by simple landslides. The former is characterised by limited storage of sediment within the cliff system, with material from the cliff top and face reaching the foreshore in a single event.
2. Simple landslide systems; comprising a single sequence of inputs and outputs with variable amounts of storage within the failed mass. Debris from the cliff may only reach the foreshore after a sequence of events involving landslide reactivation.
3. Composite systems; comprising a partly coupled sequence of contrasting simple sub-systems. The output from one system may not necessarily form an input for the next (e.g. where material from the upper unit falls directly onto the foreshore).
4. Complex systems; comprising strongly linked sequences of sub-systems, each with their own inputs and outputs of sediment. The output from one sub-system forms the input for the next. Such systems are often characterised by a high level of adjustment between process and form, with complex feedback mechanisms. Examples include landslide complexes with high rates of throughput and removal of sediment, such as the Naish Farm to Barton-on-Sea cliffs of Christchurch Bay, the west Dorset cliffs, and cliffs affected by seepage such as Chale Cliff, Isle of Wight.
5. Relict systems, comprising sequences of pre-existing landslide units which are being gradually reactivated and exhumed by the progressive retreat of the current seacliff e.g. parts of the Isle of Wight Undercliff, the Axmouth Undercliff, East Cliff (Lyme Regis) and the “slope-over-wall” cliffs of south-west England.

The concept of the cliff behaviour unit emphasises the linkage between cliff and foreshore processes. The beach, for example, has an important role in determining the rate and timing of landslide events. It is also important to appreciate the linkages with other landforms within a littoral cell, with many CBUs acting as sediment sources for beaches, dunes, salt marsh, mudflats etc. on the neighbouring coastline.

## **2.4 Cliff Behaviour**

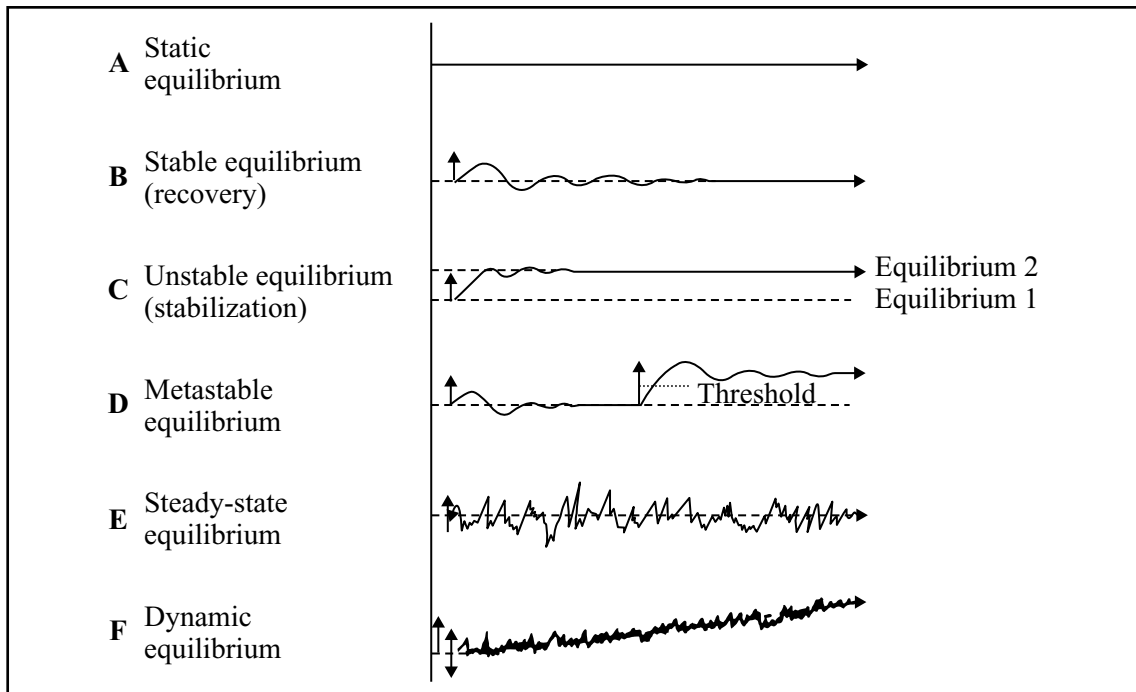
Over time, cliffs may demonstrate two contrasting modes of behaviour:

- a complex and uncertain sequence of recession events, often with variable time periods between events depending on the sequence of storms and the variable stability state of the cliff. Thus, storm events of a particular magnitude may be redundant (i.e. do not initiate cliff recession) until preparatory factors (e.g. weathering, strain softening etc.) lower the slope stability to a critical level at which time a smaller storm may “trigger” recession;
- the establishment and maintenance of a characteristic set of landforms within a CBU which persist through time, although individual components will be evolving and the pattern and interrelationships of these features will be continuously changing.

These two conditions highlight a fundamental problem for the prediction and measurement of cliff recession - the need to relate highly variable records or observations of recession events to the overall trend operating within a CBU. Here, it is convenient to view cliff recession over a range of relevant timescales:

1. *Short term behaviour*; when viewed from this perspective recession appears to be a highly variable process, with marked fluctuations in the annual recession rate around an average value. This type of behaviour is characterised by periods of no activity punctuated by short phases of recession.
2. *Medium term behaviour*; over this timescale the fluctuations smooth themselves out as there is a tendency for CBUs to maintain a balance between process and form through negative feedback and self-regulatory mechanisms (e.g. storage of debris). When viewed from this perspective the recession rate will be relatively constant. This medium term condition can be regarded as reflecting steady-state behaviour (see Table 3), characterised by maintenance of CBU form, parallel retreat of the cliff profile and a balance over time in the sediment budget, i.e. the overall rate of detachment equals the overall rate of removal from the foreshore, with minimal changes in the volume of material stored within the cliff system.
3. *Long term behaviour*; over this timescale the characteristics of the CBU may gradually change, reflecting the progressive evolution of the cliffline in response to major environmental changes, e.g. the Holocene climate and sea level changes.

It is clear that the medium term behaviour, characterised by a steady-state equilibrium between CBU form and processes, is of major importance to cliff management. This timescale provides a framework within which recession is a regular and predictable process and enables the significance of individual major events to be evaluated in terms of their contribution to the overall pattern of cliff recession.



**Figure 3** Examples of Types of System Equilibrium  
(after Chorley and Kennedy 1971)

**Table 3** Concepts of Geomorphological Equilibrium

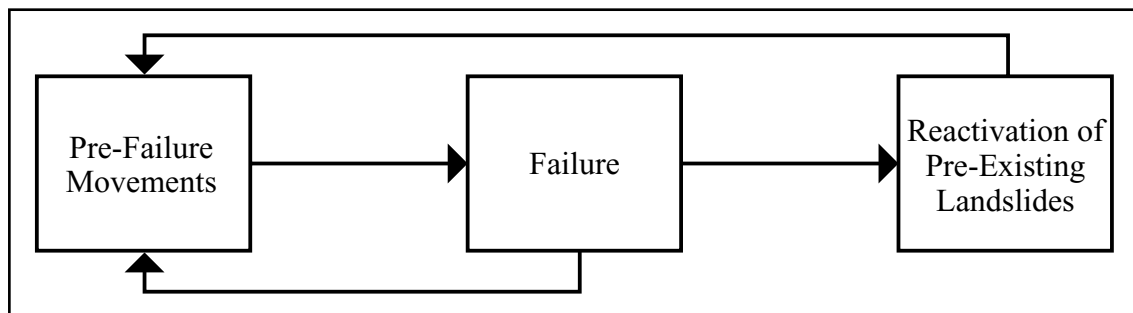
A widely used concept in coastal geomorphology is that natural systems tend towards equilibrium conditions where the inputs of mass and energy to a specific system are equal to the outputs from the same system. The gross form will remain unchanged throughout these transfers. There are a variety of types of equilibrium that are associated with quite different patterns of behaviour (Figure 3; Chorley and Kennedy 1971):

- *static equilibrium*; no change over time;
- *stable equilibrium*; the tendency for the form to return to its original value through internal feedback operations within the system following a disturbance;
- *unstable equilibrium*; the tendency for the variable to respond to system disturbance by adjustment to a new value;
- *metastable equilibrium*; a combination of stable and unstable equilibrium except that the variable settles on a new value only after having crossed some threshold value - otherwise it returns to the original value;
- *steady state equilibrium*; the variable has short-term fluctuations with a longer-term constant mean value;
- *dynamic equilibrium*; the variable has short-term fluctuations with a changing longer-term mean value (i.e. an increasing or decreasing trend).

It is worth stressing that steady state is a specific form of dynamic equilibrium when the mean recession rate is unchanging. Perhaps the most important aspect of dynamic equilibrium is the rate of change of the mean rate, rather than the short-term oscillations around it.

It is an oversimplification to suggest that all cliffs are currently experiencing steady-state behaviour. Most variations from the steady-state are probably minor and unlikely to be significant for cliff management. However, there are many circumstances where there may be significant changes to the cliff system: increased rate of marine erosion; cessation of marine erosion; climate change; exposure of different materials in the cliff profile; the effects of coastal engineering at a site or elsewhere within a coastal cell. These changes may result in accelerated erosion that is manifested by a period of process variation and the development of temporary forms and in some circumstances, new characteristic forms i.e. *non steady-state* behaviour.

## 2.5 The Recession Cycle



**Figure 4 A Geotechnical Model of Cliff Recession**

Figure 4 presents a geotechnical model of cliff recession that focuses on the character of landslide activity. Three main stages of activity are recognised:- *pre-failure movements*, actual *failure* and the *reactivation* of the displaced material. These stages form a repetitive sequence of events (“cycle”) driven by factors such as debris removal from the foreshore and periods of high groundwater levels.

Each stage in the “cycle” involves a different set of controlling factors, and their relative significance will vary between different CBUs. For example, in some complex CBUs there may be many phases of reactivation before pre-failure movements or further failure of the cliff top is initiated. By contrast, on simple cliffs the sequence is generally confined to pre-failure movements and failure.

## 2.6 Cliff Recession in a Warmer Britain

Mean sea level is predicted to rise by as much as 19cm over the next 30 years (Parry *et al* 1996). On the south coast of England sea level is expected to rise by over 50cm by the year 2050. In terms of climate, the “best estimate” of change to the year 2050 indicates that there could be notable modifications to coastal processes. The most important influences are likely to be higher winter rainfall, increased likelihood of summer droughts and increased storm activity, possibly by up to 30% by the 2050’s. The main factors influencing cliff behaviour will be the probable increase in frequency of wave attack at the cliff foot, efficiency of debris removal from the foreshore and frequency of wet year sequences.

There appears to be general agreement that extreme climatic events are likely to be more frequent over the next century; this could lead to a significant increase in the



magnitude of impact arising from recession events. The historical record provides an opportunity for developing scenarios for change in cliff recession and landslide activity in response to variations in climate.

During the late 17th and early 18th centuries there was a period of colder, wetter climate, known as the “*Little Ice Age*”. This period was characterised by frequent severe winters, reduced run-off and the occurrence of surface winds of strengths unparalleled in this century. The end of the Little Ice Age was marked by a much wetter, more extreme and variable climate which may offer an analogue to the current phase of atmospheric warming. This period from 1700-1850 has been associated with an increase in the reported incidence of major coastal landslides in eastern and southern England, including:

- the 1682 landslide at Runswick, North Yorkshire when the whole village slipped into the sea (Young and Bird 1822);
- the 1737 landslide at The Spa in Scarborough’s South Bay (Schofield 1787);
- the major failure in 1780 which destroyed the main road into Robin Hoods Bay, North Yorkshire and 2 rows of cottages (e.g. Dalton 1914);
- the great landslide at the Haggerlythe, Whitby on Christmas Eve 1787 which resulted in the destruction of 5 houses and led to 196 families being made destitute (Anon 1788);
- the landslide of 1792 on the north west of the Isle of Portland which involved more than a mile of cliff and is believed to have been one of the largest coastal landslides to have occurred in historical times (Hutchins 1803);
- the major reactivations of parts of the Isle of Wight Undercliff, at Gore Cliff in 1799 and in The Landslip in 1810 and 1818 (e.g. Hutchinson 1991);
- the 1829 landslide at Kettlewell, North Yorkshire when the whole village slid into the sea, with the inhabitants having to be rescued by alum boats lying offshore (e.g. Jones and Lee 1994);
- the great landslides on the North Norfolk coast near Overstrand of 1825 and 1832 (Hutchinson 1976);
- the famous Bindon landslide, east of Lyme Regis of Christmas Eve 1839 (Conybeare *et al* 1840).

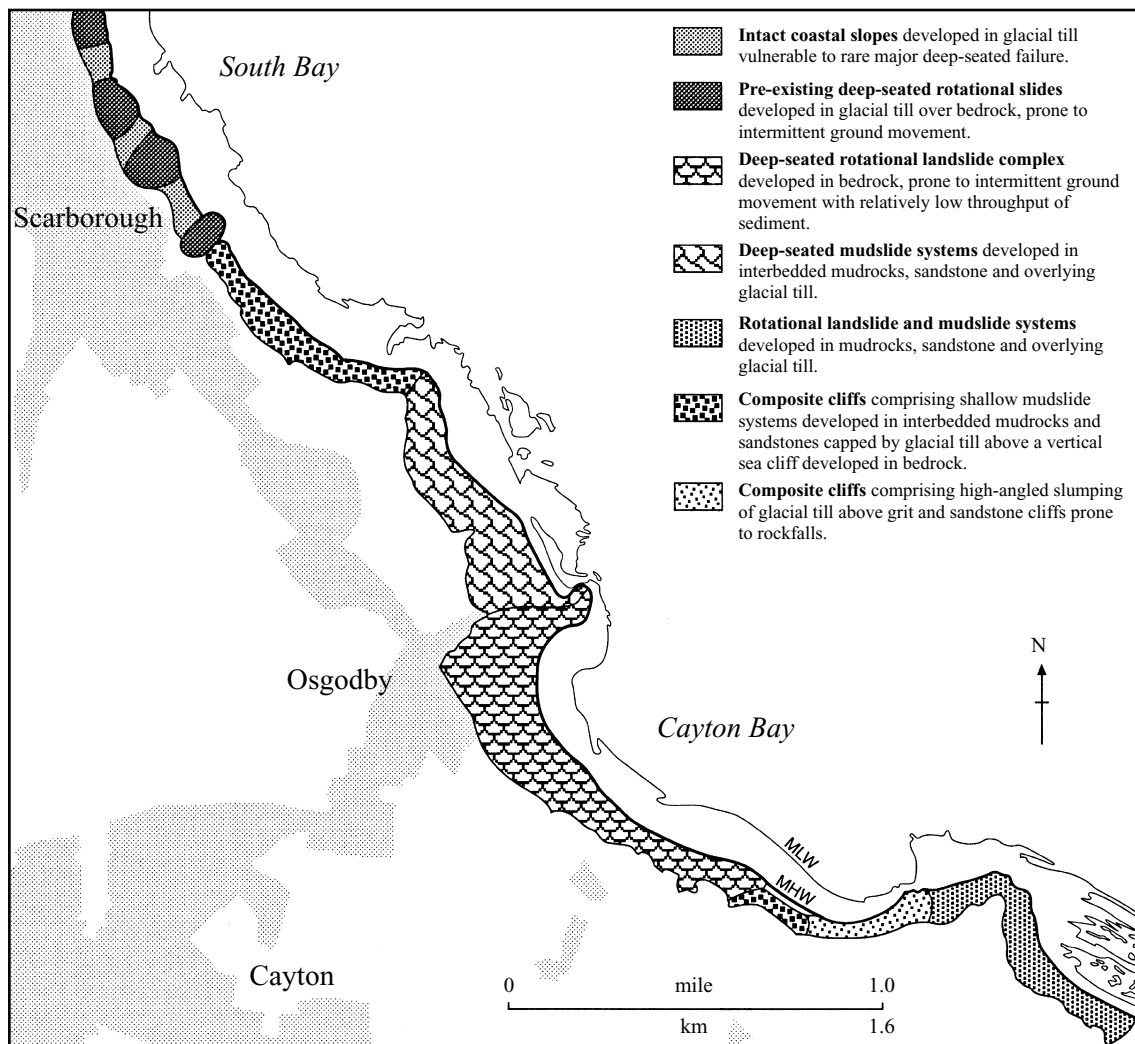
Similar events have occurred since this period (e.g. the Holbeck Hall landslide of 1993), but they have been much rarer. It is possible that the likelihood of such major events will increase in response to the environmental changes associated with global warming and relative sea level rise. There is, however, no record of cliff recession rates during the post Little Ice Age period of climatic recovery, as it took place before the production of the first Ordnance Survey maps. It could be argued that this period would have been characterised by accelerated recession but this is pure speculation. Indeed, it is possible the recession rates on some cliffs were lower than today if, as is widely believed, beaches were more extensive and larger and could provide greater protection against wave attack at the cliff foot. If this is the case the anticipated sea level rise over the next decades, together with depleted beaches and a declining sediment supply from cliff recession (due to coast protection), could result in significant changes in cliff behaviour which have no parallel over the historical time period.

## CHAPTER 3 A FRAMEWORK FOR CLIFF MANAGEMENT

### 3.1 Introduction

There is no single approach to investigation and management that is applicable in all situations. Indeed, there is a hierarchical sequence of investigations and studies that may need to be undertaken along the coastline, each relevant to different stages in the planning and management process. At a strategic level both coastal engineers and planners need to know, in general terms, the nature of the cliff recession problems as a basis for *shoreline management plan* and *development plan* preparation. The management of protected cliffs in urban areas has become a priority task for many coast protection authorities and, in some circumstances, it may be necessary to undertake a *strategic study* of the coastal defences along the urban frontage to support the Shoreline Management Plan policies or specific local development plan policies. Where an authority has identified the need for coast protection, it will be necessary to undertake a *feasibility and options study* to identify a preferred scheme. Here, engineers will need to have access to detailed information about the cliff conditions, future recession scenarios, the level of risk, and the likely costs and environmental impacts of the preferred coast protection scheme.

### 3.2 Identification of CBUs



**Figure 5 CBUs Along Part of the North Yorkshire Coast, South of Scarborough**

CBUs can range from extensive clifflines in relatively uniform materials (e.g. Holderness) to separate small units reflecting more complex geological settings. Map scales of 1:25,000 - 1:50,000 seem to be suitable for the delineation of CBUs for shoreline management and strategic coastal planning (e.g. Figure 5). Greater detail of mapping will be required to support the assessment of individual CBUs for scheme strategy or feasibility studies, or, in the case of extensive clifflines, sub-sections of CBUs.

Probably the simplest and quickest approach to defining the physical extent of individual CBUs is to identify geological and morphological units along a cliffline (i.e. characteristic assemblages of landforms), as different morphological units will generally reflect different patterns of cliff behaviour. The emphasis should be placed on the cliff system itself, although the nature of the foreshore needs to be taken into account. At the resolution relevant for *Shoreline Management Plans* (i.e. 1:25,000 - 1:50,000 scale), CBUs can be identified and defined on the basis of geological and geomorphological mapping of the cliffs and foreshore (see Cooke and Doornkamp 1990; Engineering Group Working Party 1972; Lee 2001), concentrating on identifying different types of landslide or separate landslide units. In many instances an experienced earth scientist, using aerial photographs and field inspection, can carry out this procedure quickly.

Defining CBUs on the protected coast is more problematic as the cliff and foreshore morphology rarely correspond with the natural condition. In many instances the CBU boundary may not be apparent without detailed site inspection and field mapping. It is important that CBUs are defined in terms of their current state (protected or stabilised slope) and the potential forms of failure that may occur. This often requires accurate delineation of CBU types coupled with an assessment of contemporary *ground behaviour* (Lee and Moore 1991). In certain settings it may be possible to examine the behaviour of adjacent unprotected cliffs developed in similar materials and environmental conditions, which may give an indication of the types and nature of CBUs being considered on the protected coast.

### **3.3 Investigation**

The main objective of a cliff investigation is to understand the materials, forms and processes of a CBU, together with the contemporary and, in some cases, long-term changes that have occurred. The investigation should focus on:

- the type of recession events i.e. landslide types, nature of surface and seepage erosion etc.;
- the size of recession events;
- the potential for rare, large recession events;
- the frequency of recession events;
- the causes of recession e.g. marine erosion and internal factors etc.;
- the significance of short or long term beach profile changes or foreshore lowering in the recession process;
- the relationship between the CBU and the littoral cell, including the sediment budget.

The first stage in any site assessment should be a *desk study* involving a thorough search of the relevant documentation, including current and old topographical, geological and soil maps, oblique and vertical aerial photographs, postcards, technical and topographical papers and records, and newspaper articles. Local knowledge should also be sought through discussions with the residents of the area.

*Aerial photograph interpretation* (API) has long been used in the investigation of coastal cliffs. Aerial photography provides an exact and complete record of the ground surface at a given time and hence represents the most efficient means of recording natural and man-made features of the coastline (Dumbleton 1983, Dumbleton and West 1970, 1976). Common scales of aerial photography range from 1:5,000 and larger for detailed studies to smaller than 1:25,000.

The principal advantages of using API in cliff studies include:

- the delineation of CBU boundaries;
- appreciation of nature and extent of individual elements within a CBU, including the character of the foreshore and types of slope instability;
- rapid measurement of changes in slope form and recession rates if photographs from different dates are available.

The use of aerial photographs in the preliminary design of site investigation for all engineering works has become well integrated into codes of practice and is briefly described in the Site Investigation Code of Practice BS5930 (BSI, 1981, 1999).

Irrespective of the availability of background information, there will usually be a need for ground inspection to confirm the desk study results. Surface mapping techniques such as morphological, engineering geology and geomorphological mapping can be used to establish the nature and extent of CBUs and to determine the degree of threat that cliff recession may pose to existing property.

*Geomorphological mapping* can be carried out at a variety of scales, from regional studies (e.g. Figure 5), to strategic assessments of a cliffline and detailed investigations of a particular CBU or coastal landslide system. These geomorphological maps show the spatial distribution of coastal landslide features and highlight the nature and form of this instability. As the recession processes are dynamic it is not possible to map them as such, instead various landforms are shown to indicate former, current and potential instability.

Detailed investigations will normally be required to support a Feasibility Study and Coast Protection Options Report. Successful design of erosion control measures requires a thorough investigation of the ground conditions and physical processes operating within the CBU and surrounding area. This would typically include a combination of desk study and site reconnaissance techniques described above (especially surface mapping), in addition to subsurface investigation, monitoring, numerical and physical modelling and stability analysis (see BSI 1981; Weltmann and Head 1983; Petley 1984; CIRIA 1996a).

Answers are needed to basic question such as: what types of instability affect the site (i.e. first-time failure or a renewal of movement on pre-existing shear surfaces); what

is the level of wave attack at the cliff foot; is the foreshore prone to depletion and accretion; are the piezometric conditions short-term, intermediate, long-term or a combination of these; what are the shear strength and other geotechnical parameters; is the slope already close to ultimate stability, or is it badly over-steepened and unloaded by recent erosion and thus very prone to failure; what would be the scale, speed and run-out of a potential failure; what risk is thus posed to life and property and what factors of safety should be used in the design.

A wide range of investigation techniques can be employed in a detailed assessment. The scale of the investigation will depend on the severity of the problems and the amount of investigation already undertaken in earlier studies. In general terms the investigation will need to establish:

- the geological, hydrogeological and hydraulic conditions at the site;
- the actual or potential mechanisms of recession events;
- the degree of risk from cliff recession, including geometry of failure and geotechnical parameters;
- the potential range of schemes that could be used to overcome the problems and their costs;
- the likely effects of the proposed works on the environment and other interests;
- the mitigation measures that might be used to counterbalance any undesirable effects of the works;
- the cost of works relative to the benefits they would produce.

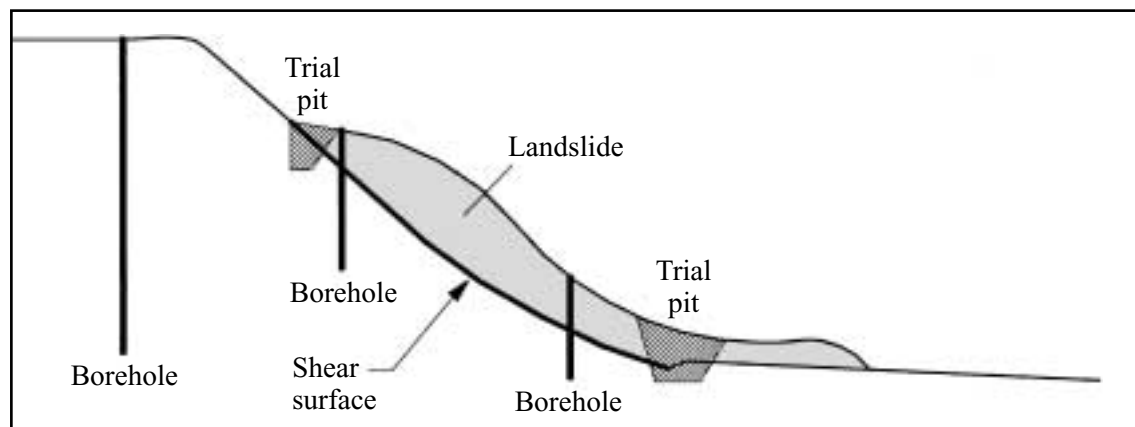
The investigation of a CBU, especially one comprising pre-existing landslides, should include techniques which will locate and define the three-dimensional shape of the shear surfaces or potential shear surfaces and allow identification of the engineering properties and groundwater conditions of the cliff (see Hutchinson, 1982; Petley, 1984; Clayton et al., 1982).

Subsurface investigation techniques must be selected carefully on the basis of the anticipated ground conditions. As with all subsurface investigations, provision should be made to modify the scope of the work or the techniques used if ground conditions are found to be different from those expected. A further aspect that must be emphasised is the high quality of work that is required in an investigation of unstable coastal cliffs. The work should be undertaken by experienced site investigation personnel using operationally sound equipment and should be supervised by experienced engineering geologists or geotechnical engineers; there are also important health and safety issues when investigating unstable coastal cliffs.

In general, the design of the sub-surface investigation will depend on a number of factors, including:

- the amount of existing information;
- the nature of the CBU and the extent and activity of the landslide units;
- the expected variability of the sub-surface conditions;
- external constraints such as the availability of equipment, access restrictions (e.g. steep slopes), costs and time available.

*Boreholes and trial pits* are the most frequently used combination of investigation methods, although shafts and adits can be of value on large landslides (Clark et al 1996a). There are no hard and fast rules for planning the location and frequency of boreholes and trial pits. It is common practice, however, to arrange boreholes along a section line from behind the cliff top to the cliff foot, guided by a geomorphological map to identify the optimum locations. In large complex CBUs it may be appropriate to investigate more than one section. Trial pits can then be used to locate shear surfaces close to the margins of the failed ground (Figure 6). Although there is no strict rule regarding the spacing of boreholes, they may need to be closely spaced to provide adequate information. However, a minimum of three boreholes is suggested along any section line, unless access restrictions dictate otherwise.



**Figure 6 Sub-Surface Investigation**

When investigating CBUs the expected borehole depth is governed by the anticipated depth of the basal shear surface of pre-existing landslides or potential failure surfaces on intact cliffs. Here, surface mapping of the landslide form and a review of the site geology can give valuable clues to the likely depths of shear surfaces. However, it is important to be flexible as actual shear surface depths may be deeper than anticipated. In such circumstances a prompt decision will need to be made to extend the boreholes, because it is cheaper to obtain the additional information whilst the equipment is on site than to remobilise a rig at some later date.

A shear surface is often less than a millimetre thick while many shear zones are only a few centimetres thick and consequently continuous and high quality sampling is required. It is important to obtain high quality results and these are best provided by site investigation contractors with proven experience in recovering good quality samples and cores.

It is advisable to take all boreholes to a greater depth than the shear surface to gain a full appreciation of the soil profile and overall ground conditions. The borehole behind the cliff top is usually the best site for a deep boring as it provides a “control” section through the undisturbed soil profile which can shed light on the degree of disturbance encountered in the downslope boreholes.

The range and scope of boring and drilling techniques are detailed elsewhere (Weltman and Head 1983) and include: hand auger; light cable percussion boring (shell and auger); rotary auger; rotary coring and; rock drilling.

*Shallow trial pits and trenches* permit direct physical examination, at a relatively low cost, of the nature of materials *en-masse* and the location of shear surfaces and shear zones at shallow depths. It is also possible to search for discontinuities that are frequently damaged or disturbed during borehole sampling (Petley 1984). Trial pits extending to depths up to about 4.5m can be excavated in suitable dry material using conventional rubber tyred back-actors while depths exceeding 6m are attainable using track-mounted or extended-arm back-actors. The optimum locations of these excavations will be largely controlled by the morphology of the CBU, such as the location and configuration of the toe, the rear scarp and intermediate scarps (Figure 6) and hence surface mapping is a useful pre-requisite to this investigation technique.

*Laboratory testing* of soil or rock samples is frequently undertaken to determine the composition and properties of the materials encountered during a site investigation. Two main groups of test are relevant for the characterisation of coastal cliffs. Classification tests are undertaken to determine the particle size distribution of the material, index property tests (liquid and plastic limits), bulk density, water content and specific gravity. These are very common tests; details can be found in BSI (1990) and Head (1982, 1985). A range of shear strength tests is available, each suitable for different situations. Further details can be found in BSI (1990), Bromhead (1986) and Head (1985). In general the most important strength tests will be the ring shear test of the materials along the shear surface in a pre-existing landslide and the consolidated-drained triaxial test of the materials in an intact protected cliff. This latter test models the long-term, drained pore water pressure conditions.

*Slope monitoring* is an integral part of cliff investigations because it provides a means of accurately and objectively gauging the stability conditions of unstable or potentially unstable slopes. There are a range of techniques (see Franklin 1984; Turner and Schuster 1996) that can be used for a variety of purposes:

- to determine whether slope displacement is sufficient to warrant further detailed site investigations and remedial measures;
- to deduce the mechanism of failure, and the location and configuration of the shear surface from the rate and direction of ground displacements;
- to assess the relationship between recession events and rainfall or groundwater levels;
- to assess the effectiveness of stabilisation measures employed by direct reference to the results of continual monitoring;
- to enable early-warning of slope failure.

*Stability analysis* is important when a judgement is needed about whether a slope is stable or not, or whether proposed stabilisation measures will be effective. A theoretical slope model is developed to which the failure criterion and loadings on the slope are introduced. The analysis then indicates whether the failure criterion is reached, and a comparison made between these conditions and those under which the modelled slope would just fail. The results of any analysis are usually presented as a “*factor of safety*” (i.e. the ratio of available strength to mobilised strength) or, less often, as a “*probability of failure*”. It is important to stress that the results for stability analyses are often of limited value in absolute terms, as they are dependent on the

assumptions made in the stability model. However, there is considerable experience in their application and they are well calibrated from the analysis of actual failures.

Stability analyses are usually undertaken for one of three main reasons: the assessment of potential slope failure; the “back-analysis” of a pre-existing landslide or the sensitivity analysis of parameters influencing slope instability. Many different analytical techniques are available (Bromhead 1986; Turner and Schuster 1996). In selecting a particular method of analysis, the reliability and quantity of soil data, the knowledge of the geological conditions and the consequences of failure should be considered. Sophisticated numerical analysis is not justified when the problem definition and soil properties are not well known. The data requirements for stability analysis include: surface topography; location and configuration of basal shear surface (if appropriate); shear strength of materials along the shear surface or potential failure surface; rock mass characteristics, including the shear strength and pattern of discontinuities; groundwater conditions.

*Foreshore investigation* is important as no cliff system is independent of the processes operating on the foreshore and beyond. However, many cliff investigations will extend no further seaward than the cliff foot; this may lead to a incomplete or inaccurate understanding of the recession process. It is important therefore, that effort should also be directed towards characterising this component of a CBU. Depending on the nature of the coastline this may involve the assessment of:

- foreshore and nearshore geology (rock type and structure);
- beach profiles, plan shape, materials and evidence of change (see CIRIA, 1996);
- bathymetry;
- rate of foreshore lowering;
- seabed sediments and evidence of sediment transport;
- remnant landslide units in the nearshore zone.

### **3.4 Characterisation of CBUs**

CBUs should be characterised in terms of the geotechnical and geomorphological factors which determine the behaviour of the cliff (Table 4). Of particular significance are:

- the controlling factors;
- the triggering and preparatory factors;
- the size and type of recession events (i.e. retrogression potential);
- the timing and sequence of events (i.e. recurrence interval);
- the recession rate;
- the consequences of cliff failure or recession.



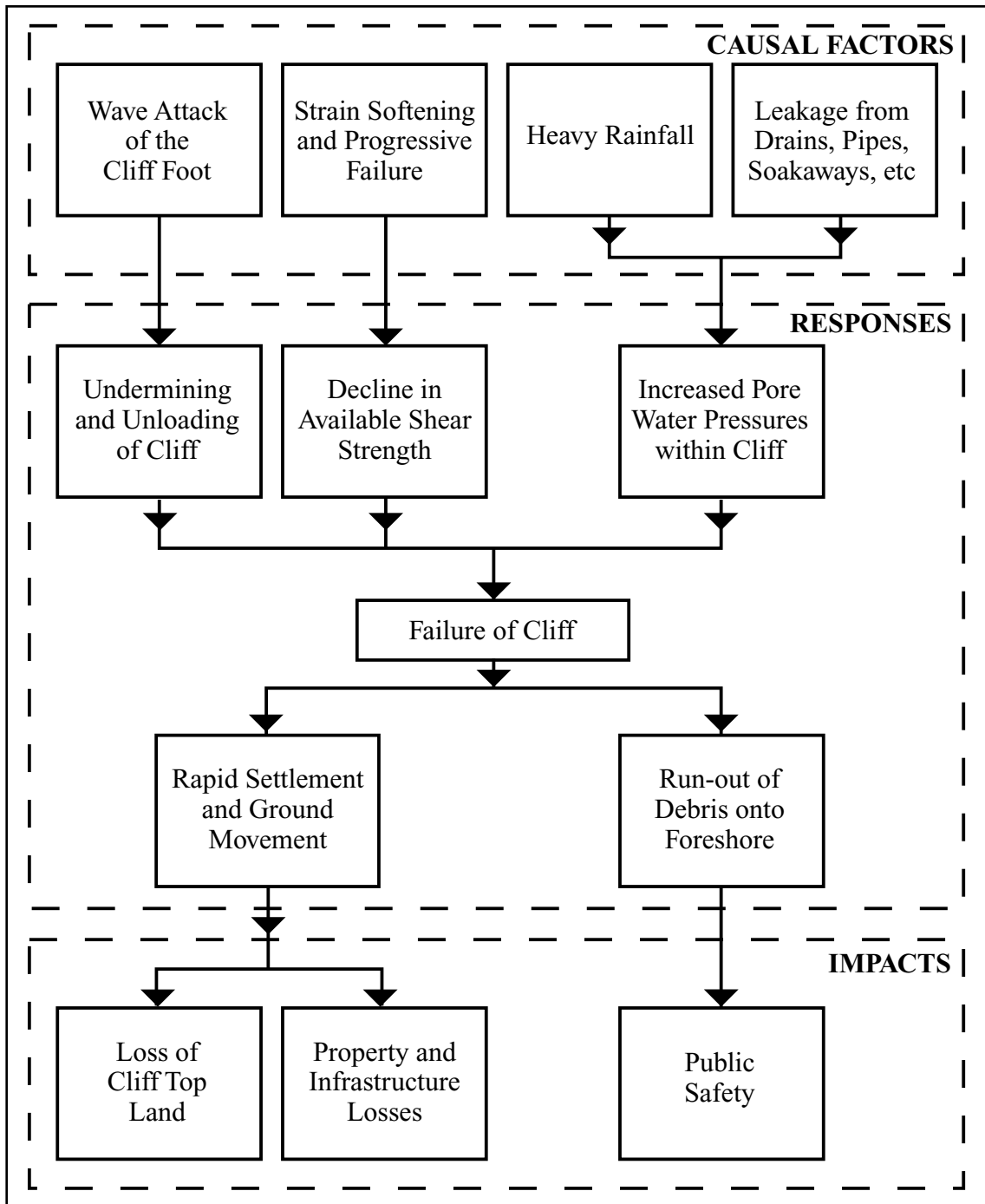
<b>CBU Type: Simple Cliff</b>	<b>Stage:</b>	<b>First-time Failure</b>
<b>Materials: Glacial Till</b>	<b>Landslide Type:</b>	<b>Rotational Failure</b>
<p><b>CONTROLLING FACTORS</b></p> <ul style="list-style-type: none"> <li>• mobilisation of peak strength</li> <li>• short term pore water pressures and soil suctions</li> </ul>		
<p><b>PREPARATORY AND TRIGGERING FACTORS</b></p> <ul style="list-style-type: none"> <li>• increase of sheer stress by erosions at the toe of the cliff during periods of low beach levels</li> <li>• dissipation of soil suctions during rainfall events</li> </ul>		
<p><b>CONTEMPORARY BEHAVIOUR AND TRENDS</b></p> <ul style="list-style-type: none"> <li>• long term average recession rate 2m/year. Previous event date unknown</li> </ul>		
<p><b>RETROGRESSION POTENTIAL AND RECURRENCE INTERVAL</b></p> <ul style="list-style-type: none"> <li>• single rotational landslides, around 18m land loss over a 25m length</li> <li>• successive failure down-drift of the previous landslide site</li> <li>• average interval between rotational landslide of 10 years</li> </ul>		
<p><b>CONSEQUENCES</b></p> <ul style="list-style-type: none"> <li>• loss of agricultural land and farm buildings</li> </ul>		

**Figure 7 CBU Characterisation Sheet: Simple Cliff**

<b>CBU Type: Simple Landslide</b>	<b>Stage:</b>	<b>First-time Failure</b>
<b>Materials: Stiff Clay</b>	<b>Landslide Type:</b>	<b>Rotational Failure</b>
<b>CONTROLLING FACTORS</b>		
<ul style="list-style-type: none"> <li>• strain softening and progressive failure along soft bedding planes</li> <li>• mobilisation of softened or residual strength</li> <li>• short term or intermediate term pore water pressures</li> </ul>		
<b>PREPARATORY AND TRIGGERING FACTORS</b>		
<ul style="list-style-type: none"> <li>• increase in pore water pressure in the vicinity of the shear surface</li> <li>• increase of shear stress by erosion at the toe of the cliff</li> <li>• increase by shear stress by loading at the top of the cliff</li> </ul>		
<b>CONTEMPORARY BEHAVIOUR AND TRENDS</b>		
<ul style="list-style-type: none"> <li>• average recession rate 1m/year. Last major event 1989</li> </ul>		
<b>RETROGRESSION POTENTIAL AND RECURRENCE INTERVAL</b>		
<ul style="list-style-type: none"> <li>• single rotational landslide, around 25-30m land loss over a 150m length</li> <li>• successive failure behind the previous landslide site</li> <li>• average interval between rotational landslides of 30 years</li> <li>• previous event 1989</li> </ul>		
<b>CONSEQUENCES</b>		
<ul style="list-style-type: none"> <li>• loss of agricultural land</li> </ul>		

**Figure 8 CBU Characterisation Sheet: Simple Landslide**

Figures 7 and 8 provide examples of CBU *Characterisation Sheets* for two contrasting cliff types; those sheets can be adapted to any CBU, with the necessary information derived from field inspection, review of available sources and historical map data, and site investigation, as appropriate. In some situations, it may be useful to prepare a chart that defines the interrelationships between various causal factors, the CBU responses and the impacts of particular recession events (see Figure 9). This type of chart can help identify the coast protection and slope stabilisation needs and the risks associated with cliff recession.



**Figure 9 Summary CBU Behaviour Chart: Protected Composite Cliff**

**Table 4 A Summary of the Key Features of a CBU**

<p style="text-align: center;"><b>i. Cliff top:</b></p> <p style="text-align: center;">the landward extent of joint opening and stress relief; the development of tension cracks.</p> <p style="text-align: center;"><b>ii. Cliff:</b></p> <p style="text-align: center;">the nature of recession processes; the magnitude and frequency of events; the relative significance of event and base fluxes of sediment output; the storage of sediment within the system; the seasonal response of the system; the coupling with the foreshore system.</p> <p style="text-align: center;"><b>iii. Foreshore:</b></p> <p style="text-align: center;">the persistence of debris stores; the variations in beach levels; the rate of foreshore lowering; the presence of remnant landslide units on the sea bed; the coupling with the littoral cell.</p> <p style="text-align: center;"><b>iv. Littoral cell:</b></p> <p style="text-align: center;">transient changes, e.g. interruption of sediment transport behind debris lobes; progressive changes in foreshore conditions.</p>
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### **3.5 Risk Assessment**

Addressing cliff recession problems has always involved some form of risk assessment, although it would have been seldom recognised as such. Traditionally the significance of recession would have been assessed by the expert judgement of experienced engineers or earth scientists. Nowadays, rigorous and systematic procedures have become available to formalise this process and enhance the “openness” of such judgements (Fell 1994; MAFF 2000).

A *risk-based* framework provides a context for managing situations where the nature of future events and their outcomes are uncertain. It is consistent with the DETR guidelines for environmental risk assessment (DETR 1995, 2000) that include the following principal elements:

1. The importance of correctly defining the actual problem at hand.
2. The need to screen and prioritise risks before detailed quantification.
3. The need to consider all risks at the options appraisal stage.
4. The iterative nature of the process.

Further background on risk assessment for flood and coastal defence may be found in FCDPAG4 (MAFF 2000).

The advantage of using risk assessment methods in cliff management is that they offer the potential to quantify the effects of the uncertainty inherent in the recession process. In this way risk assessment aids and improves decision-making by allowing consideration of a range of possible recession scenarios and consequences, each with different likelihoods. It can be an iterative process, whereby the more important issues which contribute significantly to the total risk are identified, with the less important issues screened out in a systematic and rational manner.

Although risk assessment uses probabilistic methods, either quantitatively or qualitatively, it is not synonymous with probability. The probability of an outcome is the relative proportion or frequency of events leading to that outcome out of all possible events. For coastal cliffs, the historical frequency of events is often used to estimate probability (e.g. Lee and Clark 2000). In other circumstances, *degree of belief* or *strength of belief* measures can be used to estimate event probabilities; these are best suited to complex systems or where there is inadequate data. This approach may be viewed as simply a way of quantifying engineering judgement.

Risks arise from a combination of unfavourable circumstances. Hence, it is useful to appreciate the connections between different elements within a *cliff recession scenario*, including:

1. *Initiating factors* which trigger movement e.g. seawall failure or periods of heavy rain.
2. *Propagating factors* which allow the effects of the initial movements to be transmitted throughout the cliff system and, hence, control the CBU *response*. Such factors might include high groundwater levels, oversteepened slopes, removal of toe support, weathered materials etc.
3. *Outcomes*; the consequences of particular CBU responses.

Risk assessment is needed to support the development of appropriate measurement and monitoring programmes, choice of prediction methods and the selection of cliff management strategy. It involves the following steps.

### **3.6 Hazard Assessment**

This involves the assessment of the probability of a recession or coastal landslide event of particular size and type occurring over a particular time period. An important element of hazard assessment is the definition of the recession potential, in terms of the nature and size of events that could be expected in a CBU. This will require an appreciation of:

- the nature and magnitude of historical events;
- the factors influencing the pattern of recession events;
- the causes and mechanisms of possible events;
- the theoretical occurrence of triggering or initiating events.

When assessing probabilities it is often more reliable to consider the *conditional probability*. For example:

$$\text{Annual probability of loss} = \text{Probability of Initiating Storm Event} \times \\ \text{Probability of No Beach Present (given the storm event)} \times \\ \text{Probability of a Landslide (given the preceding conditions)}$$

There are several ways of calculating the probability of a recession event, including:

1. *The number of events which may occur in a given period* based on historical data relevant to the CBU or similar CBUs and the use of geomorphological evidence.
2. *Establishing the relationship between recession events and triggering events of varying intensity.*
3. *The use of stability analysis* to model the CBU response to variables such as piezometric pressure. In recent years there have been considerable advances in developing methods for probabilistic stability analysis (e.g. Christian 1996; Wu et al 1996). Here, the probability of failure is the probability that the factor of safety (F) is less than 1, based on many stability analysis simulations using variable parameter values.
4. *The use of expert judgement.* This involves the use of experience, expertise and general principles to assess the likelihood of cliff recession scenarios from the available historical record and past cliff behaviour preferably in an explicit and consistent manner. Such judgements are usually subjective, but by proposing several possible scenarios followed by systematically testing and eliminating options by additional investigation, stability analysis and discussion it is possible to develop reliable estimates of the likelihood of recession events.

### **3.7 Identifying the Elements at Risk**

It will be necessary to determine the nature and characteristics of the property or persons at risk. Factors that may need to be considered include the location of the element at risk (e.g. behind, on or in front of the cliff) and whether the element at risk is fixed in position (e.g. a building) or mobile (e.g. persons or vehicles); this will affect the temporal probability of loss.

The consequences of recession may include:

- loss of cliff top property and land;
- ground movement damage to property and services on the slopes;
- burial or displacement of cliff foot structures e.g. seawall, roads and buildings;
- injury or death.

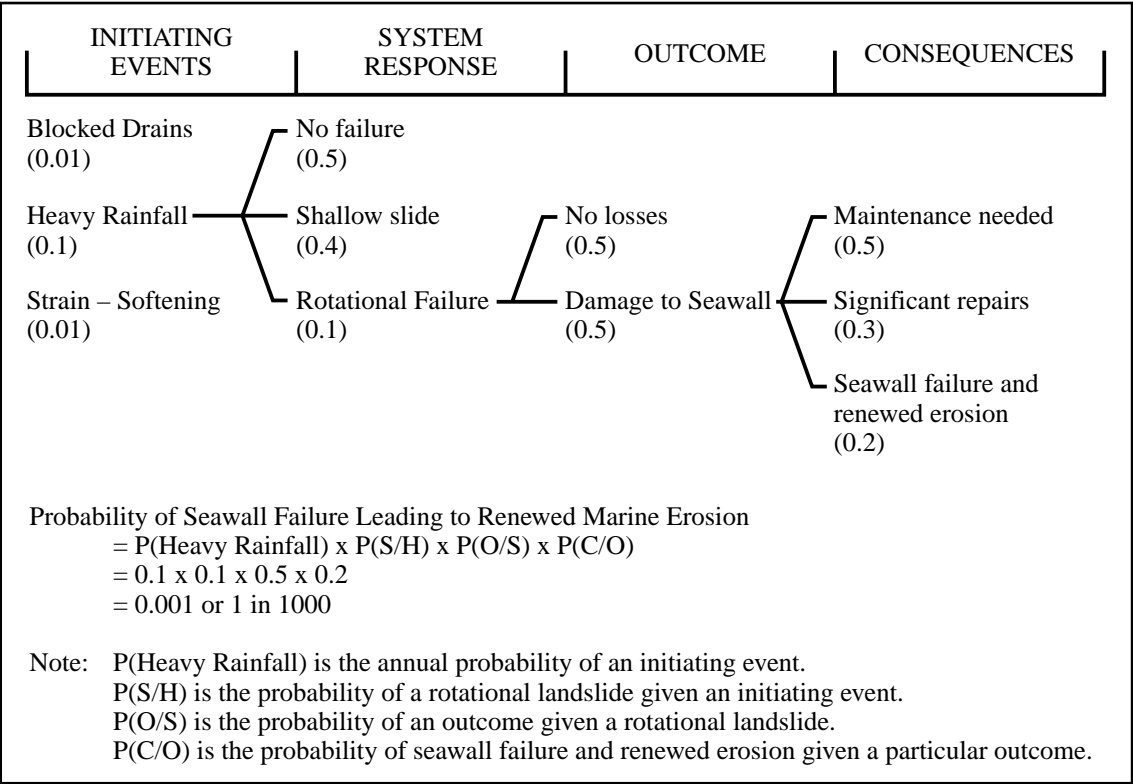
Indirect losses (e.g. loss of tourism revenue, traffic disruption etc.) and intangible losses (e.g. stress and ill health) may also be relevant considerations.

Assessment of consequences should be based on recession scenarios and scenario components relevant to the particular CBU. The aim should be to identify what damage or losses could occur over a particular time period, preferably expressed in probabilistic terms. For most CBUs, cliff top recession will equate directly with

property loss i.e. the timing of property loss is a function of the recession rate. However, there will be situations (e.g. on protected cliffs) where it will be necessary to consider other issues, such as the type of cliff failure, the vulnerability of the exposed structures and people, and the level of repairable damage.

Vulnerability has been defined as the level of potential damage or loss of a particular asset subject to a landslide of a given intensity. It is, however, difficult to quantify being dependent on the nature and intensity of the mechanical stresses generated by the failure (e.g. differential ground movement, subsidence, heave, loading etc.) and the resistance of the structure. A rock armour revetment, for example, may be more able to accommodate ground movement than a rigid seawall. For situations where there is a threat to public safety, issues such as the variable exposure to the risk (e.g. between day and night, summer and winter) and the response to early warning may need to be taken into account.

Assessments of the nature and severity of the consequences of a landslide event will inevitably rely heavily upon expert judgement. It is subjective and may lead to results that are unverifiable. Nevertheless, when the methodology is explicit and the assessment supported by peer group review, it can be an effective method of establishing the likely consequences of a range of scenarios. Event trees can be used to assess the consequences of particular events by tracing the progression of the various scenario components by inductive reasoning. The likelihood of all scenario components and consequences can be described in probabilistic terms, albeit subjectively. Figure 10 presents an example where an event tree is used to assess the likelihood of a shallow landslide on a protected cliff setting up a sequence of events that leads, ultimately, to the loss of the seawall and renewed erosion.



**Figure 10 Sample Event Tree, Illustrating Overall Framework for Probabilistic Assessment**

### 3.8 Calculation of Risk

Risk can be estimated by the mathematical expectation of the consequences of a particular event occurring (i.e. the product of the probability x consequences; Royal Society 1992):

Risk = Hazard (e.g. *Probability of Cliff Top Loss due to Landsliding*) x *Consequences of Loss*

This is based on consideration of the hazard, the elements of risk and their vulnerability. For example:

$$R = P(H) \times P(S|H) \times P(T|S) \times V(P|S) \times E$$

where R is the risk, expressed as the annual probability of loss.

P(H) is the annual probability of a the hazard (e.g. a *recession event*).

P(S|H) is the probability of a *spatial impact* (e.g. of the event damaging a building) given the event.

P(T|S) is the probability of a *temporal impact* (e.g. of the building being occupied) given the spatial impact.

V(P|S) is the *vulnerability* of the property or persons (e.g. probability of loss of life) given the spatial impact.

E is the *element at risk* (e.g. the value of the property).

In many instances it is inappropriate to evaluate risk in absolute terms because of the uncertainties in assigning values for the hazard and the assets at risk. It may be more useful to assess the relative risk to different sites from particular hazards, based on both factual data and subjective appraisal. The value of relative risk assessment is that it can quickly enable sites to be compared or allow decisions to be made about where limited financial resources should be directed (Rendel Geotechnics, 1995b).

### 3.9 Consideration of Risk Acceptance Criteria

Analysis of risks alone has limited benefits unless the calculated risk is evaluated against *risk acceptance criteria*. These may relate to loss of life, financial and environmental values. Grant-aided coast protection works are justified on the basis of technical, environmental and economic criteria (MAFF 1993b). These criteria may not necessarily be applicable to other aspects of cliff management, for example where the local authority has a duty of care to prevent accidents or injury on its own land. Further details on the application of risk assessment, acceptance criteria and tolerable risk in major industries and the nuclear power industry can be found in the various Health and Safety Executive publications (HSE, 1988, 1989a, b, 1992).

### 3.10 Non-Structural Solutions

In recent years cliff recession and coastal landsliding have been given more attention by the planning system (e.g. DoE 1990, 1992, 1996). This has led to a major shift in consideration of these issues from the site-specific problems to evaluating the constraints over broad areas with greater emphasis on managing coastal cliffs rather



than simply relying on engineering solutions. This trend has been matched by the growth of shoreline management as a mechanism for addressing flood and coastal defence interests at a strategic level. Indeed, the growing awareness of environmental issues together with greater appreciation of the broad-scale operation of physical processes, have reinforced the need to take a more strategic and pragmatic view of the problems. On many coasts it may not be desirable, feasible or sustainable to protect the entire length of eroding cliffline; to attempt to do so would not only be uneconomic but could actually intensify the problems elsewhere, for example, by disrupting the supply and transport around the coast. It has become increasingly apparent that coastal defence works are not the only solution to cliff recession problems. In many instances they need to be complemented by non-structural approaches that can involve:

1. *Avoiding placing further development in areas at risk;* coastal landsliding and cliff recession are important considerations for planners and developers. Indeed, development in unsuitable locations can lead to a range of problems from adverse effects on the stability of adjacent land to calls for publicly funded protection measures and the consequent effects on conservation or coastal defence interests elsewhere. As PPG 14 (and the subsequent PPG 14 Annex 1; DoE 1990, 1996) and PPG 20 (DoE 1992) have recognised, the planning system has an important role in minimising the risks associated with cliff recession through:

- guiding development away from unsuitable locations. This may involve establishing “set-back” lines within which development would be affected by erosion over a specified period;
- ensuring that development does not initiate or exacerbate instability problems on adjacent land, by specifying appropriate site drainage requirements and limiting slope excavation during development etc.;
- ensuring that the precautions taken to minimise risks from cliff instability do not lead to starvation of sediment supply to other important coastal sites and, thereby, increase the level of risk elsewhere.

Typical approaches have been described in Rendel Geotechnics (1992, 1995 a,b,c) and Clark et al (1996a).

2. *Minimising the effects of development;* although cliff recession and coastal landsliding are natural processes, land use and development can lead to their acceleration. Human activity has had a fundamental effect on the stability of coastal cliffs, either by initiating first-time failures or reactivating pre-existing landslides. Problems are frequently associated with the artificial recharge of groundwater levels e.g. through leaking water pipes, sewers and soakaways, the excavation of slopes causing a loss of passive support or unloading of the upslope materials, or the loading of slopes through tipping or the use of fill to create building plots.

Much can be done by local authorities to reduce the likelihood of slope failure in developed areas by simple, pragmatic slope management practices including control of construction activity and drainage. In many areas preventing water leakage is likely to be a cost-effective approach; in Ventnor, Isle of Wight, this

approach is central to the *Undercliff Landslide Management Strategy* developed to tackle ground movement problems in the area (Lee and Moore 1991; Rendel Geotechnics 1995c; McInnes 1996). This includes:

- regular inspection and maintenance of all drains on or adjacent to the cliffs to remove blockages and repair damaged sections;
- discouraging the use of septic tanks;
- monitoring of the sewerage system on or adjacent to the cliffs;
- monitoring the water supply network. Where pipes are found to be leaking they are repaired or replaced by flexible pipes;
- the use of soakaways, trench drains and other natural percolation methods of disposing of surface water is avoided, wherever possible. Where existing percolation systems exist consideration is given to connecting the systems to sealed pipes.

Coastal cliffs may also be sensitive to changes in foreshore conditions, especially starvation of sediment supply to beaches that provide a degree of protection against wave attack. Particular problems can arise from the disruption of sediment supply by coastal structures, such as groynes, or dredging operations or, possibly, the removal of sediment for the aggregate industry (e.g. sand and shingle). It is important that these issues are recognised and addressed in shoreline management plans, especially where a beach forms an integral part of an existing coast protection scheme.

In such circumstances the coastal defence authorities should consider the range of non-structural approaches that can be used to manage an unprotected eroding cliff, including:

- liaison with the minerals planning authority to ensure that mineral operations above LWM are not permitted where they could lead to erosion problems on neighbouring cliffs. The need for caution in minerals planning in the coastal zone was highlighted in PPG 20 (DoE, 1992);
  - active participation in the Government View Procedure for determining the suitability of applications for marine aggregate extraction licenses, ensuring that dredging operations do not affect cliff recession rates and sediment supply to beaches;
  - liaison with port and harbour authorities to ensure that maintenance and capital dredging operations do not affect beaches and, hence, cliff recession rates;
  - ensuring that the coastal defence strategies set out in an SMP for management units within the same coastal process unit (i.e. the littoral cell involving sediment supply, transport and deposition) are compatible and do not lead to significant adverse effects elsewhere.
3. *Early warning systems*; in recent years there has been a marked increase in the use of remote real-time monitoring as early warning systems for coastal landslide problems, especially where property or infrastructure are at risk (Clark et al 1996b). The development of monitoring systems should be seen as an integral part of the process of evaluating the risks posed by cliff recession and coastal

landsliding. There is a range of settings where such systems could be of considerable benefit in reducing the threat to public safety and property, either to detect signs of pre failure movements on the cliff top or the reactivation of pre-existing coastal landslides:

- on *protected cliffs* in urban areas where monitoring systems can provide advance warning of potentially damaging events. As part of Isle of Wight Council's (formerly South Wight Borough Council) landslide management strategy for the Ventnor Undercliff, an automatic monitoring network was installed to provide early warning in areas where ground movement could lead to the disruption of service and infrastructure;
- on *unprotected cliffs* where investment in coast protection and slope stabilisation is uneconomic, not technically feasible or environmentally acceptable, monitoring systems could provide a solution to the long term protection of public safety. This situation has arisen along parts of the South West coast of the Isle of Wight where monitoring systems have been installed at high risk locations on the Military Road since 1981 to detect settlement behind the 70m high Chalk cliffs (e.g. Barton and McInnes 1988);
- on *unprotected cliffs* where coast protection and slope stabilisation is justified, monitoring and early warning could provide interim safety cover until the scheme has been constructed and the threat to public safety reduced. This type of system was installed for coastal landslides at Scarborough and Overstrand, Norfolk, prior to major stabilisation works being undertaken. In both cases there was concern that the landslide would continue to extend inland affecting an increasing number of properties and related infrastructure.

## CHAPTER 4 MEASUREMENT AND MONITORING

Accurate and up-to-date information on cliff recession is needed to support decision-making by coastal managers. Knowledge of recession rates allows the level of risk to coastal assets to be assessed, underpins the identification of coastal defence policy options and enables these policy options to be kept under review. Measurement of recession rates can also be important in monitoring the performance and effectiveness of coastal defence schemes, especially those which attempt to reduce rather than prevent marine erosion, and their impact on the recession of neighbouring cliffs.

A range of approaches to measurement and monitoring are available, including:

- measurement of historical recession rates;
- measurement of current recession rates;
- assessment of contemporary cliff behaviour;
- monitoring of current cliff behaviour.

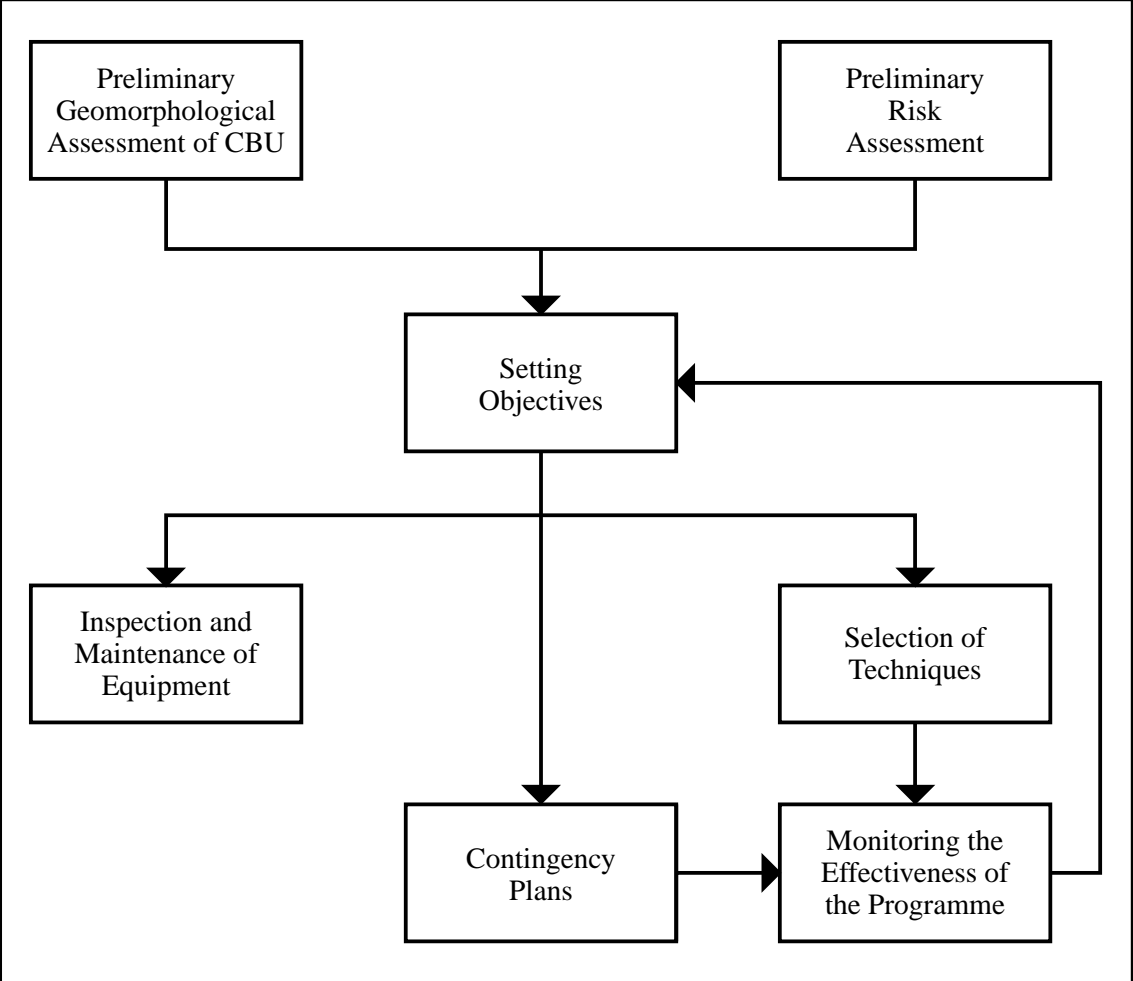
These approaches are complementary, not mutually exclusive (Table 5). When used in combination they can provide insight into the *short-term* variability in recession rates, the *medium-term* establishment of steady-state retreat and maintenance of the characteristic form within the CBU and, in some cases, the *long-term* evolution of the cliffline.

In most cases measurement of historical and current cliff top recession rates will provide sufficient information to identify spatial and temporal trends, and determine their significance in terms of risk. However, because of the variable and uncertain nature of the cliff recession process it is essential that these rates be considered within the context of the contemporary behaviour of the CBU.

### 4.1 Selection of Measurement and Monitoring Methods

Before embarking upon a measurement and monitoring programme it is necessary to have a clear idea of why the information is needed and what type of recession events might be expected. The stage in the decision-making process is of obvious importance. The preparation of a shoreline management plan will generally require less detailed recession measurements for a particular CBU than, for example, a scheme strategy or feasibility study to assess the coast protection requirements for the same CBU. In the former case, a general indication of the pattern of recession may be sufficient to support the choice of coastal defence policy options; for the latter studies accurate recession information will be needed to demonstrate the economic justification of possible capital schemes.

<b>Table 5 A Summary of the Relative Timescales Covered by Different Measurement and Monitoring Approaches.</b>		
<b>APPROACH</b>	<b>CLIFF TOP RECESSION RATE</b>	<b>CLIFF PROCESS INFORMATION</b>
Measurement of historical recession rates	Medium Term	
Measurement of current recession rates	Short Term*	
Cliff Behaviour assessment		Medium - Long Term
Cliff Behaviour monitoring		Short Term*
* In time there may be sufficient measurements to give a medium-term perspective		



**Figure 11 The Development of a Measurement and Monitoring Strategy**

The development of a measurement and monitoring strategy will need to address the following issues to determine what should be measured and how (Figure 11).

1. *The nature of the CBU*; it will be necessary to carry out a preliminary review of historical sources and a geomorphological assessment to establish, in general terms, the nature of the recession process and the key features that could be measured or monitored. This should also provide an indication of the appropriate spacing of measurement points and frequency of recording. As the characteristic CBU recession pattern becomes markedly episodic and uncertain there will be an increasing need for detailed cliff behaviour assessment to provide a framework for understanding the significance of individual recession measurements.
2. *The level of risk*; a preliminary appraisal of the current and likely future risks from cliff recession along a coastline will highlight, in relative terms, the priority sites for formal measurement and monitoring programmes. In situations where there is a significant threat to property or public safety, it is likely that there will be a need for a formal, systematic measurement and monitoring strategy. Where the level of risk is low it may be appropriate to consider an informal programme of occasional visual inspections.
3. *Setting objectives*; the objectives of the programme might involve a combination of the following in different CBUs along a coastline:
  - to keep cliff recession under review (e.g. in undeveloped rural areas);
  - to keep cliff recession under review and update predicted cliff top recession zones (e.g. in areas where coastal zone assets might be at risk over the next 50 years or so);
  - to monitor signs of pre-failure movements or landslide reactivation for public safety purposes (e.g. at sites where failure could lead to death or injury, or loss of property, services and infrastructure).
4. *Selection of technique*; the measurement techniques that are adopted need to reflect the programme objectives. For example, if the objective is to aid the updating of predictions it is essential that the measurement techniques provide the correct type of information, measured at the appropriate frequency and spacing. Measurements must be appropriate to the magnitude and frequency of the processes being studied.

Extreme events by their nature cannot be readily accommodated in a measurement and monitoring programme, although a reasonable estimate of their likely occurrence is needed for risk management. Such events tend to be recorded by chance in a pre-existing framework of observation or reported incidentally.

5. *Establishing contingency plans*; in developing a monitoring and measurement strategy it is necessary to consider the need for a formal contingency plan to set out procedures, for example, to contact the emergency services and alert the general public. These procedures could be activated if a large recession event occurs or ground movements above a specified threshold level are recorded.

6. *Inspection and maintenance of the monitoring equipment*; monitoring systems, especially those involving automatic data recording, will have routine maintenance requirements. This may, for example, involve checking that the equipment is functioning correctly, telephone connections are operating and whether measurement posts need to be relocated.
7. *Monitoring the effectiveness of the programme*; after a period of time sufficient data will have been gathered which will allow the understanding of the CBU to be reassessed. It is good practice to evaluate the data collected to ensure that it is meaningful, that critical thresholds have not been reached or surpassed and that it corresponds to the CBU model. Feedback from predicted results to the monitoring programme will allow refinement of resolutions, coverage, accuracy and techniques.

**Table 6 Historical Topographical Maps (from Dumbleton and West 1971)**

1. "One Inch" maps (1:63360 scale); commenced by the Ordnance Survey in 1805 and available for much of southern England and Wales by 1840.
2. "Six Inch" maps (1:10560 scale); commenced by the Ordnance Survey in 1840. First revision took place 1891-1914.
3. "25-Inch" maps (1:2500 scale); commenced by the Ordnance Survey in 1853, and survey was completed in 1895. First revision took place 1891-1914.

A full list is given in the Ordnance Survey catalogue of 1914 (Catalogue of 6-inch and 25-inch County Maps and Town Plans), and also in Harley and Phillips (1964).

Besides Ordnance Survey maps, large-scale tithe, enclosure and estate maps, many of them pre-dating those of the Ordnance Survey at a similar scale, are available in manuscript for many areas. From 1836 to 1860 a series of Tithe Survey maps were prepared in connection with the Tithe Commutation Acts. These maps are very detailed topographical surveys, usually at a scale of 13.3- or 26.7 inches/mile, and they exist for thousands of parishes. One copy of each map was deposited with the Tithe Commissioners, and may now be consulted along with the other tithe maps of an earlier date at the Public Record Office, Chancery Lane., London, WC 2. Other copies may be found in County Record Offices or County Libraries. The Enclosure Maps, often at a similar scale to the Tithe Maps, are generally earlier, often dating from the first decades of the nineteenth century. They are best sought at the County Record Offices, where large-scale estate maps may also be found.

A discussion of the history and art of marine cartography can be found in Robinson (1962).

## 4.2 Measurement of Historical Recession Rates

Historical topographical maps (Table 6), hydrographic charts and aerial photographs provide a record of the former positions of various cliff features, especially the rear cliff and the sea cliff. In many cases historical maps and charts may provide the only evidence of CBU evolution over the last 100 years or more. When compared with recent surveys or photographs, these sources can give an estimate of the cumulative land loss and the average annual recession rate between the survey dates. Although comparison of the oldest available maps with the most recent would be sufficient to obtain a medium term recession rate, analysis over shorter periods can give an indication of the spatial and temporal variations in the recession process.

Two main methods are often used to measure changes in rear cliff and sea-cliff positions from historical sources (see Table 7 for a summary of the limitations of these methods):

1. *Measurement of distance changes* along evenly spaced transect lines drawn normal to the coastline.
2. *Measurement of areal changes* between the cliff line position at different survey dates, along coastal segments of uniform length. The area of land loss between each successive cliff line can be measured using a planimeter or by counting squares, and is converted to an average annual recession rate by dividing by the segment length and the time interval between surveys.

## 4.3 Measurement of Current Recession Rates

Direct measurement of cliff recession is the most obvious method of obtaining information on current recession rates. In many situations visual inspection can be valuable in identifying future problem sites and keeping them under review until a more formal measurement and recording strategy becomes necessary. It should be noted, however, that the written word and memory alone are inadequate for detecting anything other than gross changes. The value of such inspections can be greatly enhanced by the use of standardised sheets accompanied by a photographic record of the cliff position at specific points (Figure 12).



DATE .....

LOCATION ..... GRID REFERENCE .....

Attach a plan to show location of event

**TYPE OF EVENT**

Pre-failure movement                       Failure                       Reactivation of  
Pre-existing slide

Tension cracks                       Fall

Subsidence                       Slide

Bulging / Creep                       Flow

Attach photographs to show key features

**SCALE OF EVENTS**

Cliff top land lost .....

Amount of ground movement .....

Width of tension cracks .....

Size and number of boulders .....

**POSSIBLE CAUSES**

Heavy rainfall                       Blocked drains

Marine erosion                       Others .....

**CONSEQUENCES**

Loss of cliff top land                       Damage to seawalls

Damage to property                       Damage to footpaths, etc

Other .....

**Figure 12 A Proforma for Recording Visual Inspections**

**Table 7 Limitations Associated with the Extrapolation of Historical Trends**

Although comparisons of cliff positions between survey points might appear straightforward, there are potentially significant problems which must be borne in mind when analysing and interpreting the results. Amongst the most important problems are:

- i. Plotting errors; although the positional accuracy of many defined objects on Ordnance Survey maps is estimated to be  $\pm 0.8\text{m}$ , inaccessible features of “marginal importance” situated away from settlements may not be mapped with comparable accuracy (Carr 1962, 1980). Whilst the rear cliff position may be relatively accurately located, extreme caution is needed when analysing changes in the sea-cliff position, especially in large, heavily vegetated CBU’s (see Brunsdon and Jones 1976).
- ii. Interpretative Errors; when the feature to be mapped is not clearly defined in the field, its position may be based on a surveyor’s perception of its form so that plotting on different editions, or different sheets of the same edition may be sensitive to operator variance (Hooke and Kain, 1982). The rear cliff position is unlikely to be subject to such error, whereas the sea-cliff is often a less distinct feature and its position is probably less reliable.
- iii. Revisions; not all features are revised for each new map edition, so it is sometimes uncertain exactly when a particular feature was last revised.
- iv. Accuracy of Comparisons; the validity of the recession measurements can be defined by the plotting errors associated with the different map editions. Error estimates can be produced for each map period as follows (Crowell et al 1991):

$$E = (eT_1 + eT_2) / T$$

where:

- E is the error estimate associated with the map period (m/year);
- $eT_1$  is the plotting error of the rear cliff on map edition 1;
- $eT_2$  plotting error of the rear cliff on map edition 2;
- T is the time period between map editions.

The error estimate (E) indicates the minimum retreat rate that can be resolved; this will vary with map scale and the period between editions. When E is greater than or equal to the average annual recession rate measured between the map editions, no reliable estimate is possible. Greater precision is possible for longer map periods because plotting errors become proportionally less as the retreat distance increases, with the implication that accurate data are needed to resolve recession over short time periods, especially when rates are slow (Bray and Hooke 1997).

- v. Distortions; in many cases it will not be possible to work directly from the original historical maps, as they are rare, fragile and valuable documents. Although copies of these maps can be obtained, it is important to recognise that there may be distortions in the photocopying or printing process of around  $\pm 1\%$  across a map sheet.

**Table 7 (Cont...)**

- |   |
|---|
| <p>vi. Continuity of Process; maps, charts and photographs are incidental observations made at a particular time (i.e. the survey date) and, hence, can present a very distorted picture of past recession.</p> <p>vii. Geological and Environmental Changes; the cliff conditions may not have remained stationary over the period between map editions, due to changes in environmental loading (e.g. sea level rise, increased storminess), recent engineering works on the neighbouring coastline or variability in the in situ geological conditions. These effects will not be identifiable from the historical record alone.</p> |
|---|

Conventional ground survey methods can give detailed measurements of cliff recession; this may involve simple taping from fixed points, traditional levelling, a total station or Global Positional System (GPS). A number of strategies can be adopted, including:

1. *Occasional surveys* of the cliff-line and other relevant features after specific recession events (e.g. a major landslide) or periods of active cliff top recession.
2. *Formal systematic surveys* of the cliff top position at fixed points, undertaken at regular intervals (e.g. on an annual or 6 monthly basis).

On the Holderness Coast, for example, the local authority (formerly Holderness Borough Council) initiated a programme of cliff recession measurement in 1951 which has been continued on an annual basis ever since. A series of 71 marker posts termed “erosion post” by the local authority were installed at 500 m intervals along 40km of the coastline, each post located at a distance of between 50m and 100m normal to the coast. These posts are replaced further inland from time to time if they become too close to the cliff top. Annual measurements from each post to the cliff top - defined as the lip of the most recent failure scar - commenced in 1953. The resulting database provides an invaluable source of medium - long-term measurements of cliff recession.

The spacing of survey lines can have a clear influence on the representativeness of the resulting measurements. The Holderness erosion posts, described above, are unable to record spatial variations in recession at scales less than 500m. This contrasts with the 10-20m length of individual failures and considerable variability in recession rates over short distances can remain undetected. The ideal survey line spacing would be less than the major recession event width along the cliffline; this is obviously impractical for many CBUs where the characteristic failure width is relatively small. In such circumstances it may be more cost-effective to undertake a nested series of surveys; including:

- a limited number of detailed surveys along closely spaced survey lines to identify short length variations in recession rates;
- a more comprehensive survey along widely spaced survey lines to identify broad patterns of recession.

When establishing survey lines it is vital to ensure that they can be easily re-established for successive surveys. The lines must have a defined bearing and be tied to independent

control points such as erosion posts. These control points should be established inland of the area that could be lost during the course of the monitoring programme and, if necessary, formally re-established further inland prior to being lost over the cliff top.

Indirect measurements of recent cliff recession can be obtained from aerial photographs and may provide an efficient alternative to establishing a formal direct measurement programme on the undeveloped coast. This method requires regular aerial photo sorties along the coastline (e.g. on an annual basis) at suitable scales for reliable measurements.

#### 4.4 Assessment of Contemporary Cliff Behaviour

Geomorphological assessment of the recent and long-term processes operating within a CBU can provide an effective method for interpreting historical recession measurements obtained, for example, from map sources. The approach is essentially an exercise in expert evaluation, drawing on rigorous, but flexible methodology and utilising all the available evidence (Figure 13). Based on a review of the historical evidence and an understanding of the surface forms and recession processes, it can provide a guide to the retrogression potential and recurrence interval of recession events within a particular CBU. This can lead on to the development of an evolutionary model of the CBU which provides a framework for evaluating the past cliff behaviour and generating possible future recession scenarios.

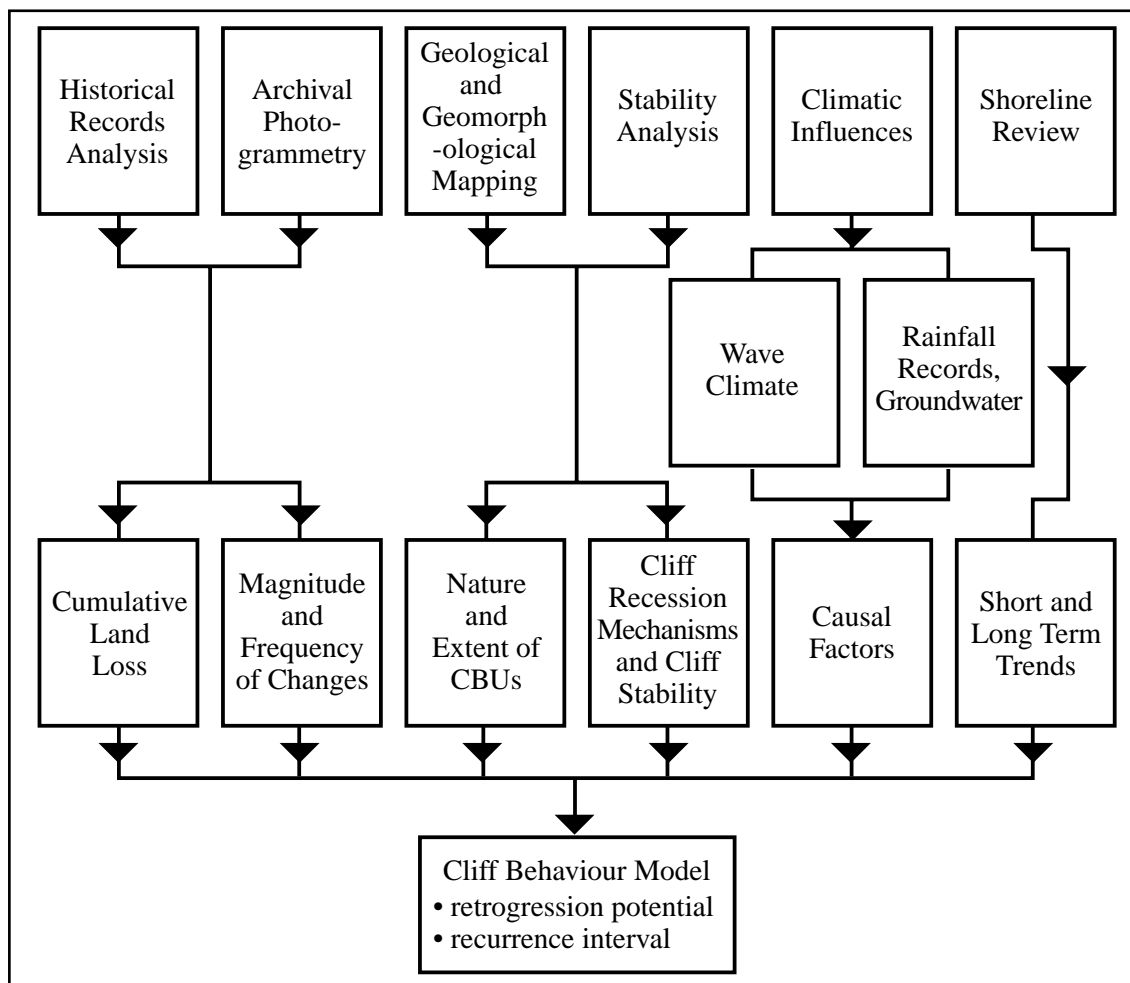


Figure 13 A Framework for the Development of a Cliff Behaviour Model

In most instances the approach will involve some or all of the following steps.

1. *Historical records analysis*; in addition to establishing past recession rates from historical maps and aerial photographs, it is particularly important to be aware of the historical incidents of recession events in an area as this will provide a general indication of the nature and scale of potential future problems. There is a wide range of sources that could provide valuable background information; some are more accessible than others. Documents such as journals and diaries can include valuable descriptions of coastal landslide events. Local newspapers are very important source of information about significant coastal landslide events over the last hundred years or so. Their value is enhanced by the fact that they enable a systematic review of events over long periods. It is important to bear in mind that historical reports, like current ones, tend to concentrate on the events that affect people or property.

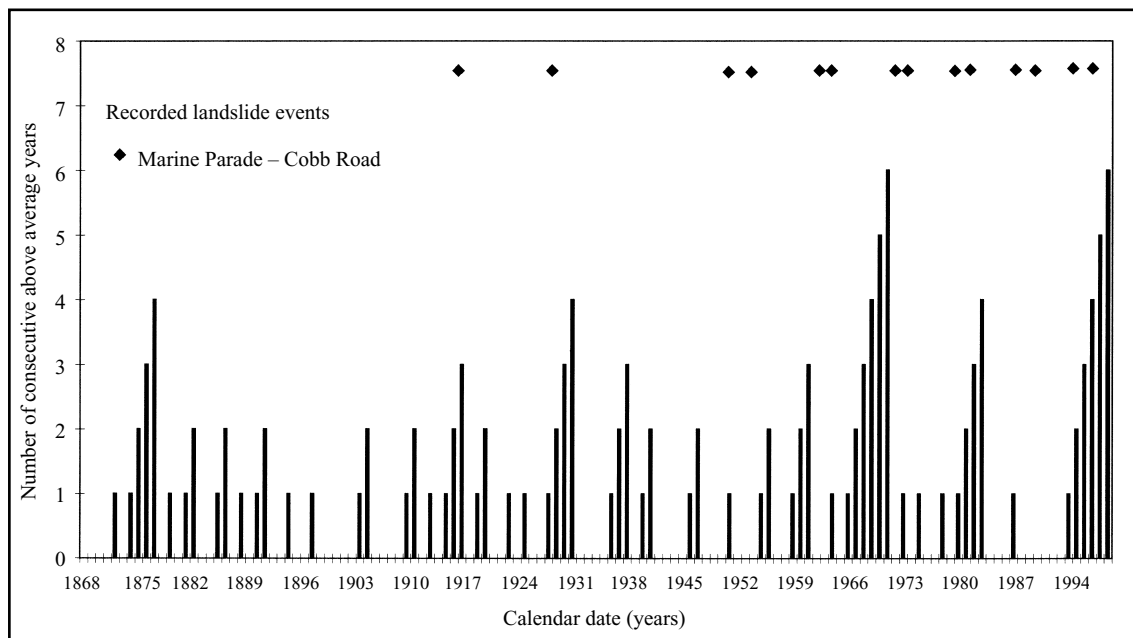
However, as Brunsden et al (1995) note, the problems with archive data can be minimised if certain “rules of interpretation” are followed:

- never assume that the whole landslide event population is represented;
  - regard surveys and diaries as a time sample, especially concerning magnitude, and base judgement on the quality of the observations;
  - use as many data sources as possible and compare trends or extremes;
  - compare with other independently collected data series (e.g. instrumental climatic records);
  - always assume changes in reporting quantity and quality over time. Never assume that the present standard of recording is better than in the past.
2. *Establishing the nature and extent of contemporary changes to CBU form*; recent advances in analytical photogrammetry, made possible by increasing computer power, have allowed the development of the archival photogrammetric technique. This technique can be used for quantifying the nature and extent of landform changes between aerial photographs of different dates by comparing the 3D co-ordinates of the same points (Chandler and Cooper 1988, 1989). The application and development of the technique for assessing slope instability problems was reviewed by Chandler and Moore (1989). The technique has been used to evaluate the nature and scale of slope instability and cliff recession over a 40-year period in a highly active complex CBU at Black Ven near Lyme Regis (Chandler and Brunsden 1995; Brunsden and Chandler 1996).
  3. *Investigation and characterisation of the CBU*; see Chapter 3. Geomorphological and geological mapping of the cliffs and foreshore, combined, where appropriate, with sub-surface investigation can provide insight into the following key issues:
    - the size of event that may be expected at a site;
    - the causal factors associated with different recession events;
    - how frequently event triggering conditions might be expected;
    - the current stability condition of the slope;
    - what area could be affected by a particular event.

These techniques can be directed towards the preparation of Characterisation Sheets and Behaviour Sheets that define the links between various causal factors, the cliff response and the resultant impacts (see Chapter 3).

4. *Assessment of climatic influences*; many coastal cliffs are sensitive to variations in groundwater levels within the slope and, hence, sequences of wet and dry years. An assessment of the climatic influence on cliff recession can, therefore, highlight possible periods of accelerated recession within the historical record. Here, the most obvious task is to relate periods of major recession events or accelerations in the overall pattern of recession to rainfall statistics. In the Isle of Wight Undercliff, for example, Lee et al (1998b) compared the winter rainfall totals associated with different return periods with the known history of landslide events in different sections of the relict landslide CBU. On this basis it was possible to identify the relative susceptibility to ground movement along the Undercliff and develop an approach to predicting the likelihood of future damaging events.

Lee et al (2000) were able to demonstrate that, for the West Dorset coast, there was a good relationship between wet-year sequences and landslide activity (Figure 14). The annual probability of wet years/high groundwater levels was estimated from the historical trends of annual rainfall in Lyme Regis.



**Figure 14 Cobb Gate, Lyme Regis: Wet Year Sequences and Landslide Events**

#### **4.5 Monitoring of Current Cliff Behaviour**

A wide variety of methods are available for monitoring cliff behaviour, ranging from simple visual inspections to the use of sophisticated instrumentation. It is important that inspections are formalised, with results recorded, for example, on standard sheets or in a diary form. In some circumstances, it can be helpful to undertake a forensic investigation of major recession events to record the nature and scale of the failure, its impact and the relevant causal factors.

The comparison of sequential photography of a CBU taken during successive inspections can be very helpful in defining the nature and scale of change in active systems (see Kalaugher and Grainger, 1990).

Slope monitoring is an integral part of cliff investigations because it provides a means of accurately and objectively gauging the conditions of unstable or potentially unstable slopes. There is a range of techniques that can be used for a variety of purposes (Franklin 1984; Turner and Schuster 1996). The most commonly used methodology is that of ground survey. A network of fixed survey markers is established on the CBU surface and the horizontal and vertical co-ordinates of each are determined by successive surveys. Movement of these markers should be monitored by reference to fixed survey control points located on stable ground outside the boundary of the CBU. This allows the determination of absolute rates of movement as well as relative displacements within the CBU.

A wide range of instrumentation and techniques may be applied to measure surface movement of unstable slopes. These range from low-cost routine measurement of pins and peg-lines to more sophisticated automatic monitoring and early warning systems. The range and scope of such instrumentation is reviewed elsewhere (see Dunnycliff and Green 1988) and includes: extensometers; tiltmeters and settlement cells.

Direct measurement across tension cracks, particularly on the cliff top, the rear scarp and the edge of the slipped mass, can provide useful information on the rate of movement especially whether it is decelerating or accelerating. However, it is important to interpret the results carefully as short-term results can be misleading and could reflect inaccuracy in the method of measurement. The most common methodology is the repeated measurement between control blocks or pins grouted into the slope. Measurements are usually made by stable invar-tape or by vernier gauges for more accurate resolution. Sub-surface movement can be detected using a variety of different methods, including inclinometer systems and the rupture of buried slip indicators.

#### **4.6 Interpretation and Presentation of Results**

It is important that measurements of cliff recession, whether historical or current, are interpreted within the context of the contemporary CBU behaviour, bearing in mind the effects of environmental change. Rear cliff and sea cliff recession are often coupled in repetitive sequences of variable time periods, governed by factors such as the intensity of marine erosion, the pattern of “wet year” sequences and the rate of post failure recovery of pore water pressures within the cliff. Although the overall effect is generally of parallel retreat of the cliff profile, the width of the CBU can be variable. Thus short term measurements of rear cliff recession can be limited to an atypical interval in the “cycle” and, hence, give a misleading impression of the recession process.

Ideally, recession measurements should cover at least one complete “cycle” of: pre-failure; failure; reactivation. This will vary according to the nature of the CBU, especially the sensitivity to triggering events of different magnitudes and the intensity of marine erosion. However, because of limitations inherent within the historical record it will be impractical to attempt to define the medium term steady-state timescale for individual CBUs. A more realistic approach is to adopt one of the following

approximate timescales that are probably relevant for particular types of CBU:

1. *Simple cliff* CBUs in rapidly eroding materials (e.g. the Suffolk coast): tens of years.
2. *Simple cliff* CBUs in slowly eroding materials (e.g. Chalk cliffs): tens to hundreds of years.
3. *Simple landslide* CBUs (e.g. the London Clay cliffs of north Kent): hundreds of years.
4. *Composite cliff* CBUs characterised by high rates of cliff top recession (e.g. the glacial till over hard rock cliffs of Durham): hundreds of years.
5. *Composite* CBUs (e.g. the glacial till over hard rock cliffs of North Yorkshire): hundreds to thousands of years.
6. *Complex* CBUs with high rates of throughput and removal of sediment (e.g. Black Ven, west Dorset): hundreds to thousands of years.
7. *Relict* CBUs (e.g. the Isle of Wight and East Devon Undercliffs): the current behaviour of these CBUs will need to be interpreted in the context of the post-glacial evolution of the landslide systems and the rate of contemporary reactivation. Although these CBUs evolve through “cycles” in the same manner as the other CBU types - the “cycles” are long term (c10, 000+ years in length).

When interpreting historical and current recession measurements it will be necessary to look for the presence of:

1. *Natural variability*; it is almost inevitable that data sets will include extreme recession measurements which may be up to 10 times the mean value. For example, the average annual recession rate of the Holderness cliffs is estimated to be 1.8m/year but has been over 15m in a single year on more than 1 occasion since 1953.
2. *Trends*; where a trend exists it is often easily recognised by a simple plot of measurements against time. The trend can be described by regression, calculating the equation of a line that “best-fits” the points in the plot. A trend can be stationary (i.e. constant) or non-stationary (i.e. increasing or decreasing); both states could be present in the same historical data set.
3. *Periodicity*; repeated high recession measurements may occur at regular intervals, corresponding to the length of the recession “cycle”. The average periodicity can be estimated “by eye” from a plot of the data or, where greater precision is required, by Fourier analysis (see Thornes and Brunnsden 1977). Where a marked periodicity occurs in the data set it may be useful to consider possible trends in terms of the variability of recession rates over the “cycle” period rather than on an annual basis. Thus, for the Holderness coast, for example, the annual erosion post data can be analysed as a series of 5-year (the “cycle” length) mean annual recession rates.

The use of average annual recession rates can provide a misleading perspective on cliff behaviour. Three alternative approaches are, therefore, suggested:



1. Expressing recession as “x” metres/relevant steady-state timescale. Thus recession on the Holderness coast could be expressed as 18m/10 years.
2. Distinguishing the base flux and event flux contributions to recession. Thus, a cliff may retreat 0.01m/year through surface erosion and small events (base flux) and 35m from a single episodic event occurring over a 100-year timescale. Using approach (1) above this cliff would yield 36m/100 years. An alternative way of expressing this could be 0.01m plus 35m (i.e. 35.01m) in any given year over the 100 years time period.
3. By expressing the variability of recession measurements in probabilistic terms. With reference to the sea cliff recession rates (for 1907-1991) in Table 8, the arithmetic mean gives an indication of the average annual recession rate; here it is 0.45m/year. This measure, however, does not convey the scatter of the observations around the mean. The standard deviation provides such an indication; here it is 0.2m.

If it is assumed that the frequency distribution is normal, given the standard deviation and the mean it is possible to calculate the relative frequency of any recession value and the proportion of measurements greater or less than any value. For example:

- 68.26% of observations may be expected to lie within one standard deviation of the mean value (i.e. 0.25m - 0.65m/year), and 95.44% may be expected to lie within two standard deviations (i.e. 0.05 - 0.85m/year);
- 50% of observations may be expected to be greater than the mean value (i.e. greater than 0.45m/year), and 10% may be expected to be greater than the mean value plus 1.3 standard deviations (i.e. greater than 0.71m/year).

In addition, the probability of a recession rate in excess of a particular value can be defined. For example:

- greater than 1.05m/year (i.e. three standard deviations) is 0.1% or 1 in 1,000;
- greater than 0.85m/year (i.e. two standard deviations) is 2.3% or approximately 1 in 40;
- greater than 0.65m/year (i.e. one standard deviation) is 15.9% or approximately 1 in 6.

<b>Table 8 Sample Recession Rates (average annual recession rates expressed in metres/year)</b>					
<b>Location</b>	<b>Sea Cliff 1907-1929</b>	<b>Sea Cliff 1929-1936</b>	<b>Sea Cliff 1936-1962</b>	<b>Sea Cliff 1962-1991</b>	<b>Sea Cliff 1907-1991</b>
1	0.09	1.5	1.31	0	0.57
2	2.09	2.0	0.31	0.06	0.83
3	1.63	0.57	0	0.34	0.57
4	0.91	0.57	0.23	0.31	0.48
5	0.64	0.28	0.31	0.28	0.5
6	0	0.28	0.15	0.34	0.19
7	0.09	0	0.54	0.18	0.24
8	1.27	0	0.54	0	0.26
Mean	0.84	0.65	0.42	0.19	0.45
Sd	0.72	0.68	0.38	0.14	0.20

Note Sd = Standard deviation

## CHAPTER 5 PREDICTION OF RECESSION RATES

### 5.1 Approaches to Prediction

An awareness of the possible cliff position at some future date is fundamental to shoreline management and coastal planning. Reliable predictions of future recession rates are needed to assist the identification of the preferred strategic coastal defence option for individual management units within a shoreline management plan (MAFF 1995) and to support the formulation of land-use planning policies which avoid locating new developments in areas where erosion is likely to occur during the lifetime of the building (DoE 1992). In those situations where coast protection works or improvements may be required, future recession rates are needed to evaluate scheme options and to test their economic viability and cost-effectiveness (Hall et al 2000a).

There is a range of approaches to prediction, including:

- extrapolation from historical data;
- expert judgement from cliff behaviour models, including structured subjective probability assessment;
- probabilistic simulation modelling;
- process response simulation modelling;
- empirical modelling.

These approaches involve an increasing degree of analysis and rigour, but not necessarily an increasing accuracy of prediction. In addition, all approaches rely, to varying degrees, on historical recession rate measurements, either as the basis for prediction or to calibrate the model. However, the historical record can, at best, reveal only a partial picture of the past recession process; it consists of a series of measurements made, typically, five times or less over the last 100 years or so. Historical measurements are often insufficient to explain the pattern of recession events (probably of different size) that led to the cumulative land loss between the measurement dates or the sequence of preparatory and triggering events that generated the individual recession event. This may be adequate in some circumstances, but in others there will be a need to expand this picture through an understanding of the contemporary cliff behaviour.

The reliance on historical data places a number of important constraints on the precision that can be achieved notably:

1. *It is not possible to make completely reliable predictions of future cliff position, partly because of uncertainty in future weather conditions, and partly because of uncertainty about the physical properties and behaviour of the cliff.*
2. *The timing and magnitude of individual recession events cannot be predicted precisely, but knowledge of cliff behaviour, geomorphological assessment and analysis of data can provide information of the relative likelihood of different events.*
3. *The future recession rate is itself uncertain: future conditions may vary from historical conditions. Even if conditions are constant (i.e. stationary), scatter in the data record means that a precise assessment of recession rates cannot be made.*

It should be stressed that predictions are seldom verifiable and are often wrong. As the accuracy of the predictions depends on the extent to which potentially complex and variable CBU behaviour is understood, it is important to be realistic about what can be achieved. The quality of predictions, especially expert judgements, will depend, in part, on there being sufficient time to make careful observations and to develop insights and concepts which improve the understanding of the unique characteristics of each CBU. In reality, many judgements will have to be made quickly with little performance history of the CBU and without the benefit of peer-group review.

## 5.2 A Probabilistic Framework for Prediction

A common problem for cliff studies is that we know that a recession event will occur, but we do not know when i.e. there is *uncertainty*. This uncertainty can be expressed in terms of the probability of failure. It should be noted that although an event can be judged to be most likely to occur by a particular date (e.g. “within the next 10-20 years”), it could actually occur before or after that date.

The pattern of past recession events is the result of a particular and unique set of wave, weather and environmental conditions. A different set of conditions could have generated a different recession scenario. The inherent randomness in the main causal factors (e.g. wave height, rain storms etc.) dictates that future recession cannot be expected to be an accurate match with the historical records; it could, however, deliver a similar overall recession rate with comparable variability between measurements, trends and periodicity.

Adopting a *probabilistic framework* for prediction can accommodate this uncertain relationship between past and future. Such a framework assumes that individual recession rates are part of a random series of recession rates whose frequency distribution can be described statistically and expressed in terms of their likelihood of occurrence.

Here, probability of cliff failure can be expressed in three ways:

1. *Classical*; in the classical approach a game of chance (e.g. rolling dice) has a finite number of different possible outcomes, which are assumed to be equally likely. The proportion of any event is then defined as the proportion of the total number of possible outcomes for which that event does occur. The classical approach has little relevance to the prediction of cliff recession.
2. *Frequency*; this approach suggests that the proportion of times any particular event has occurred in a large number of trials (i.e. its *relative frequency*) converges to a limit as the number of repetitions increases. This limit is called the probability of the event. There is no need for the number of different possible outcomes to be finite. This is essentially an empirical approach depending on a large number of trials. For example, if, on the basis of repeated historical measurements, the probability of 0.25 is assigned to the outcome that cliff recession at a particular point will exceed 1m in a given year, we might expect that 25% of all points along the cliffline will experience recession of over 1m in the next year.
3. *Subjective*; based on visual and geomorphological experience. It is related to the “*degree of belief*” that an outcome will occur and is very useful when assessment

of relative frequency proves impractical due to lack of data or information. For example, “there is a 30% chance of rain today” is a common statement made about the possibility of rain, based on the experience of the weather forecasters. They may, of course, be right or wrong; the assessment does, however, convey both the uncertainty in the weather and gives a measure of the likelihood of rain. The likelihood is quantified by assigning a number from 0 to 1 (or a percentage); higher numbers indicate that the outcome (i.e. rain today) is more likely than lower numbers. A zero (0) indicates that the outcome will not occur, a one (1) indicates that it will occur; both express *certainty* about the outcome.

Subjective assessment of uncertainty is common in geological and engineering practice, where this uncertainty is often expressed as, for example, “possibly failing in the following 10 years”, “very likely to reactivate” etc. These statements can, with experience, be replaced by quantitative subjective probabilities. Thus, rather than saying a cliff will “*probably fail next year*”, one could state that there is a “*50% probability that it will fail*”.

It is essential that *consistency checks* are performed on these subjective judgements. For example, if recession scenario 1 was assigned a 25% probability and scenario 2 a 50% probability, it is necessary to carefully compare the two cases and make sure that the historical record and contemporary cliff behaviour really imply that scenario 2 is twice as likely as scenario 1. This comparison has to be repeated as scenario after scenario is assessed; it may lead to modifications of the probabilities that were initially assigned to scenarios.

A wide variety of strategies can be used to estimate the probability of a particular amount of cliff recession or an individual event over a given time period, some of which are described in this Chapter. Many of the probabilistic methods described combine historical data together with geomorphological understanding.

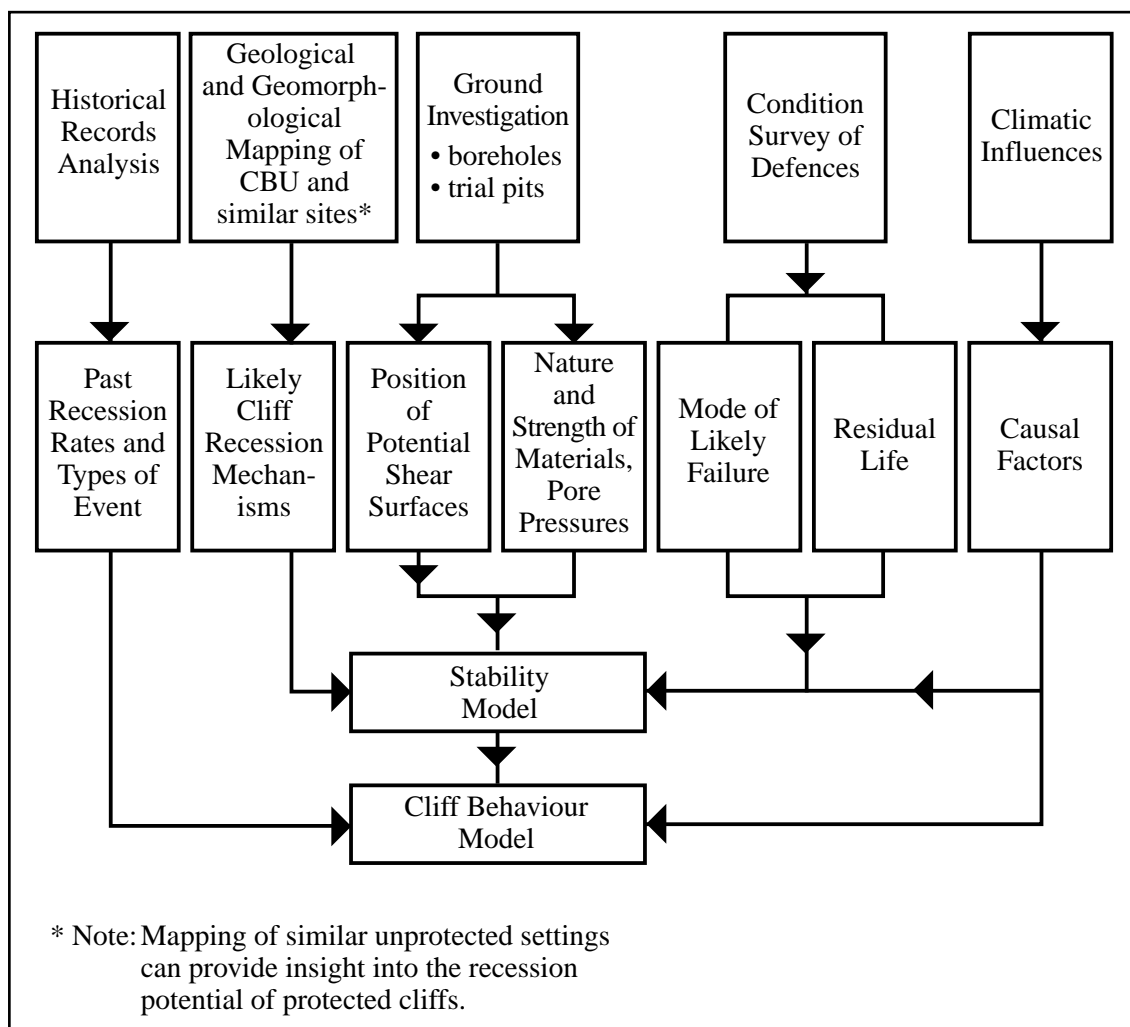
### **5.3 Selection of Prediction Methods**

There is no simple, reliable and universally applicable method of prediction due to the complexity and uniqueness of the recession problems within individual CBUs. As for measurement and monitoring approaches (Chapter 4) there is a range of issues relevant to the selection of prediction methods, including:

1. *The stage in the decision-making process*; the preparation of a shoreline management plan will need to be supported by a general indication of the probable future trends. A scheme strategy or feasibility study, however, will require more detailed predictions to assist the cost-benefit analysis of possible scheme options.
2. *The level of risk to the coastal assets*; detailed probabilistic or quantitative predictions are likely to be best suited to situations where there is a clear, but uncertain, risk to property or public safety. Elsewhere simple extrapolations, rapid expert judgements or empirical models may provide sufficient insight into future recession scenarios.
3. *The nature of the CBU*; most of the methods described in this Chapter are suitable for rapidly eroding simple cliffs and simple landslide CBUs. The probabilistic

simulation methods are particularly suited to modelling sequences of events over a relatively long period. They are less suited to complex and relic CBU's where the markedly episodic and uncertain nature of the recession process may best be considered using expert judgement of the likelihood of single events.

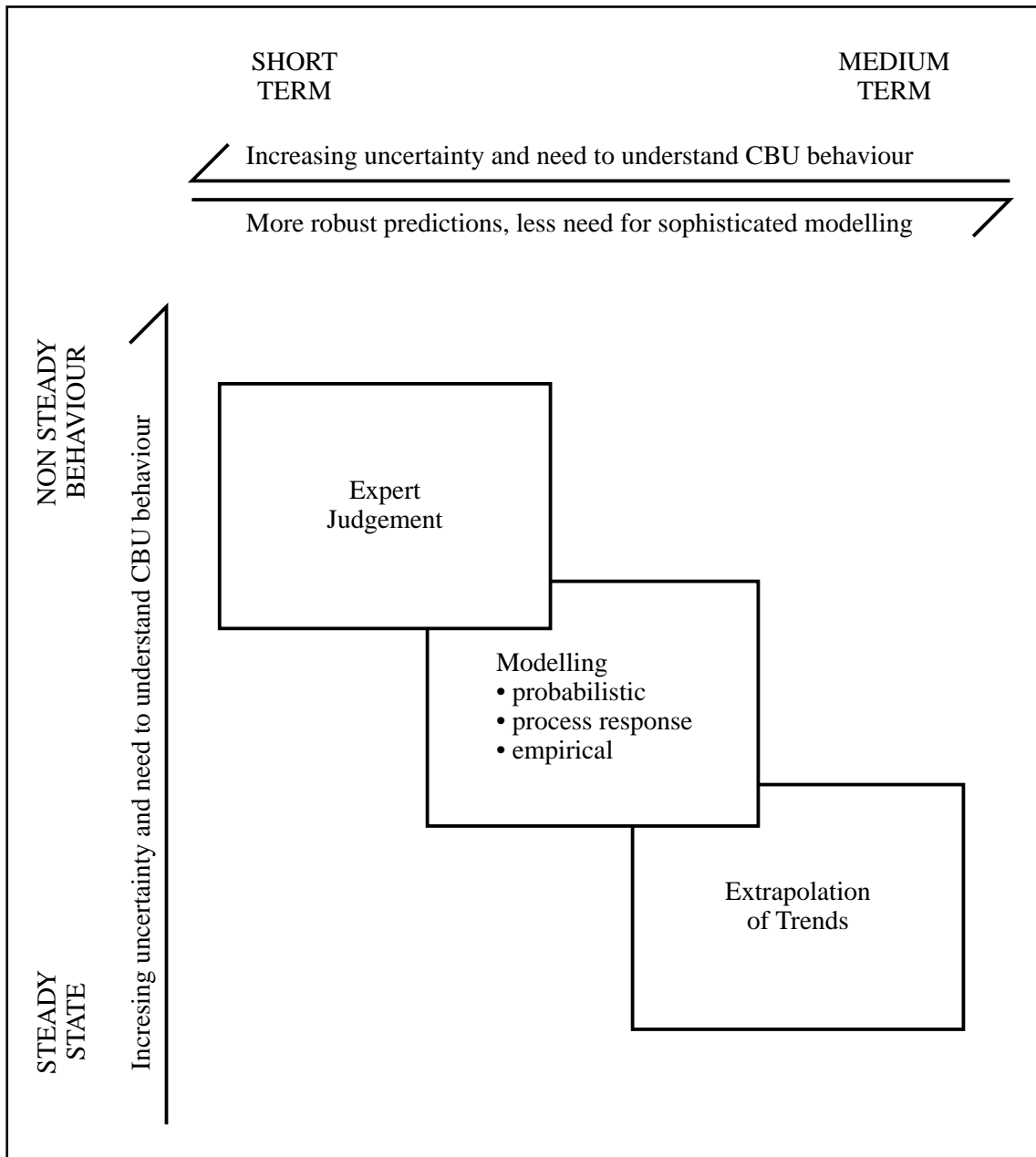
On the protected coastline, it is important that recession scenarios are developed by expert judgement that take account of the potential events that could develop if any element of the coast protection and slope stabilisation measures should fail. In such instances, it may be necessary to consider the recession mechanisms that occur on unprotected cliff lines developed in similar materials (Figure 15), as well as the residual life of the existing defences. Event trees provide a rigorous framework for the assessment of possible failure and recession scenarios on protected cliff lines (see Figure 10).



**Figure 15 A Framework for Development of Recession Scenarios on Protected Cliffs**

Complete prediction of cliff recession includes accounting for variations along the coast. These can arise from many factors, such as variation in waves and currents, geological variability, protection works, and the plan shape of cliffs related to wave incidence. Recession measured at a point can be used to infer rates at nearby locations, due to spatial correlation of many of the relevant factors, but clearly there is a limit to applicability of these rates.

4. *The timescale over which predictions are required*; when recession rates are projected over the medium term timescale (see Chapter 2), natural variability becomes smoothed out and less significant, and predictions can be made with a reasonable level of confidence. The reverse is true over the short-term timescale. Thus, the longer the period over which predictions are made, the more likely the results will be broadly accurate, provided the CBU can be assumed to be in, and remain in, a steady-state condition. Progressively more sophisticated methods of prediction are, therefore, necessary to address the inherent uncertainty in short term predictions.



**Figure 16 Guidance on the Relative Suitability of Different Prediction Methods to Different CBUs**

Figure 16 is an attempt to summarise these issues and provide broad guidance of the relative suitability of the various methods described in this Chapter. The method chosen should be appropriate to the nature of the project (i.e. the available resources), the potential losses that could occur and the type of cliff. It should be stressed,

however, that wherever possible more than one method should be adopted to provide an indication of the robustness of the predictions. In some situations, it will be appropriate to undertake progressively more sophisticated predictions as and when additional information or resources become available.

Where possible it is recommended that a probabilistic framework is adopted as this provides a mechanism for expressing uncertainty.

#### **5.4 Extrapolation from Historical Data**

Historical recession data can be extrapolated to produce estimates of future recession. However, as historical records tend to be restricted to a limited number of measurements made at irregular, lengthy intervals they tend to smooth out much of the natural variability that is inherent in the recession process and disguise the episodic nature of major recession events in many CBUs. Provided, however, that the historical records are known to cover several recession “cycles”, simple extrapolations can give a reasonable estimate of the cliff top position, but only towards the end of a period comparable to the timescale of the historical measurements. Thus, if measurements are available, on average, at 50 year intervals, predictions based on extrapolation would be most reliable around 50 years into the future. The likely effects of natural variability and periodicity could significantly restrict the reliability of estimates for earlier dates.

A number of methods can be used to extrapolate from historical records. Amongst the most widely used methods include:

1. Adopting the average recession rate over the full period of available measurements (i.e. the average rate between the earliest and latest measurements) and extrapolating this rate into the future.
2. Adopting an average recession rate calculated from the rates for each measurement period (i.e. the average rate includes intermediate measurements as well as the earliest and latest measurements) and extrapolating this rate into the future.

In both extrapolation methods outlined above the future cliff position is a function of the mean recession rate and the time period:

*Recession by Year A = mean recession rate x A Years*

The change in cliff position can be expressed probabilistically by taking account of the variability within the historical record. In the simplest way, predictions with a specified likelihood of occurrence can be calculated as follows:

*Recession by Year A = (mean rate + standard deviation) x A Years.*

The most straightforward linear regression approach to predicting cliff recession using historic data is a continuous linear model (Crowell et al., 1997, Amin and Davidson-Arnott, 1997):

$$X_t = \beta_0 + \beta_1 t + \varepsilon$$

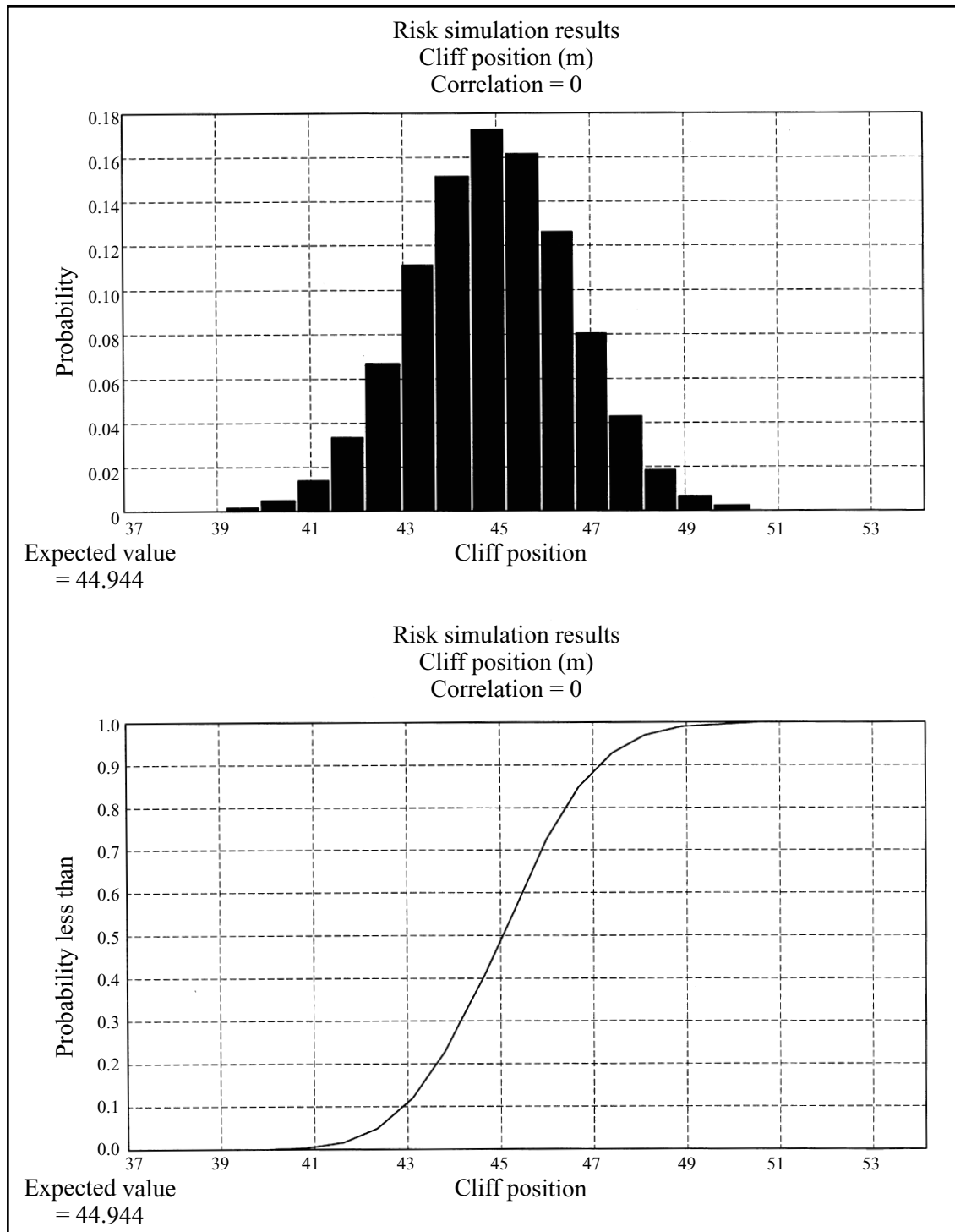


where  $X_t$  is the recession distance at time  $t$  and  $\varepsilon$  is a random variable that has a Gaussian distribution with zero mean and variance  $v$ . Hence the distribution of  $X_t$  will be Gaussian with mean  $\beta_0 + \beta_1 t$  and variance  $v$ . If there are  $n$  historic observations of cliff position  $x_i$  at time  $t_i$  then the maximum likelihood estimators for  $\beta_0$  and  $\beta_1$  can be found from simple linear regression theory. Dolan et al. (1991) compare a number of simple linear methods of characterising shoreline rate of change. Milheiro-Oliveira and Meadowcroft (2001) suggest a similar model based on a Wiener type dynamical process (Singpurwalla, 1995). Crowell et al. (1997) also examined quadratic and cubic recession models but found that they were not preferable to linear regression and can be extremely inaccurate.

Besides assuming that the regression of  $X_t$  is a linear function of  $t$ , there are three further assumptions about the joint distribution of  $X_{t_i}$  or any given values of  $x_1, \dots, x_n$ :

- i. Each variable  $X_{t_i}$  is normally distributed.
- ii. The variables  $X_{t_1}, \dots, X_{t_i}$  are independent.
- iii. The variables  $X_{t_1}, \dots, X_{t_i}$  have the same variance  $v$ .

Linear regression analysis incorporating random sampling of recession rates can be used to build up a probabilistic description of cliff position at a particular time in the future. This approach is based on the linear trend over time derived from regression analysis, but also accommodates the potential variability in the recession rate, as defined by the probability distribution for the historical records. At each timestep the recession rate can be sampled from this probability distribution, using a *Monte-Carlo* (i.e. random) *sampling procedure*, and a time series of cliff positions derived representing one possible sequence of recession events. Repeating the procedure gives another, alternative sequence due to the random nature of the sampling procedure. By running many similar simulations it is possible to establish a probability distribution for the cliff position at any year in the future (Figure 17).



**Figure 17 An Example of Probabilistic Sampling Based on Linear Regression Results**

The techniques of extrapolation and linear regression offer a simple approach to projecting historical recession measurements into the future. By using a probabilistic framework, these methods can also give an indication of the degree of uncertainty in the predictions. However, there are a number of significant limitations that should be borne in mind:

- the measurements on which the extrapolation and regression are based need to be stationary or showing a consistent trend i.e. the geological and environmental controls on the recession process should have remained the same throughout the

- period of the historical record;
- the predictions will only be strictly valid so long as the geological and environmental controls remain unchanged from those on which the extrapolations were based;
- the historical record needs to cover at least 1 “cycle” to ensure that infrequent episodic events are adequately represented in the data set. Extrapolations should be based on all reliable data covering the longest possible period (Bray and Hooke 1997);
- linear regression and analysis of variance assumes that the residuals (scatter) about the best fit line are uncorrelated. In fact, there is likely to be some serial correlation, depending particularly on the relationship between the sampling interval and the characteristic time for cliff forming events. A large sampling interval will more closely resemble a random (uncorrelated) series, whereas if the sampling interval is small or the characteristic cliff-forming interval is large, there may be very significant correlation between consecutive measurements;
- analysis of variance assumes that the residuals are normally distributed about the best fit line. In the case of cliff position, this will not be true since the cliff position changes monotonically i.e. recession cannot be recovered.

### **5.5 Expert Judgement from Cliff Behaviour Models**

Expert judgement involves the use of experience, expertise and general principles to develop future cliff recession scenarios (possible future recession patterns) from the available historical record and past cliff behaviour, preferably in an explicit and consistent manner. Such judgements are usually subjective, but by proposing several possible scenarios followed by systematically testing and eliminating options by additional investigation and discussion it is possible to develop reliable estimates of the future cliff recession.

A cliff behaviour model should provide a reliable indication of how the CBU will respond to various causal factors. However, in many instances it will be difficult to predict the precise extent and timing of future events. A range of alternative scenarios can be developed to demonstrate the changes in cliff top recession with different patterns of cliff behaviour, and the estimated change of each case occurring over a specified time period. The probability of a recession event can be expressed in terms of the number of events that may occur in a given period or the probability of a particular CBU experiencing a recession event in a year.

There are a number of generic approaches for the development of recession scenarios, including: the use of geomorphological evidence coupled with historical data (the direct approach), stability analysis (modelling the CBU response to a primary variable, such as piezometric pressure, coupled with knowledge of the material strengths etc.), historical frequency, establishing the relationship between recession events and triggering events of varying intensity and the event tree approach. Each of these approaches is described in the following sections.

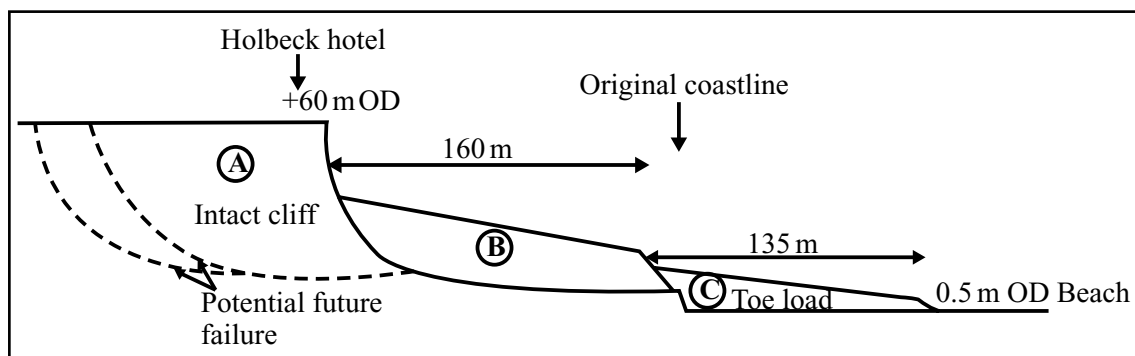
Experts in coastal cliff recession will willingly acknowledge the uncertainty that is inherent in predictions of cliff recession, and most are familiar with probability theory as a notation for expressing their uncertainty. Nonetheless, when asked to make judgements under conditions of uncertainty, human subjects tend to adopt heuristics and biases. These heuristics and biases mean that their judgements may be a distorted

reflection of their state of knowledge or uncertainty. It is therefore important to avoid as far as possible the inevitable biases in expert judgements of the probability of coastal landsliding.

Five “rules” on the use of expert judgement for probabilistic prediction of coastal cliff recession are outlined as follows:

- *problem structure*; it is often useful therefore to break down the problem using event trees and ask experts for judgements of scenarios that make up the event tree;
- *checks for inconsistencies*;
- *clearly state the evidence upon which expert judgement is based*;
- *undertake peer review of all judgements*;
- *use quantitative data to inform the expert judgement*;

*The Direct Approach*; Development of an evolutionary model from geomorphological and historical evidence can provide a framework for understanding the past and recent behaviour of a CBU and gives an indication of the possible future developments. This approach was used to provide a rapid assessment of the potential scenarios for further recession after the 1993 Holbeck Hall landslide, Scarborough. Clark and Guest (1994) describe how erosion of debris from the foreshore, (C) in Figure 18, would reduce the toe support to main landslide mass (B). This rapid unloading of zone (B) would almost certainly reactivate the landslide causing the material in zone (B) to slide forward onto the foreshore. This in turn would unload the rear cliff resulting in a new landslide extending a considerable distance inland. Such an event would damage houses behind the original landslide and if the area was abandoned the cliff top would gradually degrade and eventually reach a main through road. It was considered that if the debris continued to be removed by marine erosion then the cliff top properties would have to be evacuated within 1 year, prompting coast protection and slope stabilisation works to reduce the risks.



**Figure 18 Holbeck Hall Landslide, Scarborough (after Clark and Guest 1994)**

*Stability Analysis*; in some situations, especially on the protected coast, it may be useful to support the expert judgement of recession scenarios with computer based stability analysis. This may involve:

- developing stability models for representative cross sections along the frontage;
- assessing the sensitivity of the various model sections to changes in various parameters, notably groundwater level or pore water pressures;

- identifying critical conditions which would lead to a Factor of Safety of unity and, hence, initiate failure;
- evaluating the likely mode of failure on critical sections.

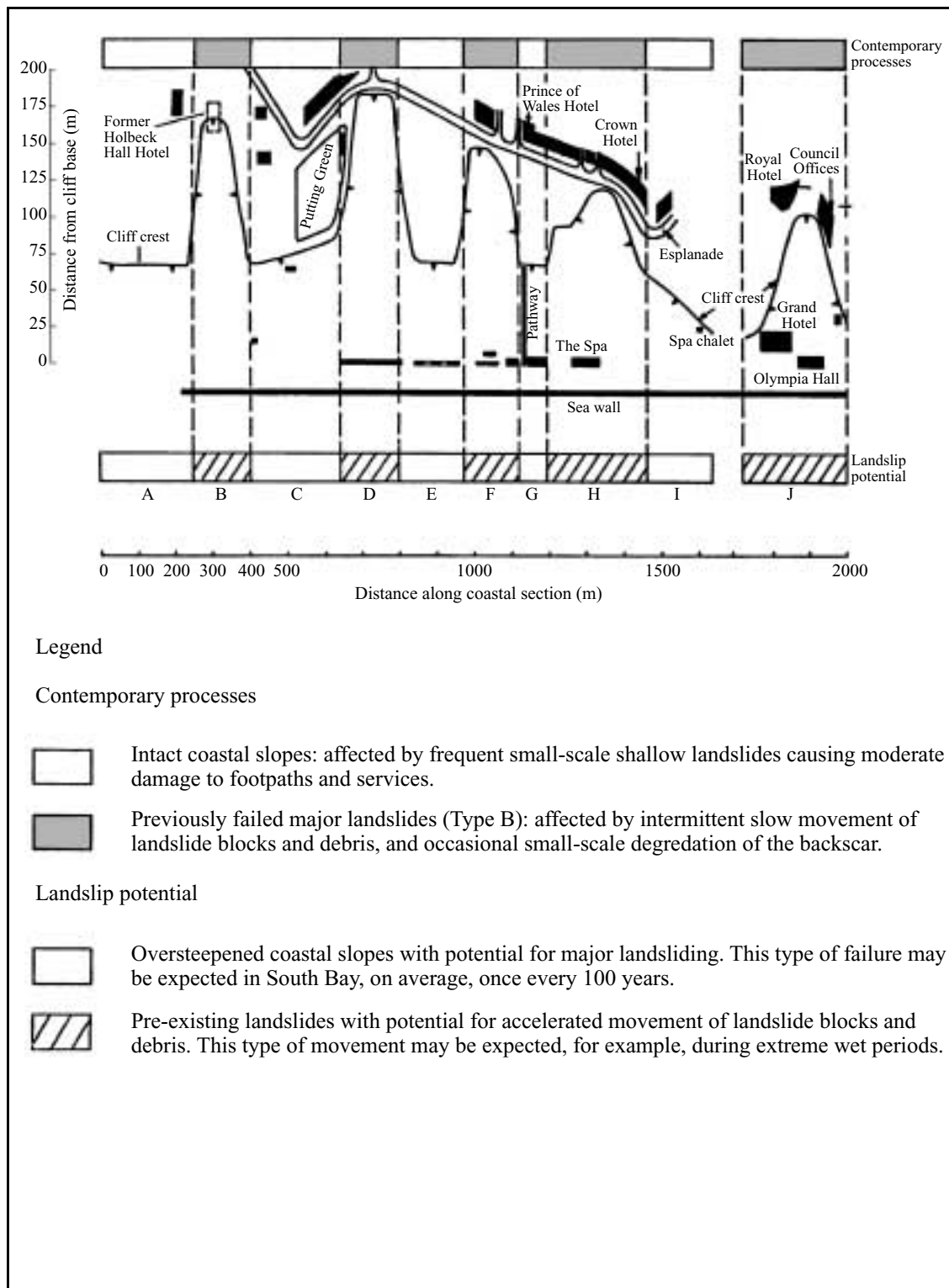
Williams et al (1994) developed numerical models based on stability analysis of rock slope failure mechanisms to predict cliff recession along the Lias cliffs of Glamorgan. The models provided probabilistic solutions to the range of rock failures that occur on this coast; a simulation method was used to determine the potential configuration failure surface from the lowest calculated factor of safety.

*Historical Frequency;* A frequent assumption of cliff recession studies is that the historical frequency of landsliding in an area can provide an indication of the future probability of such events. Lee and Clark (2000), for example, describe the historical research into landsliding along the South Bay cliffs, Scarborough that provided an indication of the nature and scale of some of the major events that have occurred over the last 350 years. The history of landsliding was established through a search through journals, prints, reports, records and local newspapers (held on micro-fiche) archived at the Scarborough local library, and charts held at the Hydrographic Office, Taunton. The study revealed that rather than being an unforeseeable hazard, the 1993 Holbeck Hall landslide was only the most recent of a series of major landslide events on this coastline (Clark and Guest 1994; Lee 1999; Lee et al 1998a).

The South Bay cliffline can be sub-divided into 8 separate cliff sections, comprising 4 *previously failed major landslides*, separated by 4 intact coastal slopes i.e. unfailed cliffs (Lee et al 1998a; Figure 19). A range of failure types was identified that could lead to the recession of the intact coastal slopes. Each failure type was evaluated in terms of potential consequences and assigned a probability, based on expert judgement:

- *small-scale shallow failures* of the coastal slopes may lead to slight to moderate damage to footpaths and other structures. This type of failure can be expected to occur somewhere within South Bay, on average, every year;
- *large failure* involving rapid cliff top recession and runout of debris. Such an event could lead to total loss of the seawalls, coastal slope structures and cliff top property within the affected area.

The earliest reported major landslide in South Bay was the 1737/38 failure at the site of the present day Spa. During this event an acre of cliff top land (224 yards by 36 yards) sunk 17 yards, complete with cattle grazing on it. This was accompanied by 6 - 7 yards of toe heave on the beach and at the cliff foot, creating a bulge 26 yards broad and 100 yards in length. In contrast, little has been found out about the timing of the other major slides on the South Bay cliffs (the South Bay Pool and South Cliff Gardens landslides), other than that they both appear on the earliest reliable map of this coastline (an Admiralty Chart of 1843) and that they are likely to be later than the Spa landslide.



**Figure 19 Summary of Cliff Instability Risk, South Bay, Scarborough (after Rendel Geotechnics 1994)**

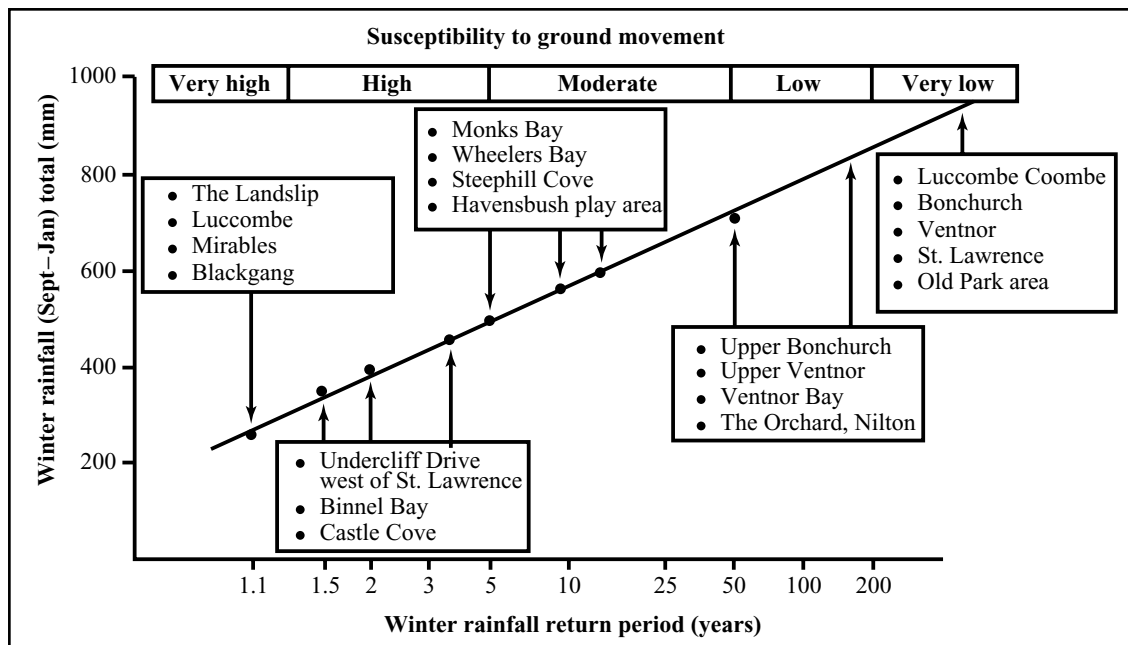
The time series generated through the archive search allows an estimate to be made on the frequency of particular types of major landslide events on different sections of the cliffline. These historical frequencies were used to assign probabilities to the occurrence of different events in the future (Lee et al 1998a). The historical frequency of failure of the intact step slopes was estimated to be 4 events in 400 years (i.e. 1 in

100, including the 1993 Holbeck Hall landslide). Thus, the annual probability of failure ( $P_f$ ) of any one of the eight original intact slopes was estimated to be:  $P_f = 4/(8 \times 400) = 0.00125$  (1 in 800).

*Developing a Process-Response Relationship;* this involves establishing initiating thresholds between various parameters (e.g. rainfall) and landslide activity. The most readily defined threshold is one that identifies the minimum conditions (or envelope) for landslide activity; above this, the conditions are necessary, but not always sufficient, to trigger landslides and below this, there is insufficient impetus for failure. For example, Lee et al (1998b) describe how a rainfall threshold was defined for parts of the Isle of Wight Undercliff and used to calculate probabilities of landslide occurrence.

The relationship between landslide reactivation and rainfall was established as follows:

1. *Analysis of historical records;* reports of past landslide events were identified by a systematic review of available records, including local newspapers (from 1855 to present day).
2. *Analysis of rainfall records;* a composite data set was derived from the various rain gauges that have operated within the Undercliff since 1839. The antecedent effective rainfall was calculated for four-month periods between August and March (the wet period of the year), from 1839/1840 to present day - this being previously identified as a good measure of the prolonged periods of heavy rainfall that appear to control landslide activity in the Undercliff (Lee and Moore, 1991). This data series was used to calculate the likelihood of different 4-month antecedent effective rainfall totals (4AER) occurring in any single year (i.e. the return period). Figure 20 shows the winter rainfall totals that may be expected to be equalled or exceeded, on average, for particular recurrence intervals.
3. *Assessment of threshold conditions;* this involved relating the historical record for each landslide system to the 4AER data series to identify the minimum return period rainfall that is associated with landslide activity in a particular area. For example, in the westernmost system, Blackgang, significant movements are a frequent occurrence, and the minimum rainfall threshold needed to initiate significant movement appears, in the past, to have been a 1 in 1.1 year event. The winter rainfall associated with recorded ground movement events in particular areas are indicated on Figure 20 to highlight the varying degrees of sensitivity of different parts of the Undercliff.



**Figure 20** Landslide Sensitivity within the Isle of Wight Undercliff (after Lee et al., 1998b)

4. *Assessment of the probability of landsliding;* that ground movement does not always occur when the winter rainfall thresholds shown on Figure 20 are exceeded highlights the importance of other factors in controlling landslide activity, i.e. preparatory and triggering factors. An assessment was made, therefore, of the annual probability of a 4AER of a particular magnitude actually triggering landslide activity. An estimate was made of the number of times a 4AER over a threshold value initiated landsliding in a particular system, compared with the number of times this threshold had been exceeded over the last 150 years.

The conditional probability of significant ground movement in a particular landslide system was calculated as follows (see “Event Trees” below):

$$P_m = P(4AER) \times P(O|4AER)$$

$P_m$  = the annual probability of ground movement in a system

$P(4AER)$  = the annual probability of a threshold 4AER being equalled or exceeded in a particular year

$P(O|4AER)$  = the annual probability of an event given the occurrence of the threshold 4AER being equalled or exceeded.



<b>Table 9 An Indication of the Estimated Annual Probabilities of Significant Movement in a Number of Parts of the Undercliff (after Lee et al 1998b)</b>			
<b>Location</b>	<b>Annual Probability of Threshold 4AER</b>	<b>Annual Probability of Threshold 4AER triggering movement</b>	<b>Estimated Conditional Probability of Significant Movement</b>
Blackgang	0.9	0.1	0.09 (1 in 11)
Lucombe	0.25	0.2	0.05 (1 in 20)
Upper Ventnor	0.02	0.5	0.01 (1 in 100)
St Lawrence	0.005	0.5	0.0025 (1 in 400)

Table 9 provides an indication of the estimated probabilities of significant movement in a number of parts of the Undercliff.

*Event trees*; this approach involves tracing the progression of the various combinations of scenario components using logic-tree techniques to identify a range of possible outcomes. The development of an event tree involves:

- identification of sequences of events that may initiate a failure (i.e. causal factors);
- evaluating the range of potential failure mechanisms that could occur, i.e. the system response (including no failure);
- consideration of the potential outcomes or impacts that may arise from each potential failure mechanism. The outcomes can be further expanded to consider the consequences in terms of loss of property, injury etc.

The individual probability of achieving a certain outcome is the product of the annual probability of various causal factors initiating an event ( $P(E)$ ) the conditional probability of the system response given the initiating events ( $P(S|E)$ ) and the conditional probability of the outcome given the system response ( $P(O|S)$ ) i.e.:

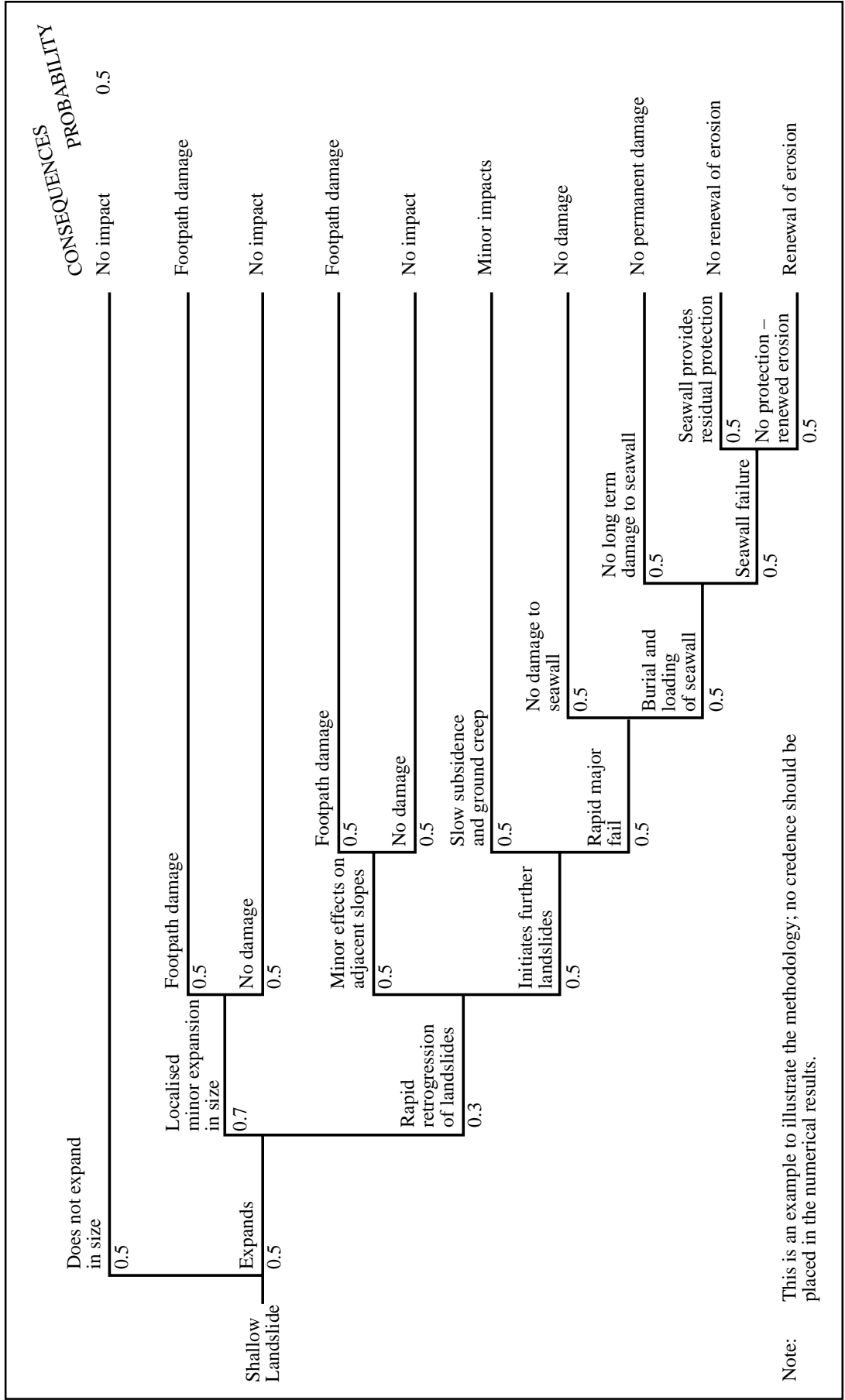
$$\text{Scenario Probability} = P(E) \times P(S|E) \times P(O|S)$$

Figure 21 presents a hypothetical example that evaluates the potential for a major rotational landslide on a protected cliffline leading to seawall failure and renewed marine erosion at the cliff foot. Of note, the branches of the trees represent mutually exclusive alternatives with a cumulative probability of 1, and that the sum of the outcome probabilities for all the scenarios equals 1.

## **5.6 Probabilistic Simulation Modelling**

Two simple probabilistic models have been developed as part of this study and are described in the Technical Report to illustrate the way in which such models can be used to assist the prediction of recession scenarios. The first method uses a single probability distribution to represent the magnitude/frequency characteristics of cliff recession events. The second is a two-distribution model in which probability distributions are used to represent the time interval between, and magnitude of, recession events. The latter is described below.

**Figure 21 Sample Event Tree, Illustrating the Consequences of a Shallow Landslide on a Protected Cliff**



Note: This is an example to illustrate the methodology; no credence should be placed in the numerical results.

The *two distribution* method considers the recession process in more detail by assuming that the cliff toe can withstand a given number storm events before the cliff fails. In this model, an event that causes undercutting of the cliff toe is defined as a wave height and water level with a certain return period. The return period, together with the number of storms required to initiate failure of the cliff define the average time interval between recession events. If a recession event does occur, then a second probability distribution can be used to represent the magnitude of the event i.e. the amount of cliff top recession. This model, therefore, has the ability to differentiate between high and low sensitivity CBUs by representing the number and magnitude of storm events needed to initiate recession events.

Cliff recession is assumed to proceed by means of a series of discrete landslide events, the size and frequency of which are modelled as random variables. A discrete model for the probabilistic cliff recession,  $X_t$  during duration  $t$  is

$$X_t = \sum_{i=1}^N C_i$$

where:

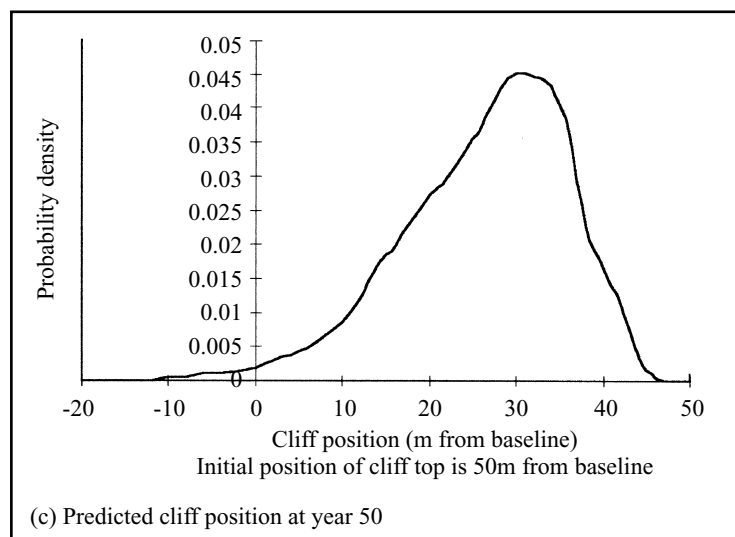
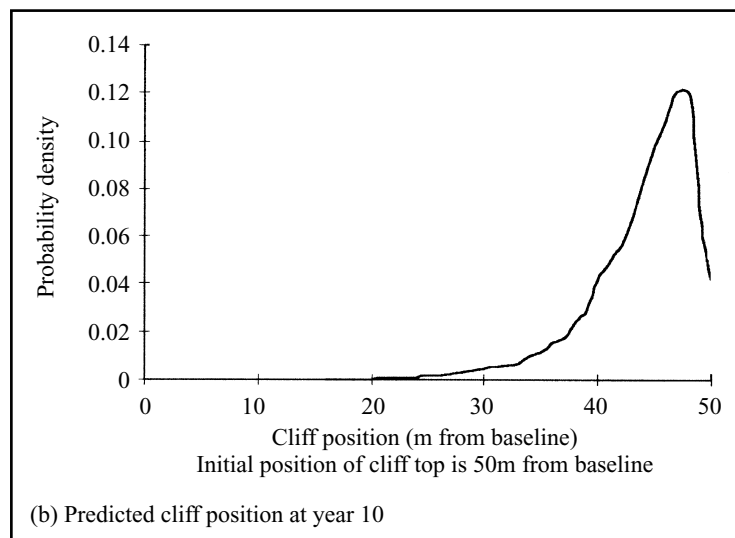
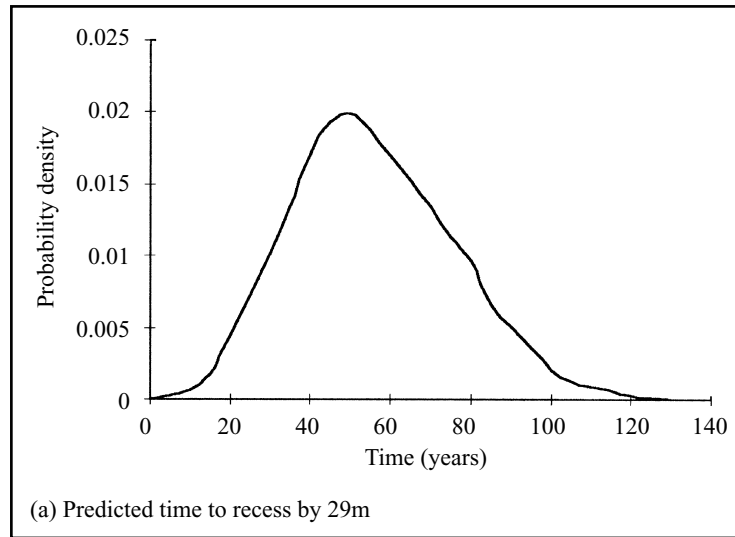
$N$  is a random variable representing the number of cliff falls that occur in duration  $t$ , and  $C_i$  is the magnitude of the  $i$ th recession event.

This model can be used to simulate synthetic time series of recession data, which conform statistically to the cliff recession measurements (e.g. Lee et al 2001b; Hall et al, in press). Three typical realisations of the model are shown in Figure 22. The time series are stepped reflecting the episodic nature of the cliff recession process. Multiple realisations of the simulation are used to build up a probability distribution of cliff recession.

The model is defined by two distributions.

1. An *event timing distribution* describes the timing of recession events. The model incorporates physical understanding of the cliff recession process by representing the role that storms have in destabilising cliffs and initiating recession events. The arrival of damaging storms is assumed to conform to a Poisson process, i.e. successive storms are assumed to be independent incidents with a constant average rate of occurrence. After a number of storms of sufficient severity, a cliff recession event occurs. The time between successive recession events can therefore be described by a gamma distribution. The shape of this distribution is defined by a scaling parameter  $\lambda$  (the reciprocal of the return period of the significant storm event) and a shape parameter  $k$  (the number of storms above a certain threshold which cause damage to the toe of the cliff that is sufficiently severe to trigger failure).
2. An *event size distribution* describes the magnitude of recession events in terms of the mean size and their variability. The form and parameters of this distribution should reflect the frequency distribution of actual cliff failures and is likely to be site specific. The model developed here uses a log-normal distribution, following the conclusions of the wave basin tests on a model cliff undertaken by Damgaard and Peet (1999). A log-normal distribution is non-negative which corresponds to

the non-existence of negative cliff recession events. The probability density rises to a maximum value, and then approaches zero as the recession distance becomes large, i.e. very large cliff recession events are unlikely.



**Figure 22 Sample Results from the 2-Distribution Probabilistic Model**

The cliff recession model is therefore characterised by four parameters,  $\lambda$  and  $k$  from the gamma distribution, and the mean,  $\mu$  and variance,  $\delta$  of the log-normal distribution. The model parameters can be estimated by maximum likelihood or Bayesian estimation methods (Hall et al in press). The maximum likelihood method is based on optimally fitting the parameters to the available data, whilst the Bayesian method also makes use of expert knowledge about the size and frequency of landslide events. There is, therefore, scope to include geomorphological knowledge of event size and timing, which may not necessarily be revealed by the historic data record.

<b>Table 10 Sample Recession Rates (average annual recession rates expressed in metres/year)</b>					
<b>Location</b>	<b>Sea Cliff 1907-1929</b>	<b>Sea Cliff 1929-1936</b>	<b>Sea Cliff 1936-1962</b>	<b>Sea Cliff 1962-1991</b>	<b>Sea Cliff 1907-1991</b>
1	0.09	1.5	1.31	0	0.57
2	2.09	2.0	0.31	0.06	0.83
3	1.63	0.57	0	0.34	0.57
4	0.91	0.57	0.23	0.31	0.48
5	0.64	0.28	0.31	0.28	0.5
6	0	0.28	0.15	0.34	0.19
7	0.09	0	0.54	0.18	0.24
8	1.27	0	0.54	0	0.26
Mean	0.84	0.65	0.42	0.19	0.45
Sd	0.72	0.68	0.38	0.14	0.20

Note Sd = Standard deviation

This method has been tested using historical recession data for 20m high cliffs, in Sussex, developed in sandstones overlain by Wadhurst Clay. The position of the cliff top was obtained from 1:2,500 scale historical maps at years 1907, 1929, 1936, 1962 and 1991. Cliff top locations were extracted at eight positions along the coast, covering a total length of about 400m. For each 'epoch' between map dates, the mean recession rate (m/year) was calculated for each of the eight locations. In addition, overall recession rates from 1907 to 1991 were calculated. For each of the five measurement periods, the standard deviation of recession rate between the different locations was calculated as well as the mean rate (Table 10).

The event timing distribution was chosen using a maximum likelihood parameter estimation model (Hall et al., in press), with parameters  $k = 0.8$  and  $\lambda = 0.046$ . With more frequent events, the statistical model would not generate sufficient variability as compared with the data. Furthermore, the number of zero recession rates in the data record indicated that the characteristic time between recession events was quite long. For example, during the seven-year period from 1929 to 1936, two of the locations showed no recession at all, indicating a significant probability (about 0.25) that the interval between recession rates could be greater than seven years. This type of reasoning was used to constrain the simulation model parameters.

Table 11 shows results of two simulations from the calibrated model. These were obtained by simulating the time period 1907 to 1991 and extracting results at the relevant years so that these could be compared directly with the measured values. As this is a sampling approach, different simulations give different results, so the two example simulations shown in Table 11 give different individual values. Nevertheless, the general characteristics of the model results are similar to the measured values in Table 10.

The statistical model was then used to make probabilistic predictions of:

- the time for the cliff to undergo recession of a certain distance, to assess when in the future a hypothetical fixed asset currently 29m from the cliff top will be lost (Figure 22a);
- the cliff position after 10 and 50 years (Figure 22b and c). Cliff position is measured relative to a fixed baseline. The baseline is 50m landward of the initial cliff position, so greater than 50m recession appears as a negative value (i.e. it is landward of the baseline).

Since these are numerical simulation results the final distribution is not completely smooth.

The stochastic simulation model has a number of fundamental advantages over conventional regression analysis. The method incorporates an episodic model of recession events, which can be closely related to known cliff behaviour. In addition, knowledge about cliff behaviour can be included in the model, in terms of the frequency and magnitude of events and the observed variability.

<b>Table 11 Two Distribution Probabilistic Model: Simulation Results (compare the mean and standard deviations with historical data in Table 10)</b>					
<b>SIMULATION 1</b>					
<b>Years</b>					
<b>Location</b>	<b>22</b>	<b>7</b>	<b>26</b>	<b>29</b>	<b>84</b>
	<b>1907-1929</b>	<b>1929-1936</b>	<b>1936-1962</b>	<b>1962-1991</b>	<b>1907-1991</b>
1	0.00	0.00	0.18	0.37	0.18
2	0.26	0.36	0.75	0.88	0.63
3	0.85	0.60	0.68	0.36	0.61
4	0.23	0.90	0.20	0.77	0.46
5	0.40	0.43	0.51	0.39	0.44
6	0.05	0.07	0.30	0.40	0.25
7	0.76	0.00	0.70	0.45	0.57
8	1.34	1.64	0.24	0.54	0.75
Mean	0.49	0.50	0.45	0.52	0.49
SD	0.43	0.52	0.23	0.19	0.18
<b>SIMULATION 2</b>					
<b>Years</b>					
<b>Location</b>	<b>22</b>	<b>7</b>	<b>26</b>	<b>29</b>	<b>84</b>
	<b>1907-1929</b>	<b>1929-1936</b>	<b>1936-1962</b>	<b>1962-1991</b>	<b>1907-1991</b>
1	0.34	0.60	0.42	0.42	0.42
2	0.58	0.74	0.90	0.69	0.73
3	0.53	0.94	0.38	0.53	0.52
4	0.97	0.00	0.46	0.67	0.63
5	0.50	0.51	0.08	2.53	1.07
6	0.13	0.00	0.28	0.13	0.17
7	0.20	0.39	0.31	0.24	0.27
8	0.54	0.19	0.22	0.97	0.56
Mean	0.47	0.42	0.38	0.78	0.55
SD	0.24	0.32	0.23	0.71	0.26

## 5.7 Process Response Simulation Modelling

The development of predictive models based on the interactions between nearshore, foreshore and cliff processes is very much in its infancy. Such models could be used to estimate the CBU response to changes in factors such as sea level rise, wave climate, sediment supply and rainfall patterns, or the effects of coastal engineering works on the recession of nearby cliffs.

A wide variety of “off-the shelf” models, developed by both coastal and geotechnical engineers, can be adopted and combined to produce simple process-response models, including:

- stability models, including probabilistic stability models;
- beach/foreshore erosion models;
- sediment transport models;
- wave and current models.

The approach, however, requires high quality information and a sound understanding of the interrelationships between cliff and foreshore processes e.g., how much erosion can be achieved by a wave reaching the cliff foot. This knowledge is generally limited to laboratory experiments using simple materials (e.g. Sunamura 1992; Peet and Damgaard 1997). Despite these limitations, a number of process-response models have been developed to predict recession scenarios.

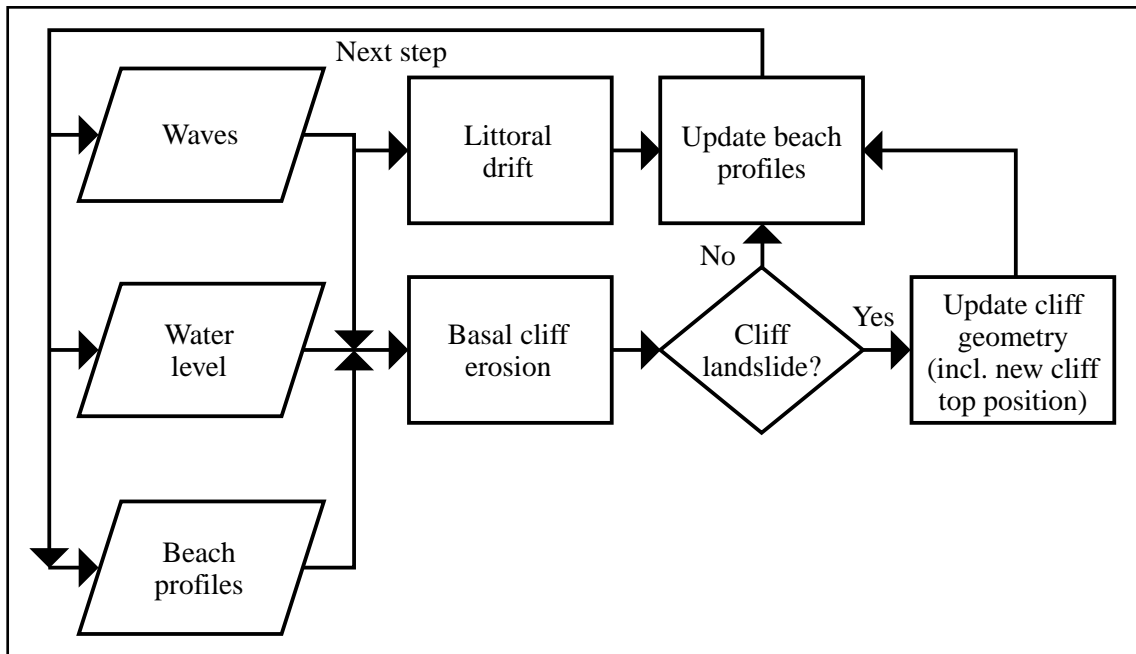
A cliff recession simulation model (*CLIFFPLAN*) was developed as part of this study (Meadowcroft et al. 1999; Hall et al. 2000b; Walkden et al. 2001; Lee et al, in press). The *CLIFFPLAN* model uses random sampling of the input parameters from probability distributions (Monte Carlo simulation) to represent uncertainty in the cliff recession process, with the output also being expressed as a probability distribution. The output probability distribution is built up by calculating the model result many times, each time selecting precise values of the input parameters at random from the input probability distributions. Each model run (each ‘realisation’ of the model) will generate a precise output, but after many realisations it will be possible to generate a histogram, and hence probability distribution, of the outputs.

*CLIFFPLAN* is a time-stepping model, which produces a time series of cliff locations during the model run. The time-step has been set to 12.44hrs, corresponding to the tidal cycle. There are thus 704 time steps per year. Each simulation consists of predictions of cliff behaviour for a number of years into the future. The model can carry out numerous simulations to build up a probabilistic picture of future cliff behaviour. The number of simulations needed to obtain statistically valid results is determined by trial, and depends on the level of confidence required.

The main processes are (Figure 23):

- wave transformation and breaking as waves approach the shore;
- longshore sediment transport on the beach;
- shore platform lowering and recession, if a shore platform exists;
- wave removal of material from the toe of the cliff (usually only during storm);
- cliff landsliding, which is governed by the geometry, groundwater and strength of the cliff.





**Figure 23 Diagrammatic Representation of the CLIFFPLAN Model**

For each time-step the littoral drift and run-up on the shore platform or beach is calculated. If the run-up reaches the toe of the cliff then material can be removed from the cliff toe. A slope stability calculation is then carried out to establish whether the removal of material at the cliff toe or the groundwater conditions at that time-step have destabilised the cliff sufficiently to cause a landslide event. If a landsliding event takes place the cliff geometry is updated and a volume of sediment is delivered onto the beach. A sediment budget calculation is used to update the beach alignment.

Three-dimensional behaviour, and hence cliff planshape evolution, is achieved by modelling a series of interacting cross-sections. Modelling long-shore sediment movements on the beach produces this interaction. Moreover, the emerging shoreline will influence the degree to which waves are refracted as they approach the coast, also introducing three-dimensional influences. Diffraction effects of large irregularities in the shoreline are not currently included in the model, which should therefore be considered to be applicable for gently curving shorelines only.

Further details can be found in the Technical Report (Lee and Clark 2002).

## 5.8 Empirical Modelling of Sea Level Rise

Although there is much uncertainty about the impact of sea level rise and climate change, it is expected to result in increased recession rates. A number of simple empirical models are available to provide an indication of the possible changes:

1. *Historical projection*; where future recession rates are extrapolated as follows (National Research Council 1987; Leatherman 1990):

$$\text{Future recession rate} = \frac{\text{Historical recession rate}}{\text{Historical sea level rise}} \times \text{Future sea level rise}$$

The model is very simple, but assumes that sea level rise is the dominant influence on recession.

2. *Geometric models*; where sea level rise is assumed to result in the parallel retreat of the cliff profile (Bruun 1962), albeit with a corresponding rise in elevation of the cliff foot. This geometric relationship forms the basis of the *Bruun Rule* for deriving the shoreline response to sea level rise i.e. the additional recession (R) above the historical rate.

$$R = S \times \frac{L}{P(B+h)}$$

where:  $S$  = sea level rise  
 $h$  = closure depth  
 $P$  = Sediment Overfill  
 $L$  = Length of CBU profile  
 $B$  = Cliff height

The *sediment overfill* function is the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium profile.

3. *Sediment Budget methods*; the Bruun Rule is essentially two-dimensional (onshore-offshore) and assumes that longshore sediment inputs and outputs are equal and equivalent, a condition rarely achieved in reality. To model reliably the three-dimensional situation, a full sediment budget needs to be calculated for the littoral cell being considered. If it is assumed, however, that the historical recession rate represents the net contribution to the sediment budget, the Bruun Rule (see above) can be modified to predict the recession increase due to sea level rise (R) as follows (Dean 1991):

$$R = R_1 + Sc \times \frac{L}{P(B+h)}$$

where:  $R_1$  = historical recession rate  
 $Sc$  = change in rate of sea level rise

The *change in sea level rise* is the difference between the historical and future sea level rise. This is believed to be the most realistic adaptation of the Bruun Rule for eroding cliffs (Bray and Hooke 1997).

4. *Shore Platform Geometrical Model*; where no beach is present to dissipate wave energy, direct relationships may be formulated to predict recession according to material strength and wave power (e.g. Sunamura 1992). Additional erosion (R) can be estimated from the amount of sea-level rise and the gradient of the shore platform, as follows (Sunamura 1988):

$$R = R_1 + \frac{Sc}{h(R_1 + L)}$$

These empirical models have been applied by Bray and Hooke (1997) to estimate cliff sensitivity to sea level rise in southern England up to the year 2050 (Table 12), using:

- *historical recession rates* obtained from maps, aerial photographs and ground survey;
- *contemporary sea level rise* estimated from mean sea level analysis of tide gauge records (Woodworth 1987; Pugh 1990).
- *future sea level rise* obtained from model estimates to 2050 (Wigley and Raper 1992).
- the *sediment overfill factor* estimated from the geological literature, together with cliff sediment sampling at some sites.
- the *closure depth* estimated as being twice the maximum wave height for a 50 year return period (Bruun 1988), and derived from extreme wave analysis.
- the *length of active cliff profile* measured from hydrographic charts by using the closure depths to indicate their seaward limits of CBUs.
- *cliff height* measured from Ordnance Survey Maps.

<b>Table 12 Parameters and Results for Empirical Modelling of Recession Rates at Sites on the South Coast of England (after Bray and Hooke 1997).</b>								
<b>Location</b>	<b>R<sub>1</sub> m/yr</b>	<b>S<sub>1</sub> m/yr</b>	<b>S<sub>2</sub> m/yr</b>	<b>P %</b>	<b>L* m</b>	<b>h* m</b>	<b>B m</b>	<b>Rb m</b>
Black Ven 1901-1960	0.38	0.002	0.006	18	4000	18	160	21
Black Ven 1958-1988	2.24	0.002	0.006	18	4000	18	160	125
Stonebarrow	0.4	0.002	0.006	19	3000	18	140	22
Seatown/Eype	0.3	0.002	0.006	50	3000	18	88	17
Hengistbury Head	0.8	0.002	0.006	52	4000	13	30	45
Becton 1869-1968	0.85	0.002	0.006	45	4000	13	25	48
Becton 1958-1993	2.14	0.002	0.006	45	4000	13	25	120
Bouldnor	0.61	0.003	0.007	15	800	10	60	34
Blackgang	0.41	0.002	0.006	40	4000	18	130	23
Hill Head	0.2	0.005	0.009	83	1000	10	9	11

<b>Table 12 (cont..)</b>						
	<b>Historical Trend</b>		<b>Bruun Rule</b>		<b>Shore Platform</b>	
	<b>R-2</b>	<b>R-2050</b>	<b>R-2</b>	<b>R-2050</b>	<b>R-2</b>	<b>R-2050</b>
Black Ven 1901-1960	1.14	64	0.88	49	1.27	71
Black Ven 1958-1988	6.72	376	2.74	153	3.13	175
Stonebarrow	1.2	67	0.8	45		
Seatown/Eype	0.9	50	0.53	29		
Hengistbury Head	2.4	134	1.52	85		
Becton 1869-1968	2.55	143	1.79	100		
Becton 1958-1993	6.42	360	3.08	172		
Bouldnor	1.42	80	0.91	51	0.94	53
Blackgang	1.23	69	0.68	38		
Hill Head	0.36	20	0.45	25		

Notes:  
 $R_1$  = Historical backscar recession       $S_1$  = Rate of contemporary sea level rise  
 $S_2$  = Mean rate of future sea level rise to 2050  
P = % of cliff sediments stable on the active shore profile  
 $L^*$  = Length of active profile       $H^*$  = Closure depth  
B = Cliff height       $R_b$  = Historical recession rate  
R-2 = Future retreat for addition sea level rise of 0.22m by 2050  
R-2050 = Total retreat by 2050

An alternative approach to empirical modelling is the calculation of *static equilibrium bay forms* (Hsu et al 1989, also see CIRIA 1996a box 8.6). This method does not allow the prediction of recession rates or the time required to develop a stable bay. However, it does give a useful indication of the area of cliffline that is likely to be vulnerable to recession and is a valuable tool in determining the potential effects of coastal engineering works on the adjacent coastline (e.g. headland control). The method is most likely to provide realistic results on coasts where the cliffs are relatively uniform, notably in material strength and structure.

## 5.9 Interpretation and Presentation of Results

Awareness of the uncertainty and variability inherent in the recession process is essential; we do not know the future sequences of initiating events, the cliff response may be chaotic and the consequences dependent upon a variety of non-technical factors. The results obtained from the prediction models should, therefore, be treated as best estimates and not definitive statements. It is also important that the predictions are kept under review, by means of an appropriate measurement and monitoring strategy, and updated when necessary.

As discussed for measurement and monitoring, the results need to be interpreted within the context of the contemporary and anticipated CBU behaviour. Short-term predictions of cliff top recession can be misleading when the CBU evolves through episodic events occurring, on average 100 years or so. Ideally predictions should cover at least one complete recession “cycle”; the pragmatic guidance on the medium term steady-state timescales provided earlier is equally relevant here, as are the alternative approaches to expressing predicted recession rates.

Cliff recession data and predictions can be presented in a variety of ways, including:

1. *Tabular form.*

2. *Graphical form*, including:

- annual and cumulative measured recession;
- cliff profile measurements;
- plots of cliff recession simulations and predictions;
- probability density functions of the cliff position at a given time;
- probability density functions for the time required for cliff recession to reach a given point (Figure 22).

3. *Map form*; showing at an appropriate scale:

- the best estimate of cliff position after a given time including confidence limits and prediction limits;
- a zoning based on the cumulative probability distribution of cliff recession over a given time (Figure 24). For example:

*Zone 1;* It is certain that land within this zone will be affected by recession within a given time period.

*Zone 2;* There is a 50% chance that land within this zone will be affected by recession within a given time period.

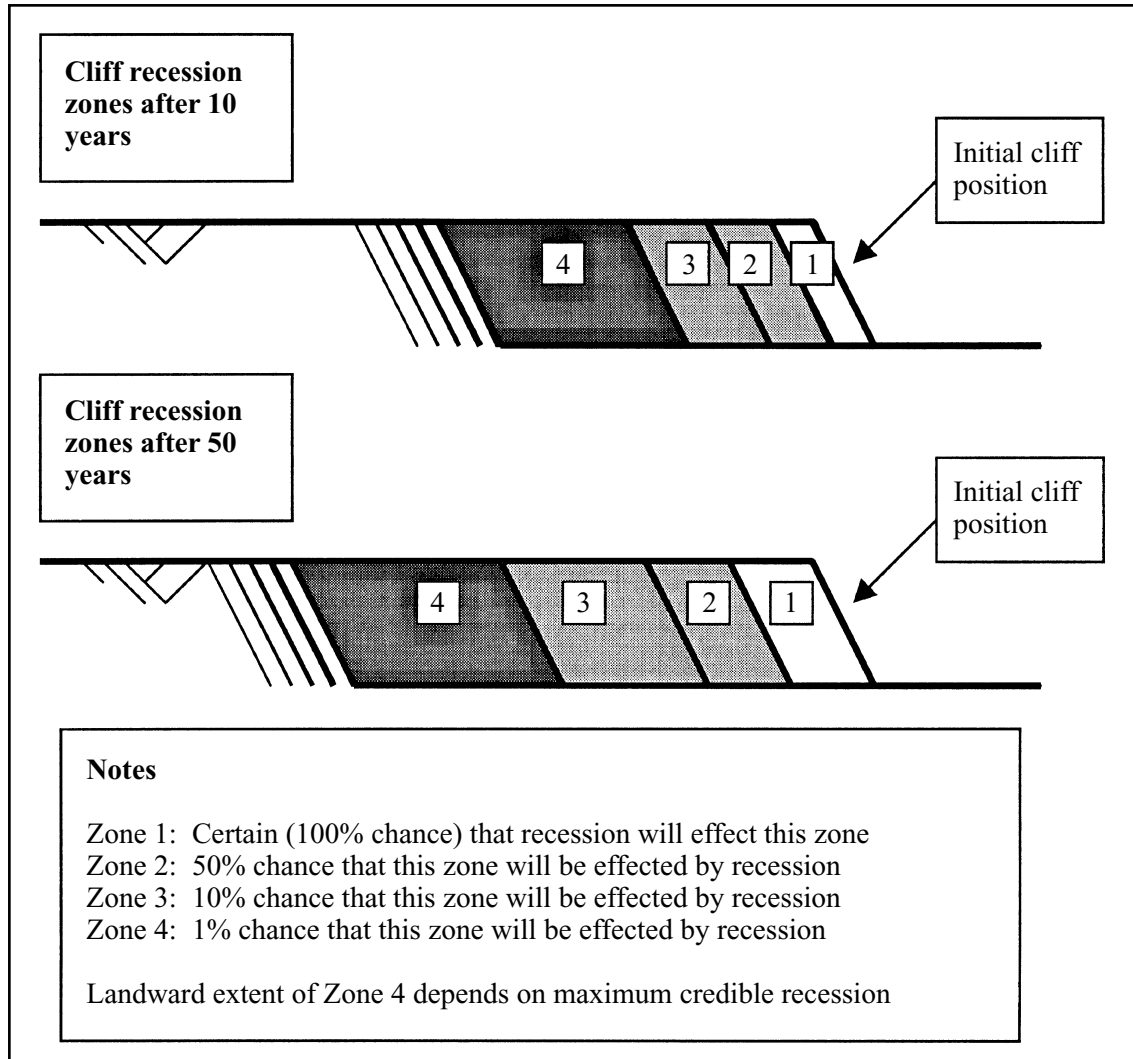
*Zone 3;* There is a 10% chance that land within this zone will be affected by recession within a given time period.

*Zone 4;* There is a 1% chance that land within this zone will be affected by recession within a given time period.

Note that the probabilities that define the zone divisions are arbitrary and can be varied to suit the purpose. More detail (i.e. more zones) may be justified in areas with more assets at risk. This form of presentation does not differentiate between different locations within the same zone, although in reality properties at the landward and seaward extent of a zone will have different probabilities of being affected by recession.

The probabilities and locations of zone boundaries can be obtained from many of the prediction methods outlined in this Chapter. For example, the boundary between Zone 2 and Zone 3 (Figure 24) is at the location where there is a 10% probability of land being lost by recession in or before the year in question.

The boundaries of the zones will progressively shift inland in response to ongoing recession, so periodic reviews are advisable. In addition, the basis for zonation may need to be modified in the light of recent cliff behaviour i.e. the predictions themselves need to be kept under review.



**Figure 24 Zoning of the Cumulative Probability of Cliff Recession over a Given Time**

## CHAPTER 6      EROSION CONTROL TECHNIQUES

Where property, services and infrastructure are at risk from cliff recession it may be appropriate to consider the feasibility of halting or reducing the rate of erosion. A wide range of techniques is available which draw from long standing experience of coastal engineering (e.g. CERC 1984) and slope stabilisation (e.g. Hutchinson, 1977; 1984a; Bromhead, 1986). Every cliff recession problem will be unique, because of the great range of CBU forms and processes and the inherent variability of the cliff materials. Solutions, therefore, need to reflect site conditions and cannot be provided “*off-the-shelf*”.

The selection of suitable techniques needs to be based on an understanding of the coastal forcing elements (waves, tides, surges etc.) and the causes of the cliff instability, which may include:

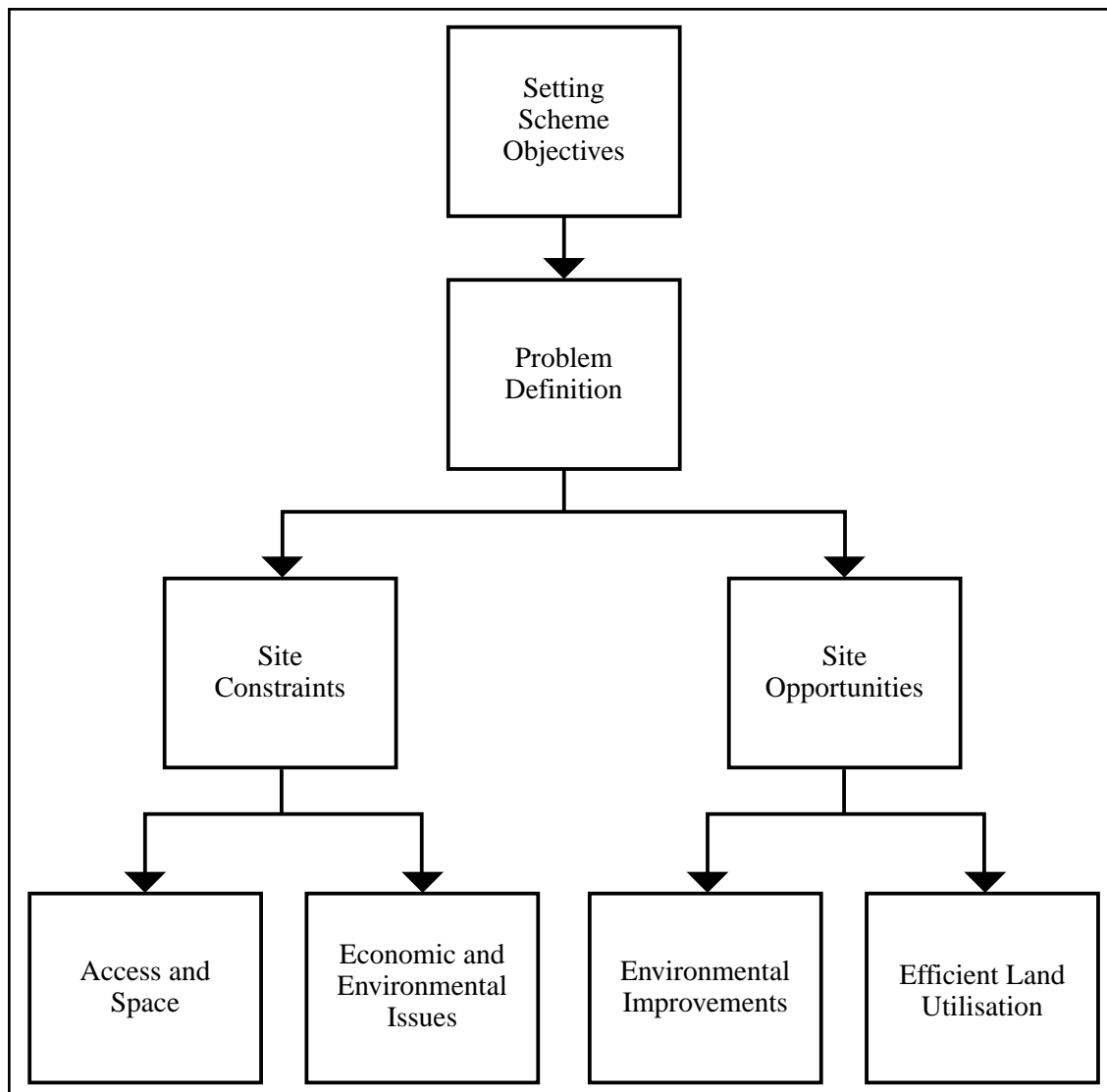
- the slope actively being undercut by wave action. This may be compounded by beach depletion or foreshore lowering;
- the slope is too high or too steep for the materials of which it is composed;
- the materials are too weak to sustain the slope at its present angle;
- the porewater pressures within the slope are too high and, thus, are adversely affecting the soil strength;
- the slope is affected by external influences such as loading at the crest.

In most instances these factors are interrelated and there will be a range of options for erosion control. However, as marine erosion will be fundamental to most cliff recession problems, the preferred option will typically include some form of toe protection to prevent or reduce wave attack. Secondary treatment measures, involving slope stabilisation, will often be needed to prevent the deterioration of the protected cliffs (Hutchinson 1983; McGown et al 1988). The combination of methods adopted and their relative importance will depend on the type of cliff, the nature of the recession mechanism, the ground materials, the level of risk to coastal assets and, increasingly, the need to maintain or enhance environmental resources.

### 6.1      Factors Influencing Scheme Selection

The key to scheme selection (Figure 25) is the identification and clear definition of the scheme objectives. In general terms, these may include:

1. To *prevent* (i.e. stop) or *reduce* (i.e. slow down) cliff recession.
2. To *minimise the risks* associated with land instability, e.g. reactivation of pre-existing landslides or rock fall activity.



**Figure 25 A Summary of the Issues Relevant to Scheme Selection**

The evaluation of potential options and combinations of options needs to be based on an awareness of the problems within different elements of the CBU and their interrelationships. These may include:

- foreshore lowering and beach loss;
- cliff foot erosion;
- active landsliding, seepage erosion and surface erosion within the CBU;
- the presence of pre-existing landslides;
- unstable or potentially unstable rear cliff faces.

Suitable scheme options will also need to reflect the constraints imposed by site factors and the role of the CBU within the relevant littoral cell (Financial considerations and environmental impacts are discussed below). Access to coastal cliffs is invariably difficult and can lead to problems during the evaluation and design of schemes and during construction. Access issues are central to buildability of different scheme options and may involve consideration of the following:



- obtaining agreements from landowners to access, use and reinstate private land;
- obtaining agreements and special requirements for the disconnection and reinstatement of services from statutory undertakers or utilities;
- upgrading of local and private roads to accommodate construction traffic;
- removal of vegetation to gain access to and across the site;
- construction of temporary and permanent access roads to and across the site;
- establishing a site compound and compliance with regulations, such as the Environmental Protection Act 1990;
- consideration of access for plant and delivery and storage of materials across the site, particularly on steep slopes and beneath sea cliffs;
- the need for barges, navigation agreements and insurance to deliver plant and materials on the foreshore beneath high sea cliffs;
- consideration of health and safety aspects with access and working on the foreshore. Temporary coffer dams may be required to protect plant and site staff from tides etc.
- consideration of poor ground and working conditions related to timing and weather fluctuations;
- health and safety issues;
- site security and fencing.

The *available space* behind the cliff top is often a key constraint to the design and construction of slope stabilisation works. Where such works are justified, it is often the case that property and buildings are situated immediately behind the cliff top, often ruling out cliff reprofiling as a viable option. In cases where property and buildings are set back from the cliff top, coast protection and slope stabilisation measures may be difficult to justify on economic grounds.

The stability of *temporary works* is a key consideration in the design and planning of any coast protection scheme. Of particular concern is the possible effect of excavation at the base of a cliff to accommodate the foundations of a seawall or rock armour revetment; the construction of trenches for slope drainage or shear keys can also be a critical element in a works programme. Should the temporary works not be adequately supported an excavation may lead to the failure of the cliff or reactivation of a pre-existing landslide.

Scheme selection should also take into account potential opportunities to enhance the utility or value of the CBU or surrounding area. Examples include:

- combined coast protection and sewage treatment works (e.g. the recent Lyme Regis scheme; Cole and Joy 1994);
- improve public access to the foreshore or cliffs, through providing promenades along the cliff foot (e.g. at Bournemouth; Lelliott 1989 and at Whitby, Clark and Guest 1991) or footpaths up or across the coastal slopes (e.g. at Scarborough, Clark and Guest 1994 and Donderry, Cornwall, Frith 1994);
- the provision or improvement of public amenity beaches (e.g. at Monk's Bay, Isle of Wight; Andrews and Powell 1993).

## 6.2 Toe Protection

Many different techniques have been used to provide cliff toe protection in England and Wales and overseas. In general, they can best be categorised as follows (Table 13):

<b>Table 13 Types of Toe Protection.</b>
<p style="text-align: center;"><b>Direct Protection Against Wave Attack</b></p> <ul style="list-style-type: none"><li>• concrete and masonry seawalls</li><li>• sloping asphalt walls</li><li>• sand mortar filled bags</li><li>• gabion baskets</li></ul>
<p style="text-align: center;"><b>Direct Protection - Wave Energy Dissipation</b></p> <ul style="list-style-type: none"><li>• rock revetments</li><li>• concrete armour units</li><li>• timber palisades</li><li>• gabion baskets, Reno mattresses</li><li>• detached breakwaters</li><li>• shore connected breakwaters</li><li>• beach sills</li></ul>
<p style="text-align: center;"><b>Dynamic structures</b></p> <ul style="list-style-type: none"><li>• beaches and groynes</li><li>• rock beaches</li><li>• headlands and pocket beaches</li></ul>

1. *Direct protection against wave attack;* In general these are shore parallel structures which are set close to the cliff toe and whose crest level is such that the amount of wave overtopping is strictly controlled. These include seawalls and revetments constructed of various materials including concrete, rock, timber, asphalt concrete, gabions etc.
2. *Direct protection by means of wave energy dissipation;* In general these are also shore parallel structures or ones angled obliquely to the coastline and which are designed to reduce wave action (but unlikely to eliminate it) at the cliff toe. These include offshore breakwaters that reduce incident wave energy by means of dissipation and diffraction. They also include low crested sills that attenuate wave energy by tripping waves offshore of the beach. The sills can also be set well up the beach face, in which case they are “redundant” structures, except under the most severe wave and tidal conditions.
3. *Dynamic structures;* Dynamic structures are based on the principle that the best method of protection is a gradually sloping beach, which will allow waves to break their energy before reaching the cliff toe. Such a beach will continue to adjust to changes in the wave conditions both in terms of its cross-sectional profile and its longitudinal (i.e. plan) shape. Dynamic structures (including sand or shingle beaches, or mobile rock beaches) therefore require management in terms of containment (by groynes or artificial headlands) or by active redistribution of material (by means of longitudinal recycling or by means of cross-shore profiling).

<b>Table14 A Summary of the Suitability of Different Toe Protection Measures</b>	
<b>Method</b>	<b>Comment</b>
Seawalls	<ul style="list-style-type: none"> <li>• not suited to CBUs comprising pre-existing landslides involving base-failure, unless designed to incorporate toe weighting.</li> <li>• not suited to CBUs where cliffs are prone to toe failure, unless in combination with slope stabilisation measures.</li> <li>• not suited to CBUs prone to foreshore erosion.</li> </ul>
Revetments	<ul style="list-style-type: none"> <li>• rock revetments suited to most CBUs except those prone to base failure, unless incorporating toe weighting.</li> <li>• timber palisades not suited to CBUs developed in soft sands, silts and clays which can be washed out, unless the aim is to reduce rather than prevent recession.</li> <li>• sand bags, rubber tyres, gabions etc. not suitable on exposed coastlines, unless the aim is to provide short term, temporary protection.</li> </ul>
Offshore Breakwaters and Beach Sills	<ul style="list-style-type: none"> <li>• not suitable on coastlines where the disruption of sediment transport would lead to a significant increase in the levels of risk, or damage to conservation/amenity sites elsewhere.</li> </ul>
Groynes	<ul style="list-style-type: none"> <li>• not suitable on coastlines where the disruption of sediment transport would lead to a significant increase in the level of risk, or damage to conservation/amenity sites elsewhere.</li> <li>• not suited to CBUs with an episodic delivery of large volumes of sediment on the foreshore.</li> </ul>
Rock Beaches	<ul style="list-style-type: none"> <li>• not suited to sites prone to large scale slope failure, unless in combination with slope stabilisation measures i.e. more suited to sites affected by small-scale failure, surface erosion or weathering.</li> </ul>
Headlands etc.	<ul style="list-style-type: none"> <li>• largely untested, probably best suited to rapidly eroding simple cliffs.</li> </ul>

Table 14 provides an indication of the suitability of these measures to different CBUs and coastal settings. In general, most are suitable in a wide variety of cliff types, although a number of important issues need to be considered when selecting the most appropriate measures:

- the inflexible nature of concrete seawalls make them vulnerable to damage caused by movement associated with deep-seated landslides;
- the potential for the disruption of sediment transport, especially relevant when considering the use of structures away from the immediate cliff foot;
- the limited durability and effectiveness of “low cost” measures such as sand bags, rubber tyres, gabions etc., especially on exposed coastlines;
- the potential environmental effects of the various measures (Table 15).

Guidance on the general application and detailed design of toe protection structures can be found in:

- Manual on the Use of Rock in Coastal and Shoreline Engineering (CIRIA/CUR 1991)
- Guide to the Use of Groynes in Coastal Engineering (Fleming 1990; CIRIA 1990)
- Beach Management Manual (CIRIA 1996a)
- Seawall Design (Thomas and Hall 1992)
- Old Waterfront Walls (Bray and Taltham 1992)
- Coastal Defence and the Environment (Pethick and Burd 1993)
- Shore Protection Manual (CERC 1984; US Army Corps 1998)
- Engineering Design Guidance for Detached Breakwaters as Shoreline Stabilisation Structures (CERC 1993)

### 6.3 Slope Stabilisation

Slope stabilisation measures are essential where potential landslides could damage any works at the toe of the slope, if development or structures are cited on coastal slopes or where recession of the cliff threatens cliff-top development. The main objective of stabilisation or preventive measures generally comprises one or more of the following (see Hutchinson, 1977; Gedney and Weber 1978; Bromhead, 1986; Holtz and Schuster 1996):

**Table 15 A Summary of the Environmental Impacts Commonly Associated with Different Toe Protection Measures**

	Scour and Foreshore Erosion	Terminal Scour	Increased Pore Pressure behind Structure	Disruption of Sediment Transport	Deposition behind structure	Trapping of litter, seaweed etc.	Change in Foreshore Character and Habitats	Visual Intrusion	Loss of Amenity of Foreshore
Seawalls and Impermeable Revetments	●	●	●				●	●	○
Permeable Revetments		○				●	●	●	●
Offshore Breakwaters		○		●	●	●	●	●	○
Beach Sills				○	●	●	●	●	●
Groynes	○	○		●		●	●	●	○
Rock Beaches						●	●	●	●
Headlands		○		●		●	●	●	●

● potential significant impact ○ potential impact

- reducing pore water pressure in slopes through surface and sub-surface drainage;
- reducing de-stabilising forces by reprofiling cliff or landslides;
- increasing stabilising forces by adding weight to the toe of an unstable area or by increasing the shear resistance along the failure surface;
- supporting unstable areas by construction of retaining structures;
- preventing the erosion of exposed slopes and cliffs.

The main methods of slope stabilisation employed on coastal slopes are:

- slope profiling by excavation and/or filling;
- drainage;
- retaining structures;
- soil reinforcement;
- surface erosion control;
- slope vegetation.

The selection of appropriate engineering measures is crucial to effective slope stabilisation. The scope of works may vary in their suitability to different CBUs in respect of variations in failure mechanisms, ground conditions and financial and other constraints. The manner in which stabilisation measures are designed and implemented is also important to the success of the works as incorrect placement of fill and drainage, for example, can lead to a reduction in the stability of slopes. It should also be realised that the design of coastal slope stabilisation measures can only be achieved with a thorough detailed investigation of the CBU; because of the nature of cliffs and variability of ground conditions, virtually every slope design problem is unique.

#### **6.4 Prevention or Reduction in Recession Rates**

On many soft cliffs it is desirable to slow down rather than stop marine erosion. This is particularly so where the cliffs are significant sources of littoral sediment or of conservation importance for their scenic value, wildlife habitats or geological features (Leafe and Radley 1994; Lee et al 2001a). Many of the methods of toe protection and slope stabilisation described earlier could form part of a scheme whose objective is recession reduction. For example, the crest heights of a revetment, breakwater or sill could be designed to permit overtopping by lower waves than would normally be the case, thus allowing cliff toe erosion to continue; beach management could be used instead of seawalls.

An alternative strategy might be to protect only part of an eroding frontage. This might be achieved, for example, by building a series of nearshore rock breakwaters, which would shelter the cliffs directly in their lee from wave action, but would allow almost unchanged wave attack in the gaps between the structures. If the breakwaters were arranged to protect the most valuable cliff-top assets, then benefits of the scheme may reduce much less rapidly than its cost. At the same time, the unprotected stretches of cliff would continue to erode, maintaining at least some of the environmental benefits of cliff recession.

There are, however, a number of potential drawbacks to adopting a recession reduction strategy:

- it is difficult to determine a target rate of erosion that is acceptable to both property owners and conservationists. This is because there is no simple relationship between wave attack and cliff foot erosion rate. In addition, it is difficult to design a scheme that would deliver the target reduction in recession rate with any degree of confidence due to the unpredictable nature of cliff recession;
- the cost of these recession reduction schemes may not decline as rapidly as their efficiency. Indeed, the performance of such schemes could be severely restricted if much of the erosion of the unprotected CBU was in response to large waves or prolonged wet periods i.e. the scheme may control the regular small-scale recession events but not the less frequent larger events;
- many CBUs may not adjust immediately to changes in the rate of cliff foot erosion i.e. there may be lag in their response before recession slows down. This will be particularly important in complex and some composite CBUs where the effects of reduced erosion may take many years to be transmitted back through the cliff system. It follows, therefore, that short-term recession reduction measures may only be viable on simple cliffs and some simple landslide CBUs where the response will be more direct and, hopefully, immediate;
- changes in the rate of cliff foot erosion may increase the uncertainty inherent in the recession process, potentially making prediction less reliable i.e. overall recession may be reduced but the natural variability in recession rate may actually increase;
- it is generally assumed that erosion reduction will maintain the conservation interest. But many soft cliffs are very sensitive to wave attack and there could be a significant reduction in landsliding even when only a limited amount of protection is provided. Once a slope is no longer seasonally active it can become heavily vegetated and degraded.

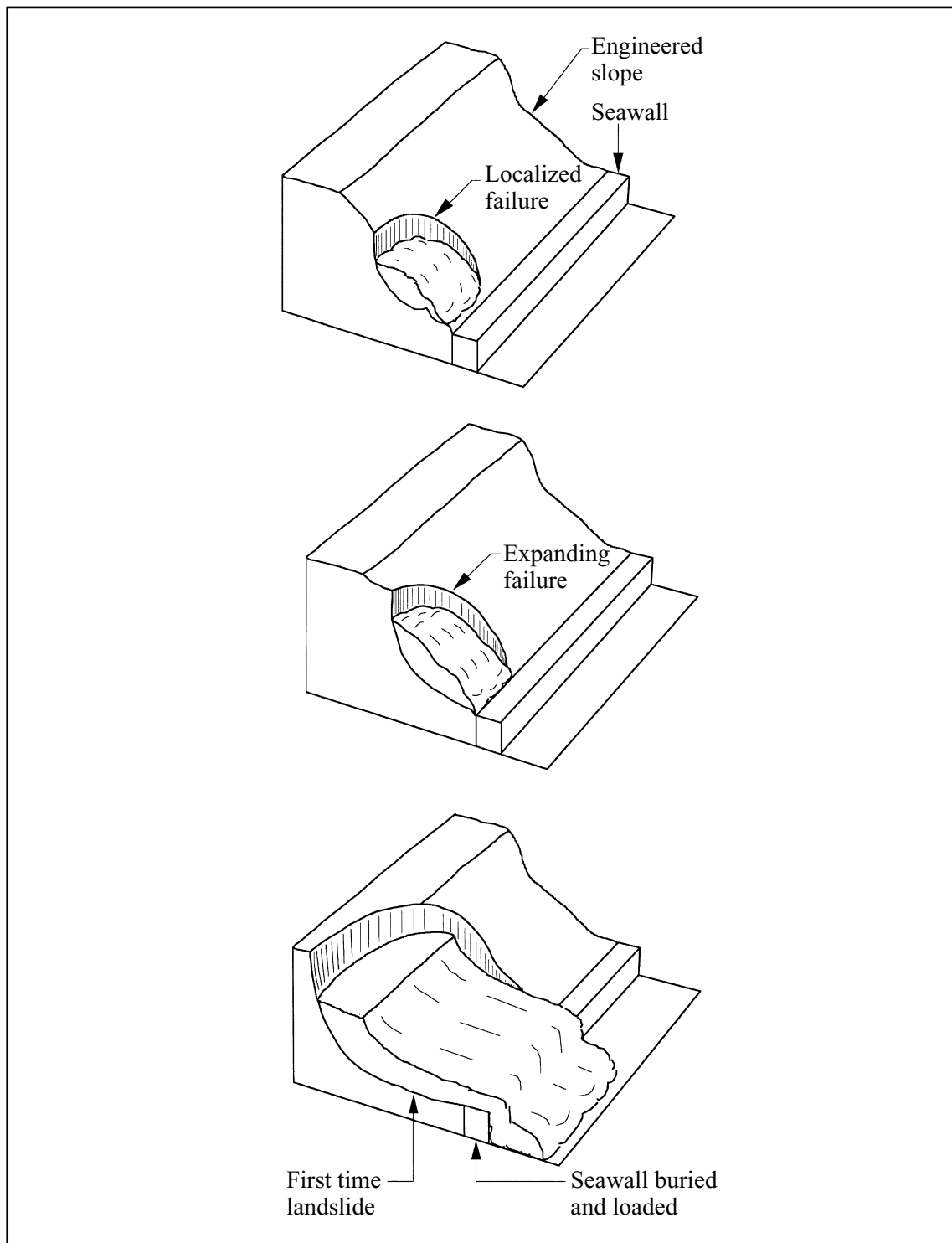
## **6.5 Management of Protected Cliffs**

For many protected cliffs, the construction of seawalls to prevent marine erosion was not accompanied by regrading or specific slope stabilisation works. Where landscaping and drainage works were undertaken these were often superficial treatments, as in Scarborough's South Bay. Whilst it is clear that the construction of seawalls has reduced the likelihood of major slope instability it has not eliminated the potential for failure.

Although landscaping the cliffs and related drainage works appear to have controlled the rate of slope degradation through shallow slides, such failures can continue to be prevalent on many protected cliffs. Indeed slope drainage can contribute to local instability problems; for example, drains damaged by ground movement or blocked by sediment and vegetation debris may lead to localised high groundwater levels and, hence a reduction in stability. It is not uncommon, therefore, for protected cliffs to show signs of continued instability; this generally involves small-scale failures, but occasionally large events do occur, as at Holbeck Hall, Scarborough (Clark and Guest 1994), Overstrand (Frew and Guest 1997) and Barton on Sea (Clark et al 1976).

It is now recognised that the stability of protected cliffs may gradually decline with time, introducing the potential for delayed failures. The main factors will include:

- the recovery of depressed pore water pressures;
- strain-softening, weathering and progressive failure;
- deterioration of drainage systems.



**Figure 26 An Illustration of the Potential Consequences of the Expansion of Small Scale Failures on an Intact Coastal Cliff**

The potential consequences of such large-scale events are self evident, often presenting a significant threat to the structural stability of the seawalls or other toe protection structures. It should also be appreciated that small-scale failures may, under certain circumstances, lead progressively to the decline in overall stability, resulting in an increase in the likelihood of a larger event. Such an event could damage the toe protection and result in a renewal of marine erosion of the cliff foot and a loss of cliff top assets (Figure 26).

Structural failure of the toe protection can be caused by ground heave and horizontal ground movements; this type of problem is associated with deep-seated landslides such as at Barton-on-Sea and Scarborough's North Bay (Rendel Geotechnics 1994). In other cases, structures may be buried or loaded by debris from rock falls or slope failures, e.g. the Overstrand landslide of 1993 (Frew and Guest 1997) and the Holbeck Hall landslide (Clark and Guest 1994).

<b>Table 16 Possible Maintenance Requirements for Certain Slope Stabilisation Options</b>	
<b>OPTION</b>	<b>MAINTENANCE PROBLEMS</b>
Re-profiling	<ul style="list-style-type: none"> <li>• settlement of fills;</li> <li>• desiccation cracks;</li> <li>• ponding;</li> <li>• vegetation cover.</li> </ul>
Drainage	<ul style="list-style-type: none"> <li>• clogging of ditches;</li> <li>• siltation of filters, pipes and culverts etc.;</li> <li>• pipe breakages;</li> <li>• seepage erosion at outlets;</li> <li>• root penetration into drains;</li> <li>• outlet blockages and back-pressuring of drains;</li> <li>• leaking pipes;</li> <li>• precipitation of ferric oxides, calcite, tufa etc.</li> </ul>
Retaining Structures	<ul style="list-style-type: none"> <li>• displacement of structure, including settlement and shearing;</li> <li>• leaning and bulging of structure;</li> <li>• undermining;</li> <li>• over-topping;</li> <li>• decay of structural element e.g. wire gabion baskets;</li> <li>• drainage behind wall.</li> </ul>
Soil Reinforcement	<ul style="list-style-type: none"> <li>• lime diffusion and leaching rates.</li> </ul>
Erosion control	<ul style="list-style-type: none"> <li>• vegetation establishment;</li> <li>• performance of meshing, bolting and scaling.</li> </ul>



## **6.6 Monitoring and Maintenance**

Post construction monitoring and maintenance of coast protection and slope stabilisation works is essential. Maintenance in this context may broadly be defined as the routine works or repairs necessary to maintain the performance and function of coastal engineering works. An important aspect of maintenance is the need for routine monitoring (e.g. of pore water pressures, signs of slope movement, beach levels etc.) to identify potential problems early enough to enable their repair before the performance of the scheme is seriously impaired. This is particularly true of subsurface drainage measures as siltation of pipes and chambers can lead to a rapid decline in the effectiveness of slope stabilisation which, in turn, may lead to renewed failure of the coastal cliff. Table 16 provides a brief summary of the potential problems and maintenance requirements of a range of slope stabilisation measures.

Potential problems should be identified early enough to allow repair before it is too late. Individual failures on a protected cliff need to be assessed in terms of their potential for deterioration and the likely consequences. With experience, this may involve no more than a site inspection of small-scale slides, but could require detailed site investigation for larger failures. Where necessary, individual failures should be treated by remedial measures. The selection and design of such measures should follow an appropriate level of site investigation.

Maintenance of coastal engineering works needs to be carried out in the wider context of cliff management as the performance and design life of schemes may be influenced by development activities and natural processes acting upon or adjacent to the site. Cliff management should take into account conditions throughout an entire CBU as well as those affecting specific sites within a CBU. Of particular importance is the need to be aware of

- the impact of slope and foreshore processes on the integrity of seawalls;
- the effect of development and land use (including existing surface water drainage) on slope conditions;
- the impact of the cumulative effects of small scale events on overall slope instability.

## **6.7 Monitoring of Cliff Management Strategies**

Global warming and sea level rise could have significant effects on cliff recession and coastal landsliding. Changing patterns and rates of recession could result in modifications to the level and extent of risks. In other circumstances, the use of non-structural measures may be a temporary strategy, until the level of risk reaches a critical threshold value. It is important, therefore, that cliff management strategies are regularly reviewed and updated to take account of changing conditions. This may involve assessing the suitability and effectiveness of non-structural solutions when the shoreline management plan or development plan is reviewed.

## CHAPTER 7 ECONOMIC EVALUATION

The decision to invest in coast protection works depends on a thorough appraisal of scheme options, costs and benefits over the expected lifetime of the scheme (MAFF 1993a, 1999b). The benefits of coast protection are the difference between the losses that would be incurred without a scheme and the delayed losses that would be incurred when the scheme fails and marine erosion is renewed. Thus, a scheme with a design life of 50 years will increase the value of the assets at risk by 50 years i.e.

Coast Protection Benefits = With Project Asset Value - Without Project Asset Value

Hence, the economic benefit of coast protection is the value of the risk reduction that a scheme is expected to achieve.

The benefit-cost ratio is the ratio of these economic benefits to the costs of a particular scheme option. If the benefit-cost ratios of all of the project options are less than unity (i.e. they have a negative Net Present Value) then the 'without project' scenario is the most efficient in economic terms. Only if the benefit-cost ratio (BCR) of an option exceeds unity is investment economically justifiable (but will not necessarily attract resources, as schemes are compared nationally and prioritised; MAFF 2001). If more than one option has a BCR that exceeds unity then under most circumstances the option with the greatest BCR is chosen.

In order to quantify the potential benefits, it is necessary to identify the consequences of a range of recession scenarios. These may include.

- loss of cliff top property and land;
- ground movement damage to property and services on the slopes;
- burial or displacement of cliff foot structures e.g. seawall, roads and buildings;
- injury or death.

Indirect losses (e.g. loss of tourism revenue, traffic disruption etc.) and intangible losses (e.g. stress and ill health) may also be relevant considerations. *Consequence assessment* is based on an understanding of possible recession scenarios and the vulnerability of the exposed assets or people.

On the protected coast the *residual life* of the existing defences can be a critical factor in economic evaluation. For example, where significant cliff top assets are at risk from a renewal of erosion, the justification of an improvement scheme may rest almost entirely on the estimated residual life and an assessment of the consequences of failure.

Principles relating to the economic evaluation of coast protection schemes have previously been presented by MAFF (1993b). The approach is *deterministic* and assumes that the year of expected property loss (E) and the scheme life (S) can be readily defined (e.g. Penning-Rowse et al 1992). In practice, and as stressed throughout this document, both the year of loss and scheme life is uncertain. Indeed, on many cliffs, especially those where recession is markedly episodic, the uncertainty in the year of loss may be considerable. An alternative approach would be to adopt a

*probabilistic* framework for the economic evaluation, drawing upon the probabilistic prediction methods described earlier (see also Hall et al 2000a). A series of possible approaches have been developed as part of this study and are presented below.

If a probabilistic framework is adopted, it is possible to calculate the losses associated with different recession and coast protection scenarios, as follows:

$$\text{Erosion Losses} = \text{Probability of Damaging Event} \times \text{Asset Value}$$

The present value (PV) of the losses in a particular year (year T) can be calculated as follows:

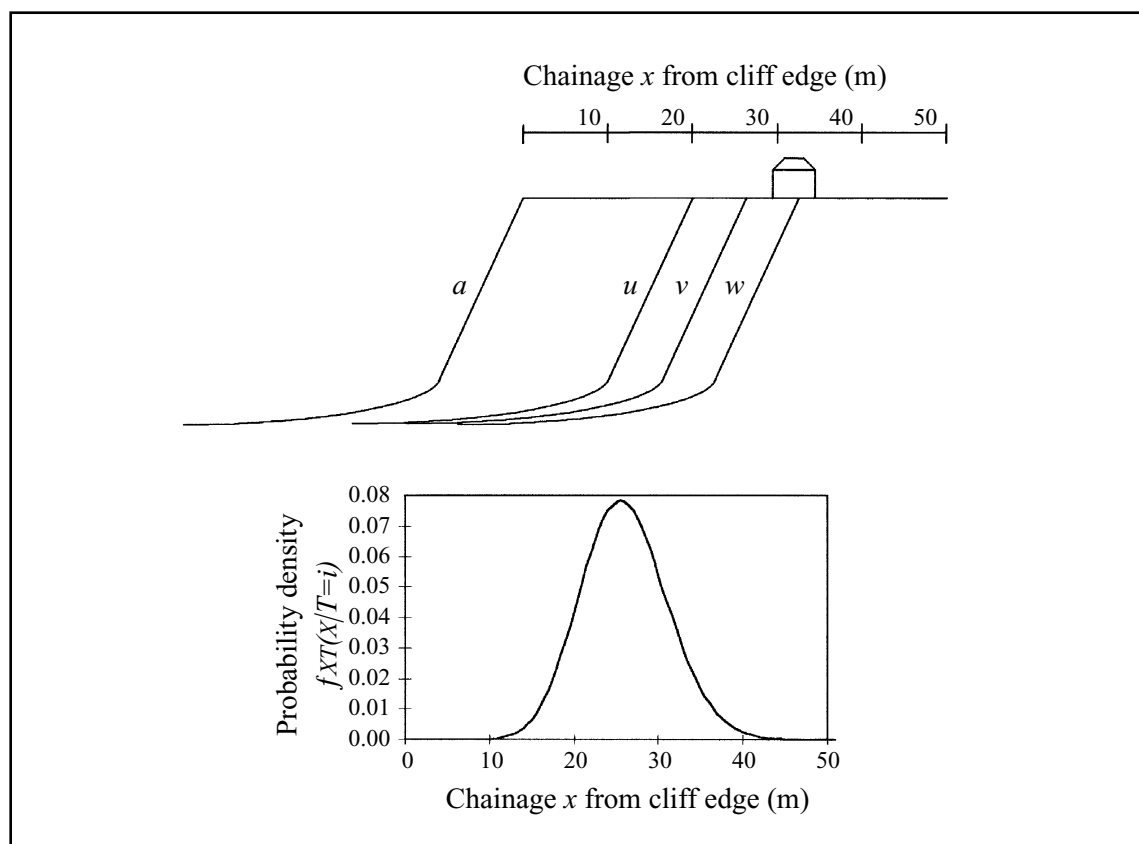
$$\text{PV losses (Year T)} = \text{Prob. (event, Year T)} \times \text{Asset Value} \times \text{discount factor (Year T)}$$

The PV of losses associated with recession over a 50-year period are the sum of the annual losses (Year 1 - 50).

As coast protection only reduces, and cannot eliminate, the probability of these losses, the scheme benefits are:

$$\text{Coast Protection Benefits} = \text{Without Project Losses} - \text{With Project Losses}$$

Considering appraisal of erosion control options in probabilistic terms enables analogies to be drawn with flood defence.



**Figure 27 An Example of the Probability of Cliff Recession Reaching a Single Property (from Hall et al 2000)**

Considering the scenario where a cliff top asset is at threat from gradual recession (albeit at some unsteady rate), the probability of damage varies with time and location. The probability density function (p.d.f.)  $f_{XT}(x, i)$  is the probability of damage at distance  $x$  from the cliff edge during year  $i$ , where  $f$  is a function of a distance random variable  $X$  and a time random variable  $T$ . For the purposes of benefit assessment  $T$  is considered to be a discrete random variable measured in years.

An eroding coastal cliff and a single cliff-top house is illustrated in Figure 27. Profile a shows the current cliff position; three of the many possible future locations are labelled in as  $u$ ,  $v$  and  $w$ . If erosion has proceeded to profile  $w$  the asset will have been destroyed, whereas if it has proceeded only as far as profile  $u$  or  $v$  it will not. The p.d.f. of cliff location in a particular year ( $T = i$ ),  $f_{XT}(x|T = i)$  is shown on the same horizontal scale as the cliff cross-section. Thus in a probabilistic analysis the conventional erosion contour for year  $i$  is distributed into a band of erosion risk. The contour of predicted average recession lies at the mean of the distribution. The probability  $P_i$  of damage to the house before or during year  $i$  is given by

$$P_i = \int_0^d f_{XT}(x|T = i) dx$$

where  $d$  is the distance of the house from the cliff edge.

The more convenient representation for the purposes of benefit assessment is the distribution of the predicted year of loss for assets at a given distance  $x$  from the cliff edge. The p.d.f.  $f_{XT}(i|X = x)$  can be entered directly into the discounting table to obtain the probability weighted sum of the damage risk, i.e.

$$PV(\text{damage}) = MV = \sum_{i=0}^j \frac{f_{XT}(i|X = x)}{(1+r)^i}$$

where  $j$  is the appraisal period.

Thus, the *present value* (PV) of the loss in any year is calculated as follows:

$$PV(\text{damage Year } i) = \text{Probability of loss} \times \text{Asset value} \times \text{Discount factor}$$

The overall present value losses are:

$$PV(\text{damage Year } 0-49) = \sum \text{Probability of loss} \times \text{Asset value} \times \text{Discount factor}$$

Table 17 shows an example of the probabilistic discounting procedure for a house with a risk-free market value of £100k situated 10m from the edge of an eroding cliff using an illustrative probability distribution (obtained using the 2-distribution probabilistic method described earlier). According to the probabilistic discounting procedure the PV damage risk is £29.6k.

**Table 17 Probabilistic Discounting for a Single Cliff-Top Asset (from Hall et al 2000a)**

<b>Year i</b>	<b>Discount factor</b>	<b>Prob. of damage in year i</b>	<b>PV damage £k</b>
0	1.00	0.000	0.00
1	0.94	0.002	0.18
2	0.89	0.002	0.19
3	0.84	0.005	0.39
4	0.79	0.006	0.47
5	0.75	0.010	0.73
6	0.70	0.011	0.75
7	0.67	0.013	0.89
8	0.63	0.018	1.11
9	0.59	0.019	1.10
10	0.56	0.024	1.34
11	0.53	0.023	1.20
12	0.50	0.024	1.20
13	0.47	0.028	1.32
14	0.44	0.032	1.42
15	0.42	0.032	1.34
16	0.39	0.033	1.30
17	0.37	0.035	1.29
18	0.35	0.035	1.22
19	0.33	0.035	1.14
20	0.31	0.037	1.15
21	0.29	0.033	0.98
22	0.28	0.035	0.97
23	0.26	0.033	0.87
24	0.25	0.032	0.79
25	0.23	0.030	0.70
26	0.22	0.031	0.68
27	0.21	0.029	0.60
28	0.20	0.030	0.58
29	0.18	0.027	0.50
30	0.17	0.025	0.44
31	0.16	0.022	0.36
32	0.15	0.021	0.33
33	0.15	0.021	0.30
34	0.14	0.019	0.26
35	0.13	0.018	0.23
36	0.12	0.017	0.21
37	0.12	0.016	0.19
38	0.11	0.013	0.14
39	0.10	0.013	0.13
40	0.10	0.012	0.12
41	0.09	0.009	0.08
42	0.09	0.011	0.10
43	0.08	0.008	0.06
44	0.08	0.009	0.07
45	0.07	0.008	0.06
46	0.07	0.007	0.04
47	0.06	0.006	0.04
48	0.06	0.006	0.04
49	0.06	0.004	0.02
		Total PV risk (£k):	29.62

Notes:

1. Risk-free market value of asset = £100k
2. Discount rate = 6%
3. Distance of asset from cliff edge = 10m

<b>Table 18 Summary of Discounted Asset Values for Multiple Assets and Different Erosion Control Options (from Hall et al 2000a)</b>							
Property/utility	Distance from cliff edge (m)	Market value (£k)	Damage risk value with different protection options (£k)				
			Option 1	Option 2	Option 3	Option 4	Option 5
Trunk gas main	7	450	252	183	152	84	12
1-5 Acacia Ave	8	350	184	132	111	62	7
Cafe	10	120	62	43	30	26	1
“Sunnyview” B	11	180	81	61	49	29	4
Sewage PS	12	2300	940	675	555	315	47
Hightrees House	13	1500	585	417	343	195	25
2-8 Acacia Ave	17	400	136	99	75	44	7
“The Saltings”	18	76	26	17	14	8	0
14-20 Rococo Blvrd	21	850	165	122	100	67	9
Total PV risk (£k)			2431	1749	1429	830	112
Erosion control benefit (£k)				682	1002	1601	2319

The “with project” losses can be calculated in the same manner, assuming that the scheme simply delays the recession scenario by a specified time (usually taken as 50 years). The uncertainty in the life of the proposed scheme can also be accommodated in a probabilistic framework that is fed into the project appraisal.

Where multiple cliff-top assets are at risk the above methodology can be repeated for each of the assets. Table 18 summarises the analysis for a hypothetical case. It shows how predictions of risk for various erosion control scenarios, ranging from the without project Option 1 to a high standard of protection in Option 5, can be summarised. Note, however, that each of the options has some residual risk.

Some coastal cliffs are prone to very large infrequent landslides, in which case economic appraisal involves evaluating the probability of a single event rather than the progressive erosion of assets. The suggested method is similar to the conventional approach for evaluating the benefit of schemes designed to reduce the risk of a breach in a flood defence i.e.:

$$PV (\text{losses, Year } i) = \text{Probability of Landslide} \times \text{Asset value} \times \text{Discount factor}$$

$$PV (\text{losses Year } 0-49) = \sum \text{Probability of loss} \times \text{Asset value} \times \text{Discount factor}$$

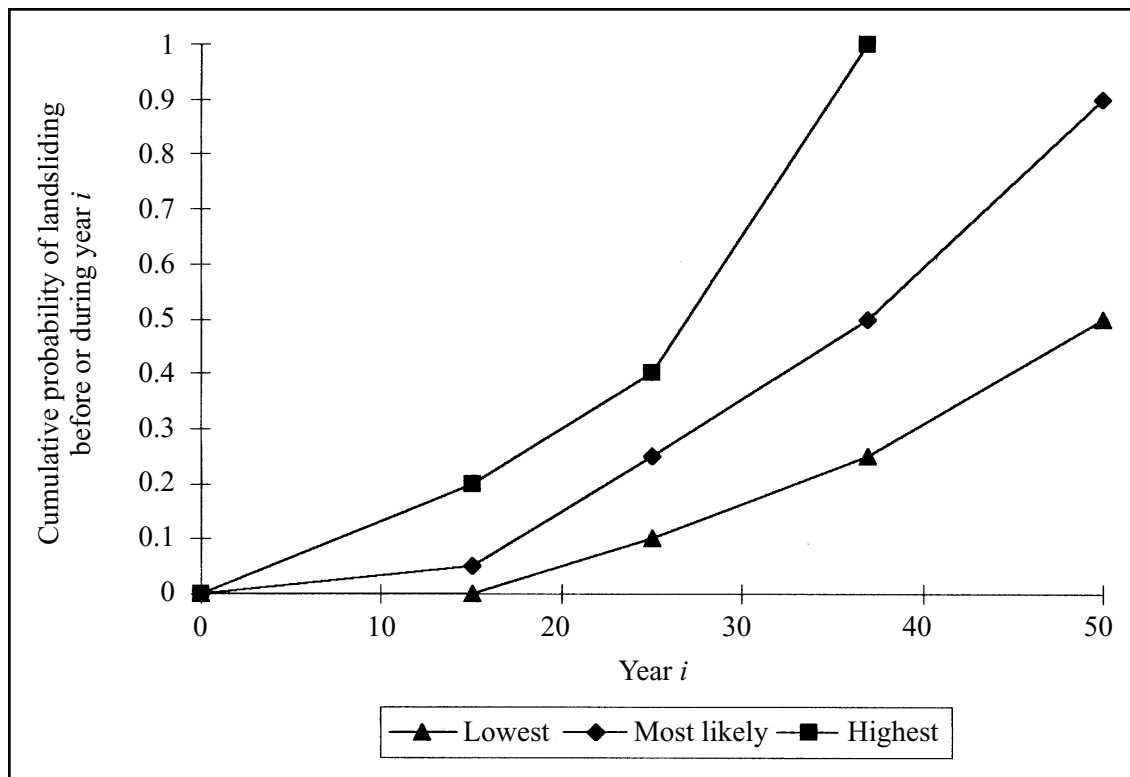
It is based on an estimate of the risk of complete destruction of all the assets in the hazard zone. The coast protection benefit is the difference between the estimated risk for the ‘without project’ scenario and the residual risk of damage for the scheme options (i.e. the options only reduce the probability of the landslide, not eliminate it).

This situation is illustrated by reference to a site where a large landslide is predicted to result in loss of property, services, amenity and environmental interests with a risk-free market value of £6.4 million. There is considerable uncertainty relating to when the predicted landslide will take place if no further works are done to protect the cliff.

Most likely, lowest and highest estimates of the landslide probability (derived from engineering judgement; Figure 28) for the without project scenario were used to provide 3 different scenarios (Table 19).

<b>Table 19 Probabilistic Discounting for a Single Landslide Event (from Hall et al 2000a)</b>										
<b>Year</b>	<b>Discount Factor</b>	<b>Lowest Estimate</b>			<b>Most Likely Estimate</b>			<b>Highest Estimate</b>		
		<b>Cumulative Probability of Damage</b>	<b>Probability of Damage in Year i</b>	<b>PV Damage £k</b>	<b>Cumulative Probability of Damage</b>	<b>Probability of Damage in Year i</b>	<b>PV Damage £k</b>	<b>Cumulative Probability of Damage</b>	<b>Probability of Damage in Year i</b>	<b>PV Damage £k</b>
0	1.00	0.000	0.000	0.00	0.003	0.003	19.84	0.013	0.013	80.00
1	0.94	0.000	0.000	0.00	0.006	0.003	18.88	0.025	0.013	75.47
2	0.89	0.000	0.000	0.00	0.009	0.003	17.81	0.038	0.013	71.20
3	0.84	0.000	0.000	0.00	0.012	0.003	16.80	0.050	0.013	67.17
4	0.79	0.000	0.000	0.00	0.016	0.003	15.85	0.063	0.013	63.37
5	0.75	0.000	0.000	0.00	0.019	0.003	14.95	0.075	0.013	59.78
6	0.70	0.000	0.000	0.00	0.022	0.003	14.11	0.088	0.013	56.40
7	0.67	0.000	0.000	0.00	0.025	0.003	13.31	0.100	0.013	53.20
8	0.63	0.000	0.000	0.00	0.028	0.003	12.55	0.113	0.013	50.19
9	0.59	0.000	0.000	0.00	0.031	0.003	11.84	0.125	0.013	47.35
10	0.56	0.000	0.000	0.00	0.034	0.003	11.17	0.138	0.013	44.67
11	0.53	0.000	0.000	0.00	0.037	0.003	10.54	0.150	0.013	42.14
12	0.50	0.000	0.000	0.00	0.041	0.003	9.94	0.163	0.013	39.76
13	0.47	0.000	0.000	0.00	0.044	0.003	9.38	0.175	0.013	37.51
14	0.44	0.000	0.000	0.00	0.047	0.003	8.85	0.188	0.013	35.38
15	0.42	0.000	0.000	0.00	0.050	0.003	8.35	0.200	0.013	33.38
16	0.39	0.010	0.010	25.19	0.070	0.020	50.39	0.220	0.020	50.39
17	0.37	0.020	0.010	23.77	0.090	0.020	47.53	0.240	0.020	47.53
18	0.35	0.030	0.010	22.42	0.110	0.020	44.84	0.260	0.020	44.84
19	0.33	0.040	0.010	21.15	0.130	0.020	42.31	0.280	0.020	42.31
20	0.31	0.050	0.010	19.96	0.150	0.020	39.91	0.300	0.020	39.91
21	0.29	0.060	0.010	18.83	0.170	0.020	37.65	0.320	0.020	37.65
22	0.28	0.070	0.010	17.76	0.190	0.020	35.52	0.340	0.020	35.52
23	0.26	0.080	0.010	16.76	0.210	0.020	33.51	0.360	0.020	33.51
24	0.25	0.090	0.010	15.81	0.230	0.020	31.61	0.380	0.020	31.61
25	0.23	0.100	0.010	14.91	0.250	0.020	29.82	0.400	0.020	29.82
26	0.22	0.113	0.013	17.58	0.271	0.021	29.31	0.450	0.050	70.34
27	0.21	0.125	0.013	16.59	0.292	0.021	27.65	0.500	0.050	66.36
28	0.20	0.138	0.013	15.65	0.313	0.021	26.08	0.550	0.050	62.60
29	0.18	0.150	0.013	14.76	0.333	0.021	24.61	0.600	0.050	59.06
30	0.17	0.163	0.013	13.93	0.354	0.021	23.21	0.650	0.050	55.72
31	0.16	0.175	0.013	13.14	0.375	0.021	21.90	0.700	0.050	52.56
32	0.15	0.188	0.013	12.40	0.396	0.021	20.66	0.750	0.050	49.59
33	0.15	0.200	0.013	11.69	0.417	0.021	19.49	0.800	0.050	46.78
34	0.14	0.213	0.013	11.03	0.438	0.021	18.39	0.850	0.050	44.13
35	0.13	0.225	0.013	10.41	0.458	0.021	17.35	0.900	0.050	41.63
36	0.12	0.238	0.013	9.82	0.479	0.021	16.37	0.950	0.050	39.28
37	0.12	0.250	0.013	9.26	0.500	0.021	15.44	1.000	0.050	37.05
38	0.11	0.271	0.021	14.57	0.533	0.033	23.30	1.000	0.000	0.00
39	0.10	0.292	0.021	13.74	0.567	0.033	21.99	1.000	0.000	0.00
40	0.10	0.313	0.021	12.96	0.600	0.033	20.74	1.000	0.000	0.00
41	0.09	0.333	0.021	12.23	0.633	0.033	19.57	1.000	0.000	0.00
42	0.09	0.354	0.021	11.54	0.667	0.033	18.46	1.000	0.000	0.00
43	0.08	0.375	0.021	10.88	0.700	0.033	17.41	1.000	0.000	0.00
44	0.08	0.396	0.021	10.27	0.733	0.033	16.43	1.000	0.000	0.00
45	0.07	0.417	0.021	9.69	0.767	0.033	15.50	1.000	0.000	0.00
46	0.07	0.438	0.021	9.14	0.800	0.033	14.62	1.000	0.000	0.00
47	0.06	0.458	0.021	8.62	0.833	0.033	13.79	1.000	0.000	0.00
48	0.06	0.479	0.021	8.13	0.867	0.033	13.01	1.000	0.000	0.00
49	0.06	0.500	0.021	7.67	0.900	0.033	12.28	1.000	0.000	0.00
		PV total risk (£k):			482			1075		1875

Notes:  
1. Risk-free market value of assets = £6.40million  
2. Discount rate = 6%



**Figure 28** Estimated Probabilities for a Major Landslide Event Having Occurred (from Hall et al 2000)



## CHAPTER 8 CLIFFS AND NATURE CONSERVATION

### 8.1 Environmental Significance

Eroding cliffs may also be of considerable environmental significance for their biological, earth science and landscape value. The main benefits of cliff recession are (Lee 1995; Lee et al 2001a):

1. *Creating and maintaining the landforms which support important habitats.* Numerous threatened species are found in cliff settings (e.g. Mitchley and Malloch 1991), such as hoary stock (*Matthiola incana*) found only on eroding chalk cliffs. Maritime grasslands occur on many cliffs and slopes, often comprising a maritime form of red fescue (*Festuca rubra*), thrift (*Armenia caroids*), sea plantain (*Plantago caroids*) and sea carrot (*Daucus carota ssp gummifer*). Soft cliffs and associated slopes provide important breeding sites for sand martins (*Riparia riparia*) and are particularly important for invertebrates such as the ground beetle *Cincindela germanica*, the weevil *Baris analis* and the Glanville fritillary butterfly (*Melitaea cinxia*). Seepages, springs and pools provide habitats for Shore Dock, as well as many species of solitary bees and wasp, the craneflies *Gonomyia bradleyi* and *Helius hispanius*, and the water beetle *Sphaerius caroids* (Wicks and Cloughley 1998).
2. *Stimulating change within cliffs through promoting instability* and ensuring that habitats evolve through natural successions, rather than remaining static. Many active landslides support a range of vegetation from pioneer communities on freshly exposed faces through grassland communities to scrub and woodland. Wet flush vegetation occurs in areas of seepage.
3. *Providing important geological exposures*, including international reference localities for vast periods of geological time, such as the Bartonian Stratotype between Highcliffe and Milford Cliff in Hampshire. Cliffs also provide opportunities for geological and geomorphological teaching and research.
4. *Creating landscapes of great cultural importance and scenic attractiveness.* Cliffs are amongst the nation's greatest landscape assets with many safeguarded by their inclusion in National Parks and AONB's or through their status as heritage coasts. At present around 1525km of coast in England and Wales has heritage coast status, with public enjoyment encouraged by the provision of recreation activities that are consistent with the conservation of the natural scenery and heritage features.

### 8.2 Cliffs and Habitats

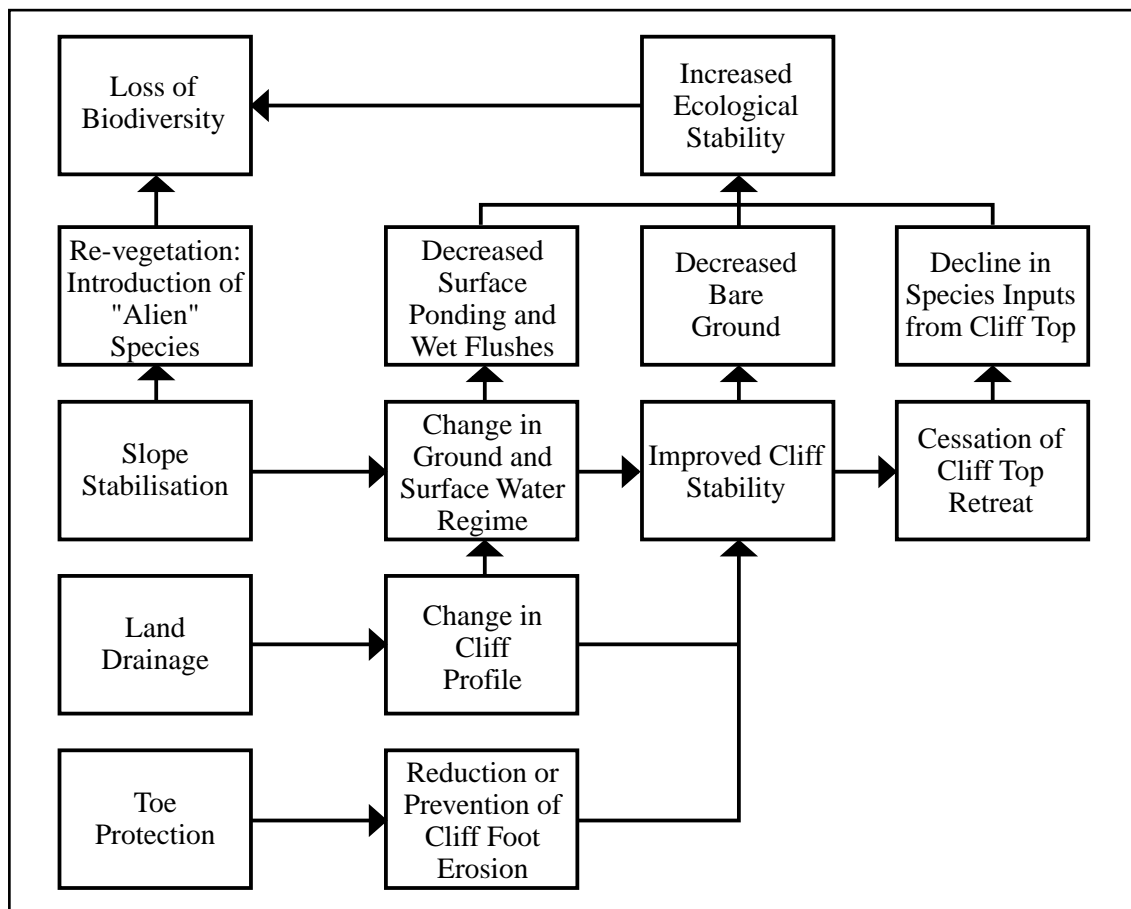
Maritime cliffs and slopes are the third ranked priority habitat in the UK in terms of the number of associated priority species (Simonson and Thomas 1999). A total of 36 priority species are associated with this habitat, with a further 59 priority species recorded as using the habitat. Often these are amongst the most natural habitats in Britain, not relying on active management to maintain the habitat mosaics and species diversity. However, each cliff will be unique because of the overwhelming influence of site conditions on the recession process. The biological value of eroding cliffs can vary with cliff type, with the characteristic habitats a product of the ground conditions (i.e.

geological, soil type and drainage), the input from salt-spray, the microtopography (i.e. exposure), the character of and connectivity with cliff top communities (i.e. the input of species onto the cliff face) and the continued instability.

Salt-spray from breaking waves is often the dominant control on exposed cliffs, overriding the importance of lithology and soils variation (Rodwell 2000). The west and south coasts are more exposed to wave attack and, hence, appear to have a better developed maritime cliff vegetation than along the eastern coast. Spray deposition declines rapidly with the distance from the breaking waves. On the Lizard (Cornwall), for example, Malloch (1972) demonstrated that only 100m inland deposition rates were less than 20% of those at the cliff edge and, after 500m, deposition was very low. Such gradations tend to create pronounced vegetation zones on sea cliffs, from the more maritime crevice communities through grasslands to heath, scrub and inland vegetation.

### 8.3 Impact of Coast Protection on Biodiversity

Maritime cliffs and slopes are a priority habitat, supporting large numbers of priority species (see Appendix B; Simonson and Thomas 1999). However, over the last 100 years or so some 860km of coast protection works have been constructed to prevent coastal erosion (MAFF 1994; this figure probably includes some low-lying areas prone to erosion). It has been estimated that there remain some 255km of unprotected soft cliff in England (Pye and French 1992).



**Figure 29 A Summary of the Impacts on Biodiversity Associated with Coast Protection (after Lee et al 2001)**

Many coast protection schemes are considered to have had significant impacts on the environment (Figure 29). Seawalls or rock revetments have been built which stop the recession process. Cliff faces have been stabilised by drainage works, regraded and landscaped. As a result, geological exposures have become obscured, hardy grasses of little or no conservation value have replaced bare soil and early pioneer stages, and wet flushes have dried out. A significant proportion of the soft cliff resource has been affected, with loss or degradation of biological sites of national and international conservation value.

Maritime cliff and slope habitats have also been affected by land use changes on the cliff top (e.g. arable farming, caravan parks etc.), reducing the potential for the maintenance of diverse mosaics of species with active links between cliff face and top habitats.

In places, important habitats have developed on protected slopes. At Tankerton, North Kent, for example, the nationally rare plant Hogs Fennel (*Peucedenum officinale*) is abundant on protected, but poorly drained London Clay slopes (Roberts 1989). The cliffs had been protected by a seawall in the 1900s. Elsewhere, coast protection works protect important cliff top habitats that would otherwise be lost because of cliff recession (e.g. Bestowe Hill SSSI, east of Sheringham on the North Norfolk coast).

#### **8.4 The Habitats Directive**

The EC Habitats and Species Directive (the “Habitats Directive”; Council Directive 92/43/EEC) requires member states to designate areas of importance for particular habitats and species as Special Areas of Conservation (SACs). Together with Special Protection Areas (SPAs) designated under the Conservation of Birds Directive (the “Birds Directive”; Council Directive 79/409/EEC), these areas form a Europe-wide series of sites known as “Natura 2000”. In Great Britain the Habitats Directive is implemented through the Conservation (Natural Habitats &c) Regulations 1994 (SI 2716), which employs the term “European Site” to encompass SACs and SPAs.

The Regulations set out measures intended to maintain at, or restore to, a “*favourable conservation status*” those habitats and species designated as SAC/SPA. The conservation status of a habitat is considered to be favourable when:

- its natural range and areas it covers within that range are stable or increasing;
- the specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future;
- the conservation status of its typical species is favourable.

The Directive identifies “Vegetated Sea Cliff of the Atlantic and Baltic coasts” as requiring the designation of SAC. The UK coast supports a significant proportion of the EC sea cliff resource and, to date, 10 lengths of cliffline have been put forward as candidate SACs, including the cliffs of Suffolk, East Devon, West Dorset and the Isle of Wight.

The Government is required to take appropriate steps to avoid the deterioration of the natural habitats and the habitats of species, as well as the significant disturbance of species, along these clifflines. A coast protection scheme that might affect the integrity of the habitats would only be approved if there were imperative reasons of overriding public

interest. In such circumstances compensation measures would be required as part of the scheme e.g. the creation of replacement vegetated sea cliff habitat (e.g. Lee et al, 2001a).

## 8.5 Cliffs and Biodiversity

The Government has set out its commitments to the Convention on Biological Diversity (the Rio Convention) in the document “Biodiversity: the UK Action Plan”. The overall goal is “*to conserve and enhance the biological diversity within the UK and to contribute to the conservation of global biodiversity through all appropriate mechanisms*”. In pursuit of this objective, the Government has published a series of Habitat Action Plans which contain habitat creation and rehabilitation targets. Coast protection authorities have specific High Level Targets in relation to biodiversity. When carrying out works they must aim to ensure that there is no net loss to habitats covered by biodiversity action plans (MAFF 1999a).

The Maritime Cliff and Slope Habitat Action Plan contains five targets, three of which are directly related to coast protection (UK Biodiversity Group 1999):

- to seek to maintain the existing maritime cliff resource of cliff top and slope habitat;
- to maintain wherever possible, free functioning of coastal physical processes acting on maritime cliff and slope habitats;
- to seek to retain and where possible increase the amount of maritime cliff and slope habitats unaffected by coastal defence and other engineering works.

Included within the HAP are a number of proposed actions agreed by various agencies and local government. These proposed actions include:

1. Encourage a presumption against the stabilisation of any cliff face except where human life, or important natural or man-made assets, are at risk.
2. Where stabilisation of a cliff face is necessary, ensure adequate mitigation and/or compensation to maintain the overall quantity and quality of maritime cliff and slopes habitat.
3. Encourage the increased use of soft (e.g. foreshore recharge) rather than hard engineering techniques where some degree of cliff stabilisation is necessary.
4. Consider the non-replacement of defences which have come to the end of their useful life.

The conservation value of Chalk cliffs is also addressed within the Littoral and Sublittoral Chalk HAP which has similar targets:

- seek to retain and where possible increase the existing extent of littoral and sublittoral chalk habitats unaffected by coastal defence and other engineering works;
- allow natural coastal processes to dictate, where possible, the geomorphology of the littoral and sublittoral environment;
- adopt sustainable management practices for all uses on littoral and sublittoral chalk habitats.

In essence, the maritime cliff and slope and the littoral and sub-littoral chalk HAPs have introduced a “no net loss” policy for maritime cliff and slope habitats, with the aspiration of achieving, over time, a “net gain”. The significance of this can be judged from the results of the Coast Protection Survey of England (MAFF 1994). This survey concluded that over 90km of new coast protection works were likely to be needed over the next 10 years (i.e. the period 1994-2004), some of which will inevitably involve protecting currently undefended maritime cliff and slope habitats. If these defences were to be provided there would need to be an abandonment of a matching or greater length of defences elsewhere (Lee 2000, Lee et al 2001a).

## **8.6 Environmental Impact**

The potential environmental impacts of coast protection need to be fully appreciated before a decision is made to defend a cliff; only then can the true benefits of the “do nothing” approach be weighed against the benefits of erosion control. Because of the dynamic nature of the coastline this involves an awareness of the sensitivity of a CBU to change and its functional relationships with other landforms within the littoral cell.

The amenity value of eroding cliffs is also diverse, ranging from the tourism and recreation importance of outstanding coastal scenery and cliff top footpaths, to their scientific and educational benefits.

The potential environmental impact associated with coast protection arises as a result of one or more of the following actions:

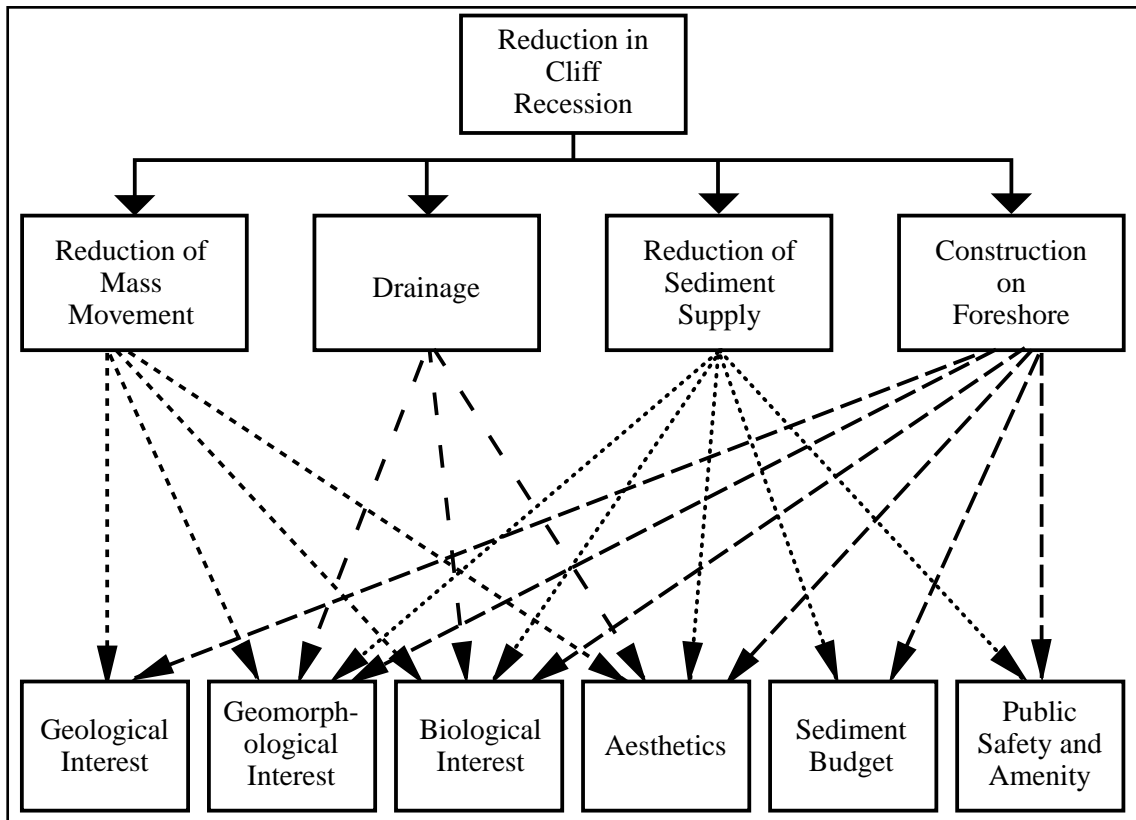
- reduction in the rate of mass movement or erosion activity;
- drainage of the CBU;
- reduction in the supply of sediment to the littoral cell;
- construction on the foreshore or in the nearshore zone.

The relationship between these actions and the resultant impacts is shown on Figure 30. Although the impacts are predominantly negative, coast protection can, in some situations, lead to positive enhancement of aspects of the environment. Most notably these include:

- the protection of fragile and irreplaceable archaeological remains;
- the partial stabilisation of an actively eroding CBU can enhance its value to wildlife by enabling plants to colonise the previously bare slopes;
- enhanced amenity value through improving beach access and reducing the perceived risk of danger. Coast protection schemes can, however, actually increase the risk to public safety by improving the accessibility to the cliff slope and the beach, resulting in more visitors and hence the opportunity for accidents to happen;
- improved aesthetic value; the question of how coast protection affects the aesthetic value of a coastline is very subjective. Schemes that result in gentle, more stable slopes supporting grassland, heathland or woodland may be regarded, by some, as more attractive than cliff faces kept bare by frequent mass failure. To others the loss of the natural condition will be a high price to pay for protecting property.

It may be possible to reduce the magnitude of some adverse environmental impacts by adopting appropriate mitigation measures. These, of course, will need to be considered at a site level but may include:

- *re-creating habitat types*; disturbed sites on cliff slopes are essential for plant primary colonisers, and solitary bees and wasps. Schemes that successfully prevent further cliff recession will eventually cause the elimination of these species. Suitable habitat could be created artificially, for example, by periodically scraping vegetation from a section of the cliff to provide area of bare soil. It may be also possible in most cases to incorporate “environmentally sensitive” reinstatement options such as reinstatement of the topsoil stripped from the site, replacement of endemic and rare plant species, and habitat re-creation such as the lining of existing ponds and surface drains;
- *control of construction methods*; the detrimental effects of coast protection works may to some extent be mitigated by the adoption of good practice. Good construction practice may limit the extent and degree of damage to coastal habitats. This may involve programming the works for certain times of the year and phasing the works to control progress and the amount of plant operating at any time. Use of certain methods, plant or machinery may be less destructive than others and should be favoured where appropriate;
- *maintaining the geological interest*; Schemes that reduce wave action at the cliff foot result in a build up of talus at the base of the cliff that may obscure the exposure. A suitable compromise between combating cliff recession and maintaining geological interest may be removing the talus from a section of the cliff mechanically. An alternative approach could be to leave a stretch of the cliffline unprotected so that the outcrop remains accessible;
- *compensating for the sediment deficit*; the adverse impact that coast protection has on coastal sediment budgets could be combated by artificially recharging beaches with sediment. It should be remembered that this is a long-term obligation and may prove expensive in the long run, (see CIRIA 1996b).



**Figure 30 A Summary of the Principal Impacts of Coast Protection Works**

## CHAPTER 9      IMPLICATIONS FOR COASTAL MANAGEMENT

### 9.1      Shoreline Management Plans

The identification of the appropriate coastal defence policy options for a coastline needs to be supported by, at least, a broad indication of the nature and rate of recession of the various CBUs. This may involve:

- identification and characterisation (in general terms) of CBUs along the coastline;
- analysis of recession rates for each CBU from historical maps and aerial photographs. On extensive coastlines a flexible approach could be adopted to the map analysis, working from 1:1250 or 1:2,500 scale maps in developed areas and 1:10,000/1:10,560 scale maps in undeveloped areas;
- geomorphological assessment to get an indication, in broad terms, of the size and frequency of recession events in each CBU;
- compilation of an inventory of significant past recession events and landslide movements, from historical sources;
- presentation of the results in map form. Because of the generalised nature of the historical recession data CBUs may be best classified according to a range of recession bands (e.g. <0.5m/year, 0.5 - 1.0m/year, >1.0m/year). Consideration could also be given to expressing recession rates in terms of metres/steady timescale for those CBUs which display marked “cyclic” behaviour;
- a review of previous measurement and monitoring strategies, together with an assessment of their effectiveness;
- development of an appropriate measurement and monitoring strategy.

It will be necessary to obtain, at least, a broad indication of the future recession scenarios over the next 50 years or so to support the identification of the coastal defence policy option for a management unit. This may involve:

- identification and characterisation (in general terms) of the CBUs along the coastline. This should include analysis of historical recession rates and geomorphological assessment of cliff behaviour;
- selection of appropriate prediction methods based on the level of risk and the CBU type. In general, simple extrapolations from historical records supported by expert judgement based on an awareness of cliff behaviour will be the most appropriate methods. The empirical models (e.g. the Bruun Model) can provide an indication of the possible effects of sea level rise. Where possible, a probabilistic framework should be adopted to explain the uncertainty in the predictions;
- presentation of the predictions in tabular or graphical form for each CBU, and in map form for individual management units. Because of the generalised and uncertain nature of the prediction, a broad range of potential recession bands might be appropriate (e.g. high, medium and low probability bands);
- development of a procedure to regularly review and, when necessary, update the recession predictions.

The setting of management objectives for the shoreline should consider the need to minimise the disruption of the sediment transport process. This will involve:



- identifying sediment sources, transport pathways and outputs for the littoral cell and establishing a preliminary sediment budget;
- identification of key sources of sediment which are likely to provide a critical contribution to the littoral cell.

The selection of preferred strategic coastal defence options will need to take account of the suitability of each of the generic defence policies (i.e. no active intervention, limited intervention, hold the line, advance the line or managed realignment). This will involve consideration of:

- the level of risk associated with continued recession, based on predictions of recession rate or recession scenarios and an overview of potential consequences. This assessment should also identify the length of time until defence works might need to be undertaken;
- the current and long term stability of protected slopes, taking into account the potential for delayed failures and their possible impact on the defences;
- the potential for structural solutions to cause accelerated erosion or increased flood risk on the adjacent coastline, and their possible impacts on the natural environmental and coastal resources;
- a review of current monitoring and maintenance practices on protected slopes, together with an assessment of their effectiveness;
- the development of a monitoring and maintenance strategy;
- identification of priority areas where a detailed cliff management strategy study may be necessary.

## **9.2 Strategic Studies and Scheme Feasibility Studies**

Reliable cliff recession measurements and CBU investigations are required to define the nature of the erosion problem and identify a suitable range of coast protection and slope stabilisation scheme options. This may involve:

- identification and characterisation of the CBUs in the study area and on the adjacent coastline. Where schemes are being considered for only part of a CBU frontage, it is important that the whole of the CBU is considered at this stage. Failure to do so can lead to mis-diagnosis of the problem;
- detailed analysis of historical recession rates from large scale maps (1:1,250 or 1:2,500 scale, as available) and aerial photographs. It will be necessary in many CBUs to measure the recession of both the sea cliff and the rear cliff, and to note any recorded changes to the CBU form;
- detailed assessment of significant historical events, including a review of potential causes and mechanisms, and the impacts;
- detailed geomorphological assessment of contemporary cliff behaviour;
- development of a cliff behaviour model as a framework for interpreting results and development of future recession scenarios;
- identification of the need to establish a measurement and monitoring programme to supplement the available information and provide interim early warning prior to the scheme construction;
- identification of the need to establish a measurement programme to monitor the effects of the proposed defences on the neighbouring coastline;

- identification of the need to establish a measurement programme to monitor the effectiveness of the scheme in reducing cliff recession.

A range of possible recession scenarios and reliable prediction are required to support the economic appraisal for the various coast protection and slope stabilisation scheme options. This may involve:

- identification and characterisation of CBUs in the study area and on the adjacent coastline, including detailed analysis of historical recession data and the development of a cliff behaviour model;
- selection of appropriate prediction methods, based on CBU type. Where the need to improve or replace existing defences is being considered, the event tree method supported by an understanding of the potential cliff behaviour will probably be most suitable. On the undeveloped coastline, the extrapolation and simple probabilistic methods will be best suited to rapidly eroding simple cliffs. Expert judgement will be needed for all complex and relic CBUs. A probabilistic framework should be developed to express the uncertainty and, where necessary, enable a rational analysis of risk, covering the whole life of a scheme from appraisal to design, construction and deterioration;
- presentation of the predictions as event trees, in graphical form and as detailed maps showing the probability that particular areas will be lost over a range of time periods (e.g. 10, 25 and 50 years);
- identification of the need to model the potential effects of the proposed defences on the neighbouring coastline.

A Strategic Study should involve liaison with the local planning authority, other responsible authorities and interested bodies to ensure that the full range of cliff management options (i.e. structural and non-structural solutions) are considered.

Scheme selection will involve the identification and clear definition of scheme objectives, based on an appreciation of the recession and slope instability problems within different elements of the CBU. Suitable scheme options will also need to reflect the constraints imposed by site factors (e.g. access and space restrictions), the role of the CBU in the littoral cell (e.g. as a key sediment source) and economic and environmental issues. The potential opportunities to enhance the utility or value of the CBU or surrounding area should also be considered. This may involve:

- a thorough investigation of the CBU and, where appropriate, the surrounding area. This may require geomorphological mapping, cliff behaviour assessment, site investigation, laboratory testing, stability analysis, numerical and physical modelling of shoreline processes, and monitoring;
- an environmental scoping study and, if necessary, a formal environmental assessment to identify potential adverse impacts and possible mitigation measures;
- a review of the potential effectiveness of the various elements in the scheme options, involving a combination of expert judgement, numerical modelling, physical modelling and stability analysis;
- economic evaluation of a range of scheme options using, where appropriate, a probabilistic framework for assessing the potential consequences and the timing of losses;
- the development of a monitoring and maintenance strategy for the preferred scheme.

### 9.3 Coastal Planning

The type and quantity of earth science information needed to support coastal planning is described by Rendel Geotechnics (1995a, b; see also Lee 1996) and is summarised below. Such information is needed to ensure that development:

- is not located in areas which are at risk from erosion, land instability, flooding or the deposition of sediment;
- does not affect the natural balance of the coastline to the extent that erosion is caused elsewhere or that coastal defences have to be constructed and maintained;
- is undertaken in a sustainable manner with due regard to the environment.

Planners will generally need guidance on the opportunities for development and redevelopment and the nature of the constraints imposed by cliff recession and coastal landsliding. This information is needed at each stage of the planning process, as follows:

1. *Strategic Planning*; in preparing or revising a development plan the local planning authority will need to:
  - undertake a *general assessment* of the physical conditions along the coastline, through the collection and interpretation of readily available data, as part of the survey of the principal characteristics of their area. This should identify the nature and extent of coastal cliffs;
  - identify the key issues which have implications for planning in each environment, e.g., cliff recession;
  - assess the extent to which the recession process may be affected by and, in particular, constrain uses of land and changes to uses of land;
  - determine which of the factors identified are of great enough significance to require consideration in local plans and Part II of Unitary Development Plans (UDPs).

In a Structure Plan or a UDP Part I, it will normally be sufficient to identify the factors that may need to be taken into account in more detailed strategic planning. Greater detail is required for surveys of principal characteristics of areas covered by local plans or UDPs Part II.

Much of the information required may be provided by the current programme of preparation of shoreline management plans (e.g. predictions of recession rates; analysis of sediment budgets etc.) although the information may need to be edited, adapted, and re-organised for planning purposes.

2. *Land Allocations*; where allocations of cliff top land are identified by local planning authorities in Local Plans and UDP Part II it is important that they should be suitable, in general terms, to be safely developed and that issues which will need to be taken into account by prospective developers are identified. Local planning authorities should, therefore, carry out a *site review* for land which may be allocated for specific uses prior to the next review of the development plan to establish:

- the nature of the ground and any processes which may affect it;
- the significance of any constraints or opportunities for planning and use of the site and, in particular, whether development of the site might lead to slope instability or increased coastal erosion and, thus, a need for improvements to existing defences or new coastal defences, elsewhere;
- the suitability of the land for development and the nature of any coastal defences which might be required before development may proceed. The planning authority needs to be sure that any new defences would be sustainable and not create problems on the adjacent coast.

Information and advice should be sought from local authority coastal engineers and the Environment Agency when assessing the suitability of any coastal land for specific types of development. Here, there is a clear need to ensure that prospective land allocations are consistent with the strategic coastal defence policy option for particular management units, as set out in a shoreline management plan. In this regard, shoreline management plans can be an important mechanism for ensuring close integration between land use planning and coastal defence interests.

3. *Planning Applications*; it is the developer's responsibility to determine that a site is suitable for the proposed use. It is in the developer's interests, therefore, to determine whether the site is in an area that may render it subject to problems which may affect the value of the land and of any development upon it.

In areas defined by the local planning authority as being subject to cliff recession and slope instability, the developer should prepare a *site report* taking account of the perceived problems, and submit it in support of any planning application. In some cases a more extensive environmental assessment may be required e.g. where the proposed development is within or adjacent to a SSSI.

Site reports should be prepared by a suitability qualified expert, or experts, and should take account of all of the relevant physical, environmental and economic factors. Particular issues that may be relevant are whether:

- the land is capable of supporting the load to be imposed;
- the site may be threatened by cliff recession or land instability;
- the development might affect the level of risk on adjacent slopes, or elsewhere along the coast;
- the nature of coastal defence scheme options which might overcome potential problems;
- the mitigation measures that might be used to reduce any undesirable aspects of the proposals.

The local authority should use the report and any other information (e.g. the shoreline management plan) to determine the application. Planners should seek advice on the implications of the report and the suitability of proposed precautionary measures from local authority coastal engineers and the Environment Agency.

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