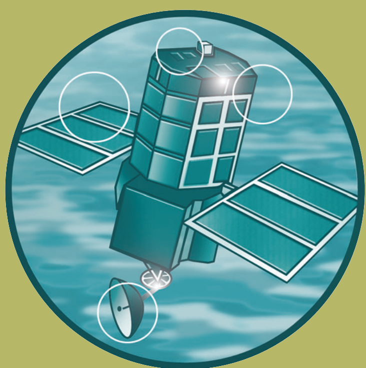
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Risk assessment of coastal erosion Part One

R&D Technical Report FD2324/TR1



Environment Agency

defra
Department for Environment Food and Rural Affairs

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

Risk Assessment of Coastal Erosion Part One

R&D Technical Report FD2324/TR1

Produced: January 2007

Author(s): Halcrow Group Limited

In association with Mark Lee, University of Plymouth and Terry Oakes Associates

Statement of use
This document provides a probabilistic methodology for assessing the hazard and risk of coastal erosion around the coastline of England and Wales. It constitutes an R&D output from the joint DEFRA/ EA Flood & Coastal Defence R&D Programme.

Dissemination status
Publicly available

Keywords
Coastal erosion, defence failure, risk assessment, probabilistic techniques,

Research contractor
Halcrow Group Ltd, Burderop Park, Swindon, Wilts, UK, SN4 OQD.
Tel: 01793 812479

Defra project officer
John Goudie

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
London SW1P 2AL

Tel: 020 7238 3000 Fax: 020 7238 6187

www.defra.gov.uk/environ/fcd

Contents

Part One – Final Report

Executive Summary

Appendices

Executive Summary

The aim of RACE (Risk Assessment of Coastal Erosion) was to develop, test and disseminate a robust and consistent probabilistic method for assessing the hazard and risk of coastal erosion. A method was required that could be supported by data and information from monitoring programmes and risk-based inspections and also be compatible with the RASP (Risk Assessment of flood and coastal defence for Strategic Planning) method used for flood risk assessment.

The methodology that has been developed is based on the source-pathway-receptor risk model. Thus, the various sources of the erosive forces and how they propagate to their point of impact are determined before the magnitude of the effect on receptors is assessed. A range of analytical techniques have been developed, with the choice of which to adopt dependent on the level of detail required for each assessment and the extent and quality of data that is available - this will ensure that proportionate effort is applied at all times, a basic principle of the methodology.

The source data is determined by a range of techniques of varying complexity, as appropriate to the level of analysis being undertaken. These techniques include approaches for assessing the potential failure of coastal defences over time and the unconstrained, natural erosion of the coastal landforms. The pathway stage brings together these two components to establish the hazard, i.e. the probability of erosion taking account of defence influence. The final receptor stage takes the erosion assessment and combines this with spatial (receptor) data to make the risk assessment. The latter stage is being taken forward at a national level by the Environment Agency to produce the National Coastal Erosion Risk Map for England.

The project team was led by Halcrow and included the University of Plymouth, Terry Oakes Associates and Mark Lee (independent consultant). The Client Steering Group was made up of representatives from Defra, the National Assembly for Wales, the Environment Agency, Local Authorities and Academia.

This project is delivered in two parts. Part 1 is the technical report describing the approach that has been developed (this report plus appendices).

Part 2 comprises the tools that enable application of the approach, in the form of:

- Appendix A – Techniques for Assessing Erosion;
- Appendix B – Techniques for Assessing Coastal Defence Failure;
- Appendix C – Hazard Assessment (Probability of Coastal Erosion Spreadsheet) Description;
- Appendix D – CD containing spreadsheets developed to test the methodology.

1 Introduction

1.1 Background

Successful management of the coast requires a clear understanding of the risks of coastal erosion and instability. The importance of understanding and managing these risks is recognised in Defra’s High Level Targets (Output Measures), which require Local Authorities to assess coastal erosion risks and reflect these in their development plans. In recognition of that, this project was undertaken to establish a probabilistic approach to assessing coastal erosion risk.

1.2 Objective

The objective of this project was to develop, test and disseminate a robust and consistent probabilistic method for assessing the hazard and risk of coastal instability and erosion. The method must be supported by data and information from monitoring programmes and risk-based inspections and also be compatible with the RASP method used for flood risk assessment.

1.3 Implementation

This research set out to provide methods suitable for application at a range of scales commensurate with different end user requirements. A key driver for the research was the need to provide coastal authorities with the means to better understand appraise and quantify the coastal erosion risks they manage. As such the tools developed are appropriate for application without requiring expert inputs. Consistent erosion risk evaluation at a local level, fused with ‘high level’ methods, will also benefit National Government in its assessment of coastal erosion risk in the context of the scale and prioritisation of funding.

The outputs would be used to support:

- Informing public safety assessments and planning of necessary improvements;
- Informing the development of SMPs and strategies for their implementation;
- Informing the development of regional and local plans and consideration of planning applications;
- The management of coastal cliff instability and erosion risk.

1.4 *End User Consultation*

End-users have been consulted at various stages of the project.

An initial stage of consultation was undertaken at the start of the project in order to determine how end-users could derive the most benefit from this project. End-users stated that the methodology should have the following characteristics:

- Provide a robust and consistent approach that can be applied by all coast protection authorities;
- Have the ability to aggregate local results to inform national assessments of coastal cliff instability and erosion risk;
- Use information provided from monitoring programmes and risk-based inspections;
- Include a hierarchy of methods, to allow for proportionate effort;
- Map of hazards and risks, together with associated probability.

A second stage of consultation was undertaken later on in the project regarding the detailed techniques that had been developed. End-users were requested to trial the techniques that had been developed together with the supporting tools.

1.5 *Definitions*

For the purposes of this project, the following definitions have been assumed:

- Coastal protection – includes all interventions along the coast, such as defence structures, stabilisation measures and cliff drainage;
- Erosion – unconstrained erosion of all coastal landscapes and including coastal instabilities such as landslips;
- Defence Failure – total failure of a coastal defence structure;
- Hazard – the process of coastal cliff/slope erosion and instability;
- Risk – the impact of an erosion hazard on built and natural assets;
- Timescale – periods of up to 100 year would be covered.

The project considers the probability of loss for any erodible coastal landform, i.e. any coastal backshore landform which does not front a flood area. These landforms are predominantly cliffs, but also include slopes, gently rising ground and significant dune structures. Consequently, most work to date on erosion relates to cliff recession and behaviour, but the principles adopted also apply to most other erodible landforms and has been found to be appropriate for this project.

2 General Approach

2.1 The Erosion Process

Flood risk can be described in terms of present-day annual probability of exceedence – coastline instability and erosion risk for the most part, however, cannot be described in this way. This is because of the nature of the erosion process: for any single asset, recession of the coastline will take place year on year with zero loss, followed by total and instant loss of the asset once recession reaches it. Coastal defence failure does not necessarily constitute immediate loss or damage to the asset either – a coastal defence will delay and influence the natural rate of erosion but there will often still be a period of time between failure of the defence and asset loss. Assets located on potentially unstable coastlines are a different case: each year there is some likelihood that the asset may be damaged or destroyed by erosion.

The risk to any asset from instability and coastline erosion will be dependent upon the mechanism, frequency and magnitude of the recession. For instance, cliff recession is determined by cliff type and composition, as well as forcing events that could cause cliff instability and erosion.

Influential upon this will be any coastal defence structures, in particular with regard to the time aspect. Not only can a defence delay erosion but it may also influence the initial rate and nature of the recession; the so called 'catch-up' process.

The likely time at which asset loss will occur or, taking this a stage further, the probability of loss in any given year, can be calculated through considering these two components together. Each of these is likely to be variable, ie have a range of likelihoods both in terms of time and magnitude. However, the combination of these variables will act to define the point at which the loss of an asset is inevitable (Figure 2.1).

Adopting this basic approach, it was been possible to determine the coastal instability and erosion risk at any point in time.

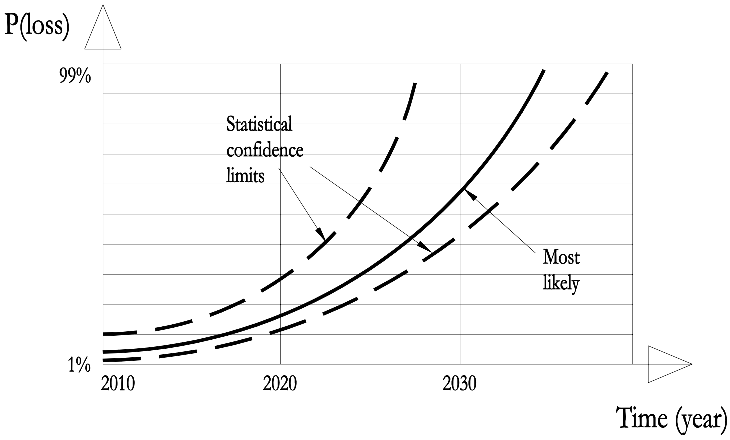


Figure 2.1 Probability of Asset Loss

2.2 ***Assessment Framework***

Outputs are required at different scales, eg national and local, and the amount of effort expended in obtaining the output should be proportionate to the accuracy required, whilst making the best use of available data. Despite these differences, the basic requirement of the analysis is the same, namely to answer the fundamental question "how long will it take for an asset to be lost?" To this end, one single approach was adopted, irrespective of scale or data. It comprises three components, the only difference being the level and accuracy of analysis that sits behind them. As illustrated in Figure 2.2, the components are:

- What assets are there? Where are they?;
- What is the mechanism for the landform to erode? How fast will this occur?;
- By how long and how much will any defence delay this process? What is the mechanism for defence failure? What is the chance of this occurring each year?

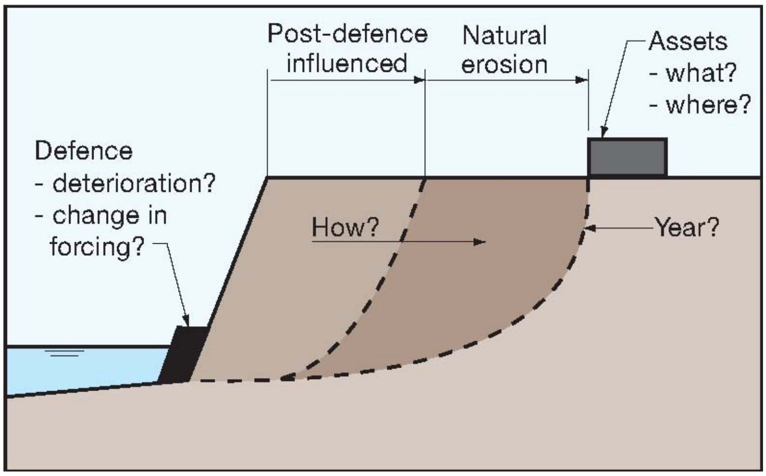


Figure 2.2 – Asset Risk Influences

Through this project it was concluded that whatever the level of detail of the analysis or the scale of the assessment these questions remain the same and consequently so do the basic requirements of the analysis. Therefore it was determined that the approach to assessing risk could be considered to have three distinct elements;

- assessment of the mechanisms for erosion and defence failure;
- determining the hazard as a result of these mechanisms; and
- establishing the consequences, i.e. the risk.

Compartmentalising the problem in this way enabled development of a methodology which could address many of the potential complications of dealing with diverse situations and information. This methodology can be considered in terms of the source-pathway-receptor risk model, i.e. the various erosive forces and constraints (= sources) are determined and subsequently combined to establish how they propagate to their point of impact, where they become a hazard (= pathway), before assessing the magnitude of the effect or risk (= receptors). This is illustrated in Figure 2.3.

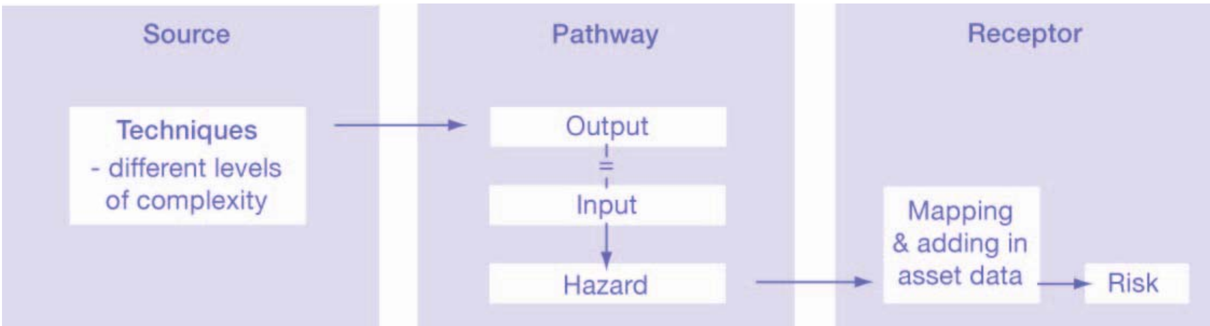


Figure 2.3 – Assessment Framework

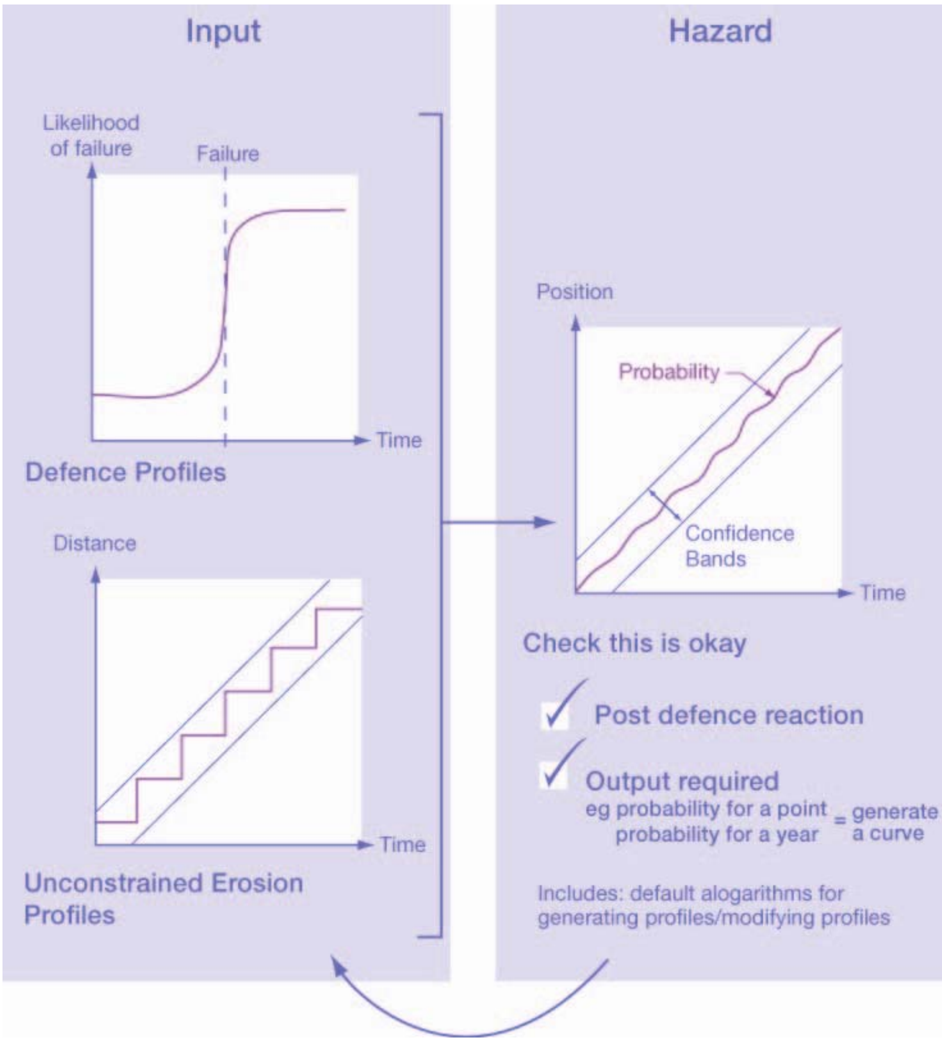


Figure 2.4 – Pathway Analysis

There are two components providing the source data to the hazard assessment: erosion potential and defence failure potential. Both components have a number of factors that require consideration and a range of analytical approaches are associated with them which vary in degree of sophistication and complexity. These range from very detailed to coarse, and use information ranging from qualitative or subjective, through to quantifiable and expertly applied models. Typically these can be categorised as:

- Educated assessment/engineering judgement;
- Qualitative/simple assessments;
- Broad numerical analyses;
- Detailed analyses;
- Complex models.

Figure 2.4 provides more detail on the pathway stage. It shows typical defence performance and unconstrained erosion curves produced by the initial source data analysis. It also indicates that other criteria can be included in the assessment at this time, such as the mode of reaction of the coastline post-defence failure. These analyses include default algorithms to both generate and modify profiles. As part of the hazard analysis, these curves are combined to produce a probabilistic estimate of the position of the coastline over time, within certain confidence bands. There is provision for the user to intervene at this stage to check this result and, if necessary, return to the previous stage to vary the analysis criteria and produce an improved prediction. There is also provision for the user to make certain choices at this stage, such as the format of the final output that is required - for example, whether the output is required as the probability for a certain point or the probability for a certain year.

The separation of analytical techniques and hazard calculation also ensures that proportionate effort can be applied at all times without the need for a suite of hazard assessment models. The output from any of the analytical techniques provides the input to the hazard model, the only difference being the level and accuracy of analysis that sits behind them, i.e. the techniques for determining the erosion potential and defence integrity.

2.3 Output

The scale of output that can be produced by the methodology is variable. It may be necessary to get results nationally, regionally, locally or perhaps for an individual asset, for instance a single property or feature of interest such as a power station.

The methodology therefore needs to be one constructed from the most detailed level, even if the data is crude. This is due to the potential for variation in the larger units - for instance, at a local scale, the differences in cliff conditions and defences within one SMP Policy Unit level. It is possible, however, for broad aggregations to be made even at this local level if necessary.

The output may be required in two forms: numerical and spatial/visual.

Numerical outputs might take several forms, such as:

- total number of assets at risk over time;
- value of assets at risk over time;
- probability of an asset/group of assets being lost;
- average annual risk;
- distance of assets from cliff edge though time;
- time until an asset is lost;
- individual/ societal risk.

All of these formats can be delivered with the general approach outlined above.

Spatial, or mapping, output might also take a number of forms, including:

- lines/zones of equal probability, although these would necessarily relate only to one point in time as this probability varies year-on-year;
- future shoreline positions;
- probability mapping relating to the assets themselves, which itself might take different forms, eg probability of being lost by a particular time.

It was not within the remit of this commission to develop a mapping tool or produce the mapping - however, the ability to generate these outputs from the results of the hazard assessment has been taken into consideration and accommodated (see Section 4).

3 Source Data Analysis

3.1 Overview

The methodology for determining either erosion or coastal defence failure potential provides a hierarchy of techniques to accommodate this range and allow for proportionate effort by the user conducting the assessment. These are, quite simply, more or less sophisticated techniques that can be applied to generate the solution. Decisions on the appropriate use of any of these techniques relate to the nature of the problems, the importance of the assets, the data available and the accuracy of output required.

Irrespective of the simplicity or complexity of any given techniques, each will lead to the same basic output; a timeline to defence failure or unconstrained erosion distance. These are also the required inputs to the hazard assessment. The principal difference between the outputs from various techniques is their accuracy and the level of confidence that can be attributed to them.

Figure 3.1 illustrates the output that the user is required to produce from the techniques. The middle lines indicate the best assessment, whilst the degree of uncertainty is shown by the lines either side.

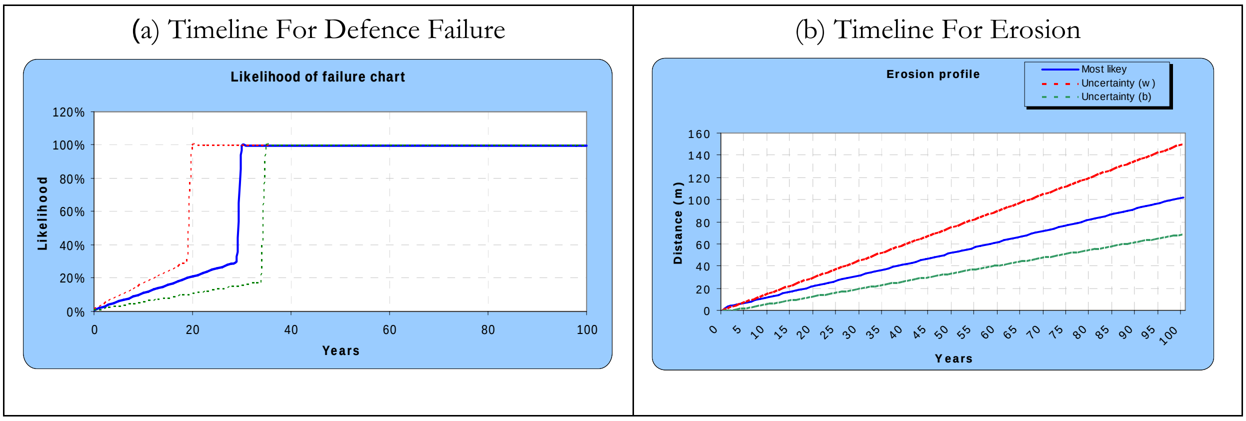


Figure 3.1 – Output/input requirements

The first example shows the user's assessment of the condition of the defence and its potential deterioration (Figure 3.1a). It indicates that it is expected to stand up for another 30 years, but might collapse after 20years or else could last for 35years.

During the lead in period the user has assessed that there is a 1% chance of storm conditions exceeding design conditions year-on-year and leading to defence failure, although this could be as much as 1.5% or as low as 0.5%. Put another way, under the 'best assessment' the user is saying that the defence will almost certainly have failed by year 30, but recognises that there is a small chance that this failure could actually happen this year, next year, or at any point forward.

For the erosion potential, (Figure 3b), the user's assessment of cliff recession indicates that without defences the cliffs would be expected to erode inland by an average distance of 100m over the next 100 years, although there is potential that the cliffs could eroded by a little as 70m, or as much as 150m over this period.

3.2 Erosion

The recession process is central to the risk analysis: the time taken for any asset to be lost is dependant upon the rate of erosion. A full description of this and factors to be considered is provided in Appendix A to this Part One report. A range of techniques have been developed for assessing erosion potential depending upon data and level of assessment appropriate, but again all leading to the same form of output.

The considerations here are:

- rate of erosion, ie how quickly the coastline retreats;
- behaviour, ie the mechanism by which instability and recession occurs, whether it is linear or made up of larger sections at less frequent intervals;

Each of these is likely to be variable, ie have a range of likelihoods both in terms of time and magnitude. There is uncertainty over the time as to when erosion will occur, how much it will be and whether it would be instantaneous or gradual. In addition, different coastal landforms will be affected in different ways and to varying degrees. However, the overarching principles can be applied to any situation, irrespective of scale or level of information available. Again, it is the choice of the technique that inputs to this that accommodates the variability and allows for proportionate effort to be applied, providing incremental improvements in the quality of output but also usually necessitating higher levels of data input, knowledge and time.

A brief overview of the five techniques for assessing erosion potential is given in Table 3.1, with the full techniques presented in Part 2 of this report, Appendix A.

Technique		General Description	Main Points
1	Technical Judgement	Experience based assessment for use with minimal data	Quick and easy method. Crude examination.
2	Futurecoast Assessment	Uses data from the Futurecoast cliff database	Consistency of available data lends itself to national application.
3	Site Specific Assessment	Combines data from Futurecoast with real data (e.g. more up to date aerial photographs)	More accurate than Technique 2, although some aspects remain imprecise. Some Local Authorities may already have such studies available
4	Single Recession Rate Method	Uses purely real data and methods recommended by the Soft Rock Cliffs manual to calculate single recession rates.	Very robust method that will deliver reliable results. Data requirements exceed Techniques 1 to 3. Methods require extensive data and expert input.
5	Probabilistic Method	Uses purely real data and methods recommended by the Soft Rock Cliffs manual to calculate single recession rates.	Likely to provide most accurate output. Methods require extensive data and expert input.

Table 3.1 – Techniques For Determining Erosion Potential

3.3 Coastal Defence Failure

A general framework has been developed for assessing the probability of coastal defence failure. This is included in Appendix B to this Part One report. The different techniques have been developed around this, depending upon available data and the appropriate level of assessment – but, as for the erosion case, all lead to the same form of output as discussed earlier. In all cases, there are two factors to consider when taking account of the influence of coastal defences:

- general deterioration of the defence over time - due to general wear and tear alone, at some point in the future the defence will cease to be effective;
- failure of the defence due to design conditions being exceeded, e.g. destroyed by a storm, or undermined by falling beach levels (forcing conditions).

Both of these factors are variable - but in different ways. Regarding deterioration, there is uncertainty over the time at which the defence will fail and whether this would be instantaneous or gradual. Deterioration can be addressed relatively simply based upon defence type and condition. This can be derived from generic assumptions or thorough detailed calculation - but both provide the same form of output, namely a timeline to failure. Considering failures resulting from changes in forcing conditions, then there is an annual probability of exceedence and thus failure - an extreme storm could occur this year, next year or not for ten years. Trends in forcing conditions can be identified by analysing data from site surveys and past and present conditions affecting a defence structure. Whilst extrapolating these trends, consideration of future influences such as climate change and beach level variation (for example, to account for longshore influences) can be included.

Different forms of defence structure will also be affected in different ways and to varying degrees by these components. However, the overarching principles can be applied to any situation, irrespective of scale or level of information available.

Five different techniques have been developed that can be applied to generate the defence failure timeline. Each technique includes guidance on how it can be carried out, advice on when to use and limitations of the method. A brief overview of each technique is contained in Table 3.2, with the full techniques presented in Part 2 of this report, Appendix B.

Technique		General Description	Main Points
1	Engineering Judgement	Experienced based assessment for use with minimal data.	Quick and easy method. Crude approximation.
2	Qualitative Assessment	Uses qualitative data from NFCDD to apply indicative tests.	Consistency of available data lends itself to national application. Imprecise output.
3	Broad Numerical Analysis	Combines physical information from NFCDD with data from other sources (e.g. beach levels and general wave/water level conditions)	More accurate than Technique 2, although some aspects remain imprecise. Can be coded to deliver national level application.
4	Detailed Calculation of Failure Potential	Calculation of stability, overtopping undermining etc with good knowledge of the structure and forcing conditions.	Very robust methods which deliver reliable results. Data requirements exceed Techniques 1 to 3. Some LAs may already have such studies readily available.
5	Probabilistic Models	Detailed analysis of failure mechanisms and interactions of each structural component	Likely to provide most accurate output. Methods require extensive data and expert input.

Table 3.2 – Techniques For Determining Defence Failure Potential

4 Hazard Assessment

4.1 Methodology

A major complication with making risk assessments for coastal erosion is successfully combining information on defence integrity with knowledge of erosion processes. This project has developed a mechanism for integrating these aspects, albeit confirming that our ability to assess this accurately is not constrained by analytical techniques, but rather by our limited understanding of the elements that we are dealing with. A good example of this is the nature of the 'catch-up' erosion process following failure of a defence that has been preventing erosion for a number of years.

Where defences exist, the post-failure retreat will possibly differ from natural retreat, at least for some period of time. This might take two forms:

(a) a rapid (probably non-linear) catch-up process, ie the cliff reassuming its position had defences not existed by initially eroding at a rate much faster than the natural rate;

(b) an initially slow retreat rate, with the residual effects of the failed defences still offering some limited protection and not allowing full cliff instability and erosion to take place.

Both of these are known factors, but there is virtually no information on either, which makes quantification of the associated times and rates difficult to determine. However, it is still appropriate to have facility within the analysis to incorporate such modifications, enabling it to be addressed where either some local knowledge does exist or an educated assumption can be made.

Recognising this difficulty, an approach has been developed that enables the user to account for such processes, but has to use experience to quantify time and scale until such time that our industry has better data available.

The method provided takes both components of erosion and defence failure probability and combines them to deliver two measures of hazard: the probability of erosion for a given distance and the probability of erosion for a given time. In both cases three defence-erosion scenarios are calculated, with the user determining the most appropriate for their section of coastline:

- Scenario 1 shows the hazard curves considering the onset of potential erosion is simply delayed until the point in time at which the defence fails, Figure 4.1a;
- Scenario 2 assumes that the potential erosion line stays in the originally defined position (i.e. starting in year 0) but the onset of actual erosion is delayed until the defence fails followed by a 'catch up', which would be a straight line up from the zero erosion to meet the (original potential) erosion profile after a set period of time (which the user can define), Figure 4.1b.
- Scenario 3 considers the effect on the erosion timeline if the defence had been in place (delaying erosion) for certain period of time. Thus the potential erosion line is shifted back in time to a starting time representative of the age of the defence (the user can specify how old the defence currently is), and once the defence fails there is again a catch up period that the user can define, Figure 4.1c.

Under all scenarios three cases are calculated to produce an envelope of probabilities, namely best and worst cases and an intermediate, most likely case. These are illustrated in Figure 4.1.

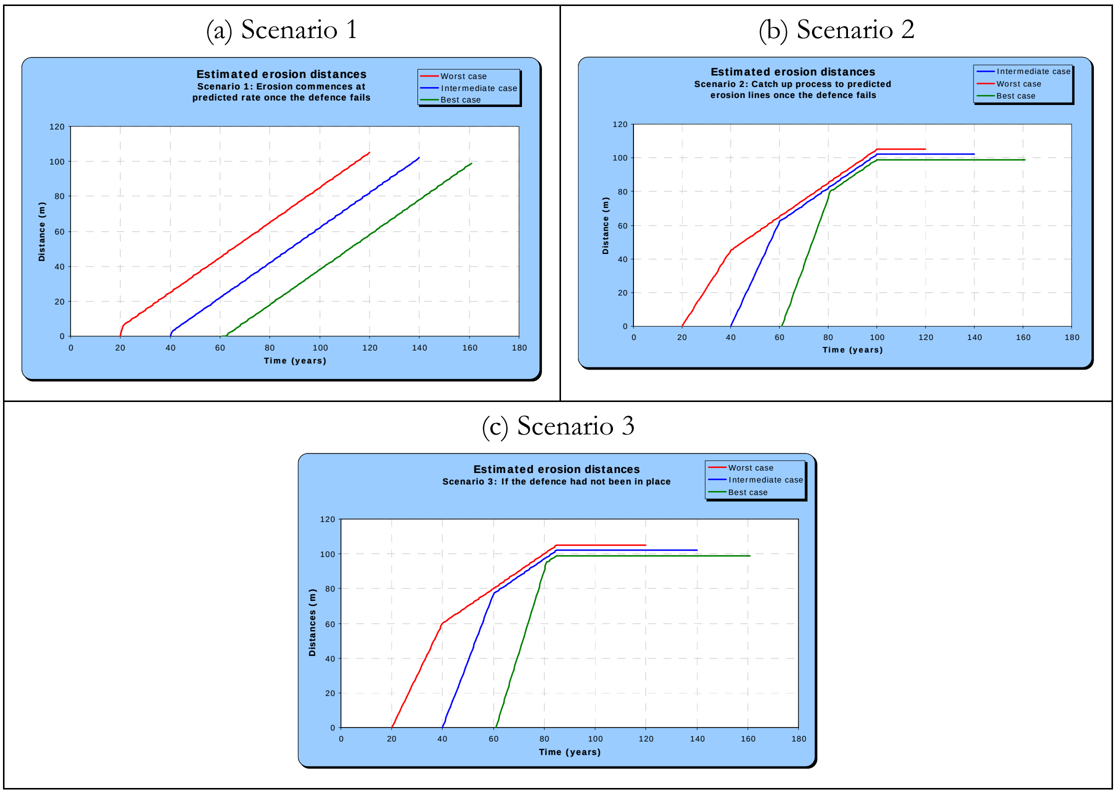


Figure 4.1 – Erosion Scenarios With Defence Influence

4.2 *Probability Of Erosion For A Given Distance (Asset Location)*

In order to work out the probability that we reach a given distance as time progresses, it is necessary to convert the deterministic erosion profiles into some probabilistic measure of erosion. In the absence of additional information the method employed here is essentially to create an empirical distribution from the profile. From this the probability of erosion through time for a given distance is calculated, to produce results in the form of the example shown in Figure 4.2. This is described in greater detail in Part 2 of this report, Appendix C.

4.3 *Probability Of Cliff Erosion For A Given Time*

In order to obtain a probability of erosion from the likelihood of defence failure and the erosion profile, the analysis finds the estimated erosion distances for the specified year *N* and previous years, back to the first year. These erosion distances are associated with the probability of failure of the structure for each year starting with year 1 until year *N*. This array is plotted as the example in Figure 4.3. This is described in greater detail in Part 2 of this report, Appendix C.

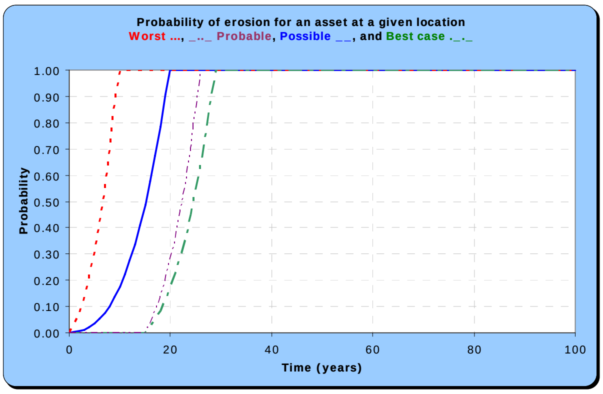


Figure 4.2 – Probability Of Erosion For A Given Distance

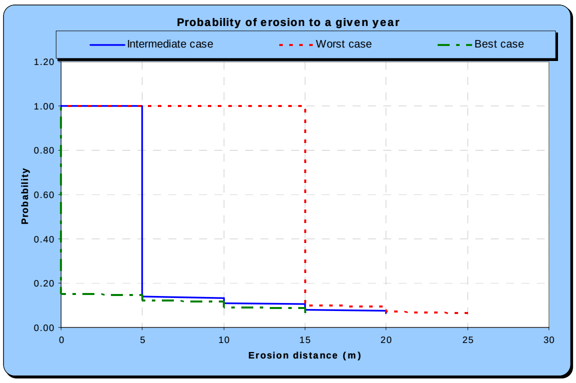


Figure 4.3 – Probability Of Erosion For A Given Time

5 Risk

The remit of this project was to produce the procedures to enable assessments to be made, not to develop a mapping tool or risk evaluation mechanism. However, the ability to generate these outputs from the results is necessary and was a primary consideration in the development of the methodology.

Risk is the combination of the hazard assessment with information on consequences, e.g. the loss of particular assets (see Figure 5.1). Asset information is available in different forms and may have a variety of attributed data, but is all essentially spatially configured.

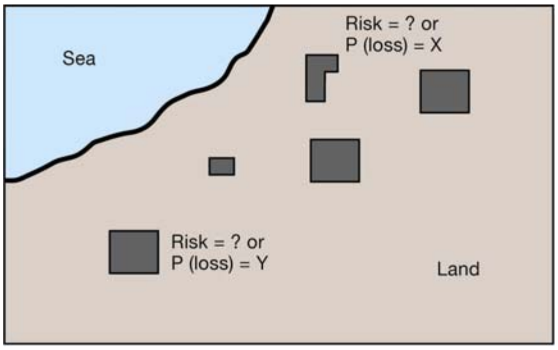


Figure 5.1 – Risk = Hazard x Consequence

Key to the ability to quantify risk is knowledge of the relationship between coastline position, time and probability of change. This is generated as output from the hazard analysis, from which it is possible to map probability of loss through erosion at any locality at a given point in time. The assessment of probability of erosion for a given distance enables the risk for any asset to be established. The assessment of probability of erosion for a given time enables an assessment of multiple assets through assessing the probability for a range of timescales, which can then be interrogated.

These outputs are best illustrated through mapping of results as follows:

- lines/zones of equal probability, relating to a defined point in time (as this probability varies year-on-year), see Figure 5.2a;
- future shoreline positions, see Figure 5.2b.

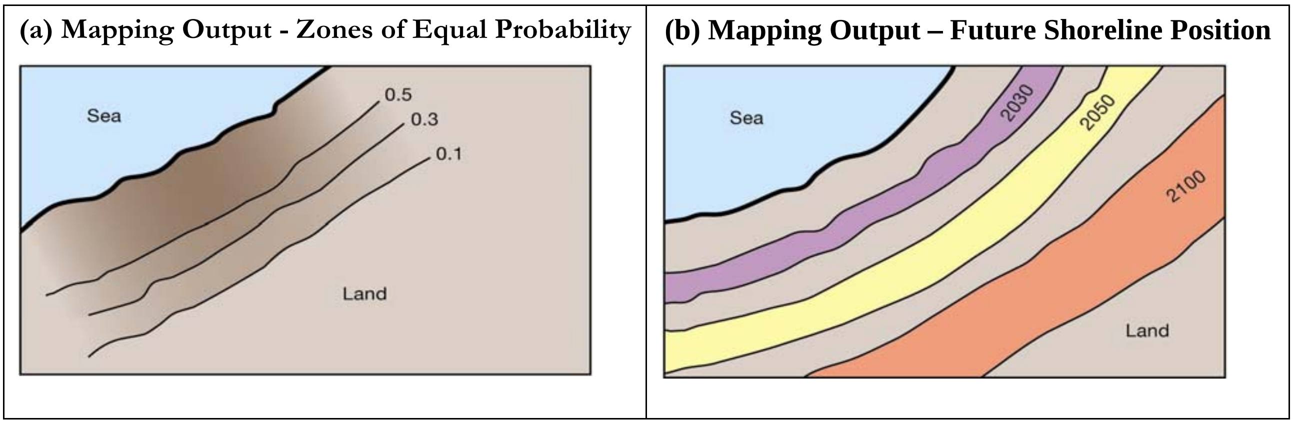


Figure 5.2 – Mapping Of Hazard And Thus Risk

There are strong parallels here between the considerations of receptors in the Risk Assessment for Strategic Planning (RASP) work quantifying flood risk in economic terms. This has primarily been through the location and quantification of assets within the floodplain (e.g. built property and agricultural land) that can be valued, enabling economic damages to be calculated. In a similar fashion, for coast erosion, the area and value of land likely to be lost at particular time intervals can be assessed, as can the number and value of built properties. These receptors can be readily mapped, using data sets such at the EA's National Property Dataset or Defra's Agricultural Land Classification map.

The ability to produce risk assessments from the hazard assessments has been tested through the project and the methods that have been developed are to be used for production of the forthcoming National Coastal Erosion Risk mapping.

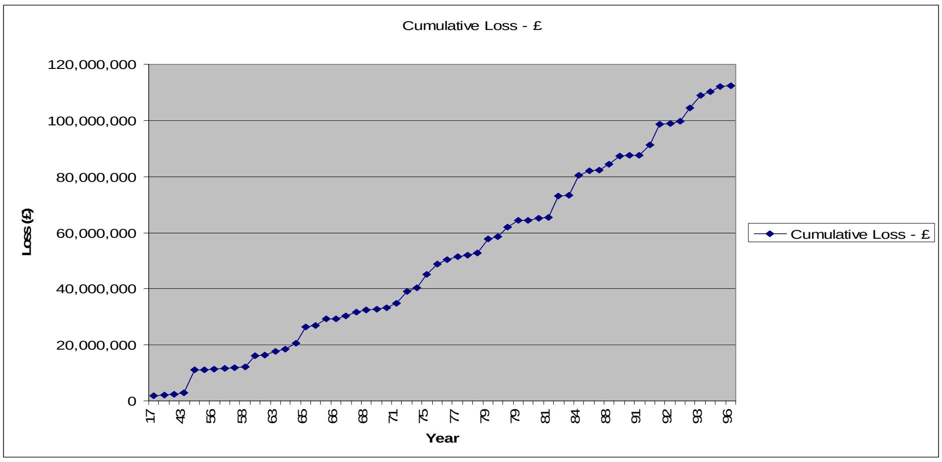


Figure 5.3 – Sample Cumulative Plot Of Value Of Asset Loss

6 Consultation

6.1 Approach

The involvement of end-users was a key aspect of the project to ensure that the final product meets their needs and can be applied directly by them. Although the scope of work for the project did not include for ongoing consultation during the project, several consultation and participation activities with end-users were undertaken - in the first instance, to establish the needs of end-users and later on to disseminate what had been produced and participate in trials of the final deliverable. A project steering group was set up to provide peer review of the project. A review of existing knowledge was also undertaken during the early stages of the project.

6.2 Steering Group

A project steering group was established during the early stages of the project. The aim of the steering group was to provide regular peer review of the project and the product being developed. The steering group was comprised of representatives from DEFRA, EA, Welsh government, academia and local authorities. Three steering group meetings were held at key milestones during the project, namely broad scale methodology, detailed methods and final dissemination. All comments raised by the steering group were addressed as part of the project.

6.3 End-User Consultation

6.3.1 Initial Consultation

The first stage of the project was a scoping exercise to determine the exact requirements of the project and this included finding out the needs and views of end-users. This was done by means of a presentation by members of the project team at a national meeting of the Coastal Group chairmen in March 2005. The chairmen then discussed the project with their respective coastal groups, which are comprised of end-users, and passed the comments that they received back to the project team. A wide range of comments was received - these gave a good illustration of what end-users require and formed the basis for the development of the final product.

6.3.2 Final Dissemination

A dissemination seminar was held in London in April 2006. The purpose of the seminar was to present the final product and explain its development to end-users, as well as to appraise volunteers to trial the product in their own areas. Members of the project steering group were invited, along with key local authority end-users. As part of the seminar, a presentation was made on the National Coastal Erosion Mapping project, which will extend the methodology developed by this project to produce maps of coastal erosion risk around the coastline of England and Wales.

A second seminar was held in June 2006, again in London. This seminar was a combined event with the National Coastal Erosion Mapping Project. After an initial session explaining the background of this project, the mapping project was introduced along with its context within DEFRA policy. Delegates then joined small breakout groups to discuss different key aspects of the mapping project. During this seminar, the methodology and spreadsheets were demonstrated to a number of delegates, all of who thought them to be extremely useful. It also became apparent that several of these delegates were in the process of developing their own similar tools and spreadsheet-based techniques for assessing coastal erosion along the coastal frontages they were concerned with.

6.4 Review of Existing Knowledge

One of the main initial activities that was undertaken on the project was a thorough literature review. This included a comprehensive review of information, methods, techniques and knowledge that is currently available and to determine its relevance to the project. As well as published reports and technical papers, this also included existing erosion assessment methods and tools and the data sets available for their application. From this process, key information was identified for defence, erosion and risk assessment methods - these were important starting points for these areas of the project.

As part of the literature review, links and interfaces with a number of other ongoing DERFRA projects were identified. In these instances, contact was made with the parties conducting these other projects to ensure that everyone was aware of each others' work – as well as defining interfaces between projects and preventing any duplication of effort, this also revealed a number of new opportunities for each of the projects being undertaken. Where appropriate, communication was continued during the course of the project – as well as telephone conversations and emails, this included attendance at a number of combined meetings.

7 Validation

7.1 *Approach to Validation*

The remit of this project was to produce a probabilistic methodology for assessing the risk of coastal erosion only – it did not include the development of software or a mapping system, although the potential for the methodology to be developed in these ways in the future was recognised. Although not strictly a project deliverable, spreadsheets were, however, developed in order to trial the methodology, its results and individual components, and also to demonstrate that software could be developed for the entire procedure.

7.2 *Erosion*

The erosion model developed for this project was based on a qualitative recession prediction model that was developed for a well-documented UK coastal erosion site in order to give a probabilistic prediction of erosion risk at that location. This work has been published at international conferences, for which it was subjected to peer review, and the model has also been used extensively in the assessment of erosion risk at other coastal sites. The model developed for this project has been updated to incorporate the experience of experts in this field who are part of the project team and who have a significant portfolio of publications and history of research in this area. As such, the erosion model incorporates the best available knowledge on the probabilistic prediction of coastal erosion risk.

7.3 *Defences*

The methodology developed for the assessment of coastal defences was mostly based on previous NRA-funded research work and also other projects within the industry that have assessed risks to coastal assets. The previous work was extensively tested and the assessment techniques were proven at that time. It was also the subject of a number of international conference papers, for which it was subject to peer review. The methodology developed for this project is an extension of these previous techniques, which principally concerned coastal flooding, so that they relate to coastal erosion and its particular characteristics. The assessment techniques that have been developed have been incorporated into a spreadsheet and individual defence data used to ensure that the resultant answer is representative of the durability of the defence given the prevailing coastal conditions.

7.4 *Risk Assessment*

The hazard assessment methodology developed for this project used proven statistical methods in the new application of coastal erosion risk assessment.

The validation of this component of the overall methodology included ensuring that individual probabilities were calculated correctly and ensuring different scenarios, such as cases with/ without a defence and also with just the defence itself present. The methodology developed has been presented to the Steering Group, end-users and at specialist international conferences and as such has been subject to peer review.

7.5 *Overall Methodology*

The resultant probabilistic curves produced by the methodology are the first of their kind and thus, at present, there is limited data and experience available for their verification. It is possible to conduct detailed validation of the individual components of the methodology, but there is little information to validate the entire procedure.

Internal validation was undertaken by the project team as far as possible using data available to them. Verification of the overall methodology was then undertaken by volunteer local authority end-users following the final dissemination seminar in April 2006 - as such the methodology has thus been subject to industry review. As part of the seminar, end-users were provided with copies of both the methodology and spreadsheets for them to test with their own data. They were requested to report back to the project team with their findings and any comments they may have. A limited number of comments were subsequently received. Whilst a number of minor matters were identified, and subsequently addressed, the general consensus was that it was considered that the methodology provides an appropriate and clear way forward as a functional tool. The overall methodology has been approved by the project steering group.

8 Conclusions

A methodology has been developed that enables the risks from coastal erosion to be determined. It provides a means of better understanding the extent of coastal erosion risks, taking account of both natural processes and human intervention at the coast. This will provide a strengthened framework for erosion risk assessment, and in turn risk management, which is a key aspect of Defra's current Strategy Review.

The methodology fulfils the end-user requirements regarding consistency, different levels of reporting, using best available data, proportionate effort and also that the resultant hazards and risks can be presented in mapping formats.

The techniques developed can be applied to any scale, from assessment for a single section of coast, through to national appraisals. They can therefore be applied by a wide range of users to fulfil any of the following:

- Informing public safety assessments and planning of necessary improvements;
- Informing the development of SMPs and strategies for their implementation;
- Informing the development of regional and local plans and consideration of planning applications;
- The management of coastal cliff instability and erosion risk.

The method is to be applied to produce the National Costal Erosion Risk Mapping.

Appendices

Appendix A

Erosion Technical Report

Derivation of Erosion Profiles

Broad Methodology

The RACE methodology seeks to mathematically combine probability functions of time to coastal defence failure with expected erosion distance over given time periods to undertake risk assessments of coastal assets (Figure 1.). This appendix presents information on the detailed methodologies for deriving data on coastal erosion.

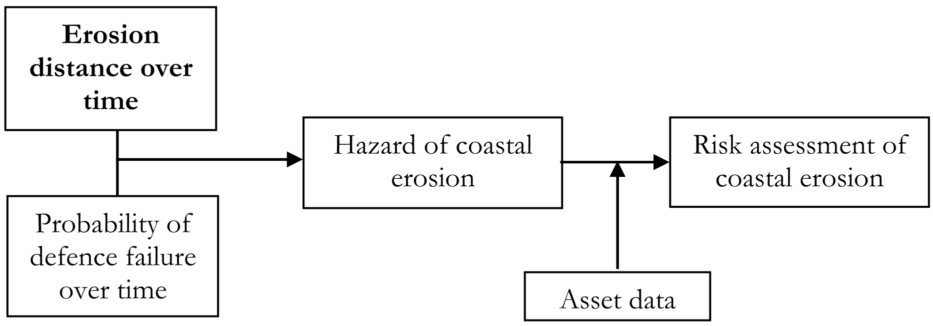


Figure 1. The Methodology For Risk Assessment Of Coastal Erosion.

Data on future coastal erosion needs to be presented in terms of cumulative loss over the next 100 years. In most cases, is not possible to make completely reliable predictions about future recession, because of the uncertainty in future weather conditions, the physical properties and behaviour of the coastal landform and the inherent randomness in the main causal factors (e.g. wave height, rainfall etc). Because this uncertainty is recognised, it has been fully incorporated into the RACE methodology, and therefore 'best guess', 'worst case' and 'best case' erosion profiles are required. There will rarely be enough recession data to reliably calculate the precise confidence intervals, because of the small sample sizes typically available in cliff recession studies, and therefore these three erosion profiles are assumed to represent the 50%, 5% and 95% statistical samples (confidence limits) from the full range of possible erosion profiles. In this sense, the worst case scenario (i.e. the 95% confidence limit) would represent a sustained period of historically very high rates of erosion and cliff recession, rather than the impact of a single highly improbable erosion event, such as a tsunami.

Coastal Erosion Processes And Rates

Coastal landform recession can be simply classified into annual losses from coastal erosion, and episodic losses from landslide events. Over long periods of time (>1000s of years), the cumulative recession resulting from these different modes of failure is likely to be the same, but over shorter time periods, i.e. 'human timescales' (10s to 100s of years) covered under the RACE methodology, it is essential to have an understanding of the magnitude and frequency of episodic events (e.g. how much cliff is likely to lost in each landslide event, and how regular are the landslide events?).

Understanding And Predicting Future Behaviour

In order to gain an understanding of coastal landform behaviour, it is necessary to have some factual information on historical and current change in the landform and of the geology and geomorphology. This information can then be used to develop a conceptual behaviour model, encapsulating interacting geomorphic components, which can then be used to derive a predictive model (Figure 1). A detailed discussion on methods of deriving such models, e.g. a cliff behaviour model, has been presented elsewhere (Lee and Clark, 2002), and approaches to deriving the predictive model are concentrated on here.

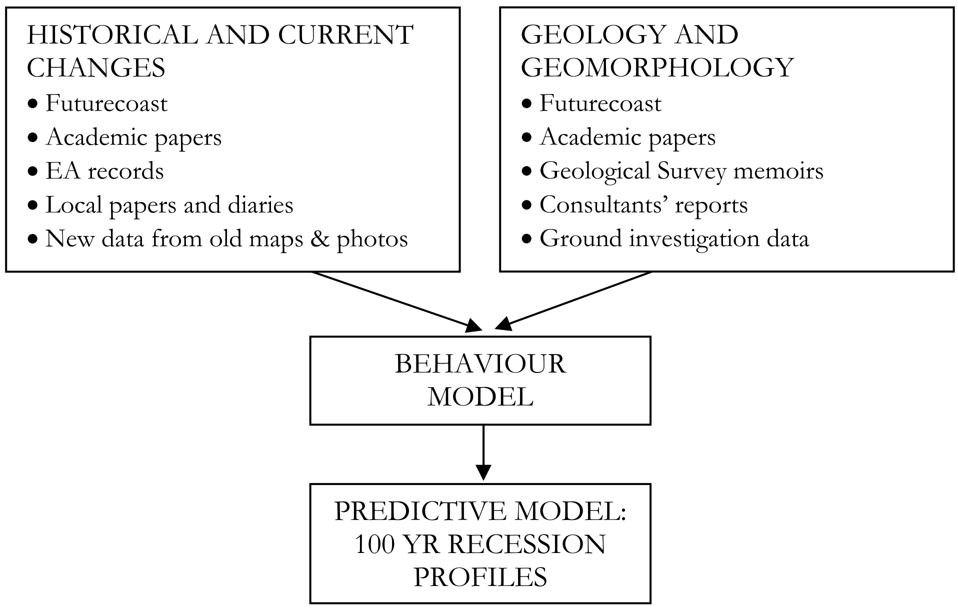


Figure 1. Derivation Of Behaviour And Predictive Models

Sources Of Historical Recession Data

Published site-specific historical recession data is available from a range of sources, including academic papers, consulting reports and local council or Environment Agency records. These documents are likely to present results derived from either analysis of historical maps and photographs or detailed monitoring of a particular section of coast. In addition to these sources of existing information, Halcrow's Futurecoast study provides estimates of future annual and episodic cliff erosion rates for the whole of England and Wales derived from expert judgement and aerial photograph interpretation. The scale of the Futurecoast study means that the data is somewhat generalised, but it does provide basic information that can be used for initial tests of the RACE model.

In the absence of available detailed data, new information can be derived from careful analysis of historical maps or aerial photographs. Historical data are readily available from a variety of sources in the UK, including the Ordnance Survey and the English Heritage National Monuments Records Centre (see Lee and Clark, 2002 Appendix A for further details).

Recession rates are derived by measuring the location of some feature relating to the landform, e.g. the cliff top relative to a fixed baseline in each 'epoch' of data. This can be done using tracing paper and scale rule but such an approach leads to unknown but probably significant errors in the calculated recession rate. The preferred approach makes use of digital geo-rectified maps and photos in a Geographical Information System (GIS). This technique allows the errors in the different data to be calculated and fully incorporated into the resultant recession data (Moore et al., 2003a).

Erosion Prediction Models

Future coastline behaviour is determined by the impact of changing system controls on past behaviour. Changing system controls include external factors, such as sea-level rise and climate change, and internal factors such as variations in materials or hinterland geomorphology.

The impact of changing system controls on the behaviour of the coastal landforms can be determined by a range of approaches, including the following:

- Extrapolation of historical data;
- Expert judgement, e.g. from cliff behaviour models;
- Probabilistic simulation modelling;

- Process-response simulation modelling; and
- Empirical modelling.

These approaches involve an increasing degree of analysis, but do not necessarily provide an increasing level of accuracy. Furthermore, all approaches rely on the provision of historical recession rates, either as the basis for prediction or for model calibration.

The ultimate precision of outputs is constrained by uncertainty over future weather conditions, the physical properties and behaviour of the landform, the precise timing and magnitude of individual recession events and the future recession rate is itself uncertain. For this reason all approaches presented below can be used to derive best estimate, worst case and best case predictions of landform behaviour.

Most work on this subject relates to the study of cliffs and their behaviour. The remainder of this report therefore refers to that in particular and also to the Soft Rock Cliffs Manual, or SRC (Ref. Lee E.M. & Clark A.R., 2002. 'The Investigation and Management of Soft Rock Cliffs. Thomas Telford). However, these same principles apply to other erodible landforms, i.e. those which are not part of a flood protection system.

Extrapolation Of Historical Data

Historical recession data can be extrapolated to produce estimates of future recession. 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 potentially disguise the details of episodic recession events. This problem can be eliminated if the historical records are known to cover several recession 'cycles', in which case simple extrapolations can give a reasonable estimate of the cliff top position.

A number of methods can be used to extrapolate from historical records. In general, linear extrapolations (as opposed to non-linear methods) are preferable because of their simplicity. However, there may be clear reasons why recession (both past and future) is non-linear, such as construction or loss of coast protection works, changes in sea-level, or changes in geology. If historical data is sufficiently closely-spaced, it may be possible to detect the impact on recession rate in the past.

To ensure accuracy when extrapolating historical data it is essential that geological and environmental controls on the recession process have remained the same throughout the period of the historical record and that the historical record includes data on infrequent episodic events. Extrapolations should therefore be based on all reliable data covering the longest possible period.

(a) Simple Extrapolation

The most widely used methods include:

- 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.
- 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.

(b) Linear Regression Analysis

The most straightforward approach to predicting recession using historical data is a continuous linear model (Crowell *et al.*, 1997):

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

where X_t is the recession distance at time t and ε 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 β_0 and β_1 can be found from simple linear regression theory. Crowell *et al.* (1997) also examined quadratic and cubic recession models but found they can be extremely inaccurate.

It is possible for linear regression analysis to incorporate random sampling of recession rates so that a probabilistic description of cliff position at a particular time in the future can be derived. This approach is based on the linear trend over time, but also accommodates the potential variability in the recession rate. 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 coastline positions derived representing one possible sequence of recession events. By running many similar simulations it is possible to establish a probability distribution for the position of the coast at any year in the future.

Modification Of System Controls

The extrapolation of historical data can be developed further by applying an understanding of impact of various controlling factors on the historical recession data and modifying it accordingly. Two recent approaches are presented below where historical recession data are used in simple spreadsheet models.

(c) Barton-on-sea

Using detailed and accurate historical recession rates from both actively eroding and stabilised cliffs at Barton-on-Sea, Hampshire, Moore et al. (2003b) developed a simple model to project future recession rates based on modifications of the historical recession rate. The model is able to produce 'best estimate', 'best case' and 'worst case' scenarios depending on the historical recession rate used, and enables the impact of climate change to be investigated. Because historical cliff recession data is available from both defended and undefended cliffs, the impact of degradation and eventual loss of coastal defences can also be assessed in this model.

In this model, the impacts of climate change are incorporated by increasing the historical recession rate by a given percentage. The default level is set to 10%, but the user can change this and test the results.

The model can be operated in a probabilistic mode by random sampling probability distributions of different sea-levels and historical recession rates and re-running the model many times.

(d) Covehithe

A recent development of the extrapolation of historical data approach has recently been presented by Lee (2005) based on data from rapidly eroding cliffs at Covehithe, Suffolk. In this paper, the factors determining cliff recession, such as sea-level, wave climate and cliff material resistance to erosion, are separately considered and probabilities distributions for the impact of each factor are estimated. For example, probability distributions of a number of different future sea-levels are estimated, based on published data and expert judgement. The future cliff recession rate is calculated using a spreadsheet-based model which requires the user to enter the historical recession rate and to select the probability of each controlling factor. This approach allows any number of scenarios to be developed, where the probability weighting of one or all of the controlling factors are changed, resulting in a modification of the historical rate of cliff recession.

These models offer considerable benefits because they are simple to use, have a clear methodology and can be run many times to determine the impact of various scenarios. The main disadvantage of these approaches is that the model outputs are usually a single modified future recession rate, meaning that the short-term impact of episodic landslide events will not be represented.

Expert Judgement

Expert judgement involves the use of experience, expertise and general principles to develop future recession scenarios (i.e. possible future recession profiles) from the available historical record and past 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 site investigation and discussion it is possible to develop reliable estimates of the future recession.

For example, a cliff behaviour model should provide a reliable indication of how that length of coast 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 the cliff experiencing a recession event in a year.

There are a number of generic approaches for the development of recession scenarios that are appropriate to the RACE methodology:

- the use of geomorphological evidence coupled with historical data often to derive an evolutionary model of the landslide (the direct approach); and
- historical frequency, establishing the relationship between recession events and triggering events of varying intensity. In Britain, there is a wide range of sources that can provide useful information on the past occurrence of landslides, including: aerial photographs, topographic maps, satellite imagery, public records, local newspapers, consultants' reports, scientific papers, journals and diaries;

- the event tree approach, involving tracing the progression of the various combinations of scenario components using logic tree techniques to identify a range of possible outcomes. The development of a event tree involves identification of sequences of events that may initiate a failure (i.e. causal factors) and evaluation of the range of potential failure mechanisms that could occur, i.e. the system response (including no failure).

Key rules on the use of expert judgement for probabilistic prediction of coastal recession are outlined as follows:

- Problem structure; in complex situations it will be very difficult for experts to handle the numerous factors which determine the probability of coastal landsliding. It is preferable to break down the problem using event trees and ask experts for judgements of scenarios that make up the event tree;
- Checks for inconsistencies; by logically structuring and obtaining several judgements relating to different aspects of a problem it is possible to check for inconsistencies in the expert testimony and where they do exist work with the expert to develop a more coherent set of probabilities.
- State evidence upon which expert judgement is based; expert judgements of probabilities are based on evidence which will range from the tacit knowledge of the expert to specific analysis, data and historical evidence relating to site in question. The expert judgement should as far as possible be made transparent by documenting the sources of evidence and the process by which expert judgements of probability have been obtained.
- Peer review; expert judgements should be subject to critical review by the expert's peer group. Approaches to conducting peer review vary from informal discussions to more formal mechanisms for eliciting collective judgements such as the Delphi method. Peer review should be a routine aspect of assuring the quality of expert judgements.
- Use of quantitative data to inform the expert judgement; under many circumstances cliff recession predictions will combine some quantitative evidence relating to the historic frequency of landsliding with site-specific analysis and expert judgement.

Probabilistic Simulation Modelling

The techniques discussed above have drawn attention to the problems that may arise when trying to extrapolate future recession scenarios from historical data without an understanding of the contemporary behaviour of the landform. A frequent problem is the scarcity of historical data relating to its position, which can limit the usefulness of many conventional statistical methods, such as linear regression. One approach to addressing this problem is the use of expert judgement, discussed above, another is the development of probabilistic models to simulate the recession process, based on Monte Carlo sampling (see Meadowcroft et al. 1997). The main elements of developing a probabilistic model are:

- development of a conceptual model of behaviour, e.g. a cliff behaviour model, with particular emphasis on assessing the potential event sizes and the event timing;
- assigning probability distributions to represent variability and uncertainty in the key parameters (e.g. event size, event timing, extreme wave heights etc.) Some parameters such as extreme wave heights have been extensively studied and probability distributions for these can be established using standard methods. Other factors are more difficult to quantify and may call for a degree of subjectivity, but this should be guided, where possible, by informed arguments about what ranges of values are likely with what degree of confidence.
- developing a probabilistic prediction framework and selecting a simulation strategy. Simulations may be 'static' or 'dynamic' to simulate a given time period using a time-stepping approach. The static approach is simply a Monte Carlo simulation of the model. There is no attempt to simulate any variation in time, though future prediction can be made by setting, for example, climate parameters to their predicted values.
- the dynamic approach, ideal for long term prediction, involves repeating many simulations of the required time period to establish a histogram of probability distribution of the given response at a given point in time. The dynamic approach means that events (both deterministic and probabilistic) that will occur in future can be included. As well as random loadings this could include deterioration of a structure, or management intervention.
- running repeated simulations, the key requirements are for a pseudo random number generator which produces a stream of values between 0.0 and 1.0. Correlated variables require additional functions to ensure that sampled values are correctly correlated. After a large number of simulations, the frequency distributions and correlations of the sampled data should conform to the specified probability distributions, and the result will be a stable frequency distribution, reflecting the variability of the input data and the form of the response function.

Simple response functions and models can be accommodated on a spreadsheet and can be set up and run quickly. An advantage of the ever-increasing speed of computers is that multi-simulation techniques can now be used even with relatively complex process - response models, and can include long-term prediction.

Process-Response Simulation Modelling

The development of predictive models based on the interactions between nearshore, foreshore and backshore processes is very much in its infancy. Such models could be used to estimate the 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 existing 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 requires high quality information and a sound understanding of the interrelationships between backshore 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 the simple materials. Despite these limitations, a number of process-response models have been developed to predict recession scenarios.

(e) Holderness predictive model

The predicative model developed by IECS (1994) was used to investigate the impact of coastal defence works on the northern Holderness coast, with particular reference to the formation of stable bays. The model relates the potential recession rate to the longshore sediment transport rate and the probability of occurrence of a beach at the cliff foot, involving:

- calculation of shoreline orientation with respect of wave approach; this is a critical aspect of the coastal response to defence construction since it controls the wave approach angle and therefore longshore power gradients. Net potential annual transport rates were, therefore, calculated for every possible coastal orientation on the Holderness coastline;

- calculation of annual potential sediment transport for the shoreline orientation and sediment inputs to a cliff section;
- estimation of the probability of a beach being present over an annual series in front of a cliff section, as follows:

$$\text{Probability of Beach} = \frac{\text{Net Transport - Net Inputs}}{\text{Net Transport}} \text{ x No in Annual Series}$$

- estimation of annual cliff recession, as follows:

  Erosion rate = k(e^{10} (probability of beach))
  Where k is a calibration constant.

- re-calculation of shoreline orientation.

The model was found to provide an accurate simulation of the development of the coast to the south of Hornsea following the construction of the Hornsea defences over 70 years ago. The model showed that, given a single defence deployment with an open coast to its south, a shallow bay develops whose southern extremity lies some 10km to the south of the hardpoint.

(f) Cliff recession model

CLIFFPLAN is a recently-developed cliff recession simulation (Meadowcroft et al. 1999; Hall et al. 2000b; Walkden et al. 2001). 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.

The model was developed to simulate the recession of an unprotected coastal slope developed in London Clay and is based on two-dimensional (i.e. cross-shore) models of beach/cliff behaviour. The main stages in the model are:

1. wave conditions and water level are selected from the appropriate probability distribution, using Monte Carlo sampling. The wave height is limited to account for wave breaking effects. This effectively introduces a correlation between wave height and water level as only high water levels can result in high wave heights;
2. the wave approach angle and longshore drift rates are calculated, using the appropriate CERC formulae;
3. wave run-up levels are calculated;
4. erosion of either the foreshore debris (if there is any) or the cliff toe (if it is not protected by debris) is estimated. The erosion rate is assumed to depend on wave height and is calculated from the erosion/transport formula outlined above. If there is debris, then the model goes back to step 1. If not, then it is assumed that the cliff toe may have been further eroded, and a check on the stability of the cliff (factor of safety) is carried out, using the relevant stability tables. When accessing the stability charts, the amount of basal erosion is defined by the current position of the modelled cliff profile and the groundwater level is selected randomly.
5. if the factor of safety is less than 1.0, then cliff failure takes place, the cliff retreats by a distance corresponding to the amount specified in the relevant stability table. The debris from the cliff is distributed on the beach where it protects the toe of the cliff for subsequent time-steps. The program writes out the cliff position and resultant geometry for later plotting and returns to step 1. Note that as the model progresses through a series of recession events, the relevant stability chart will change. If the factor of safety is greater than 1.0, then a cliff fall takes place and the simulation continues, returning to step (1).
6. The beach plan position and beach level are updated at all sections, taking account of longshore drift rates and sediment supply from the cliff.

These steps are repeated as necessary to build up a sequence of cliff position predictions over the required time-span. The simulation can then be repeated, but with a different random sequence of waves, water levels and groundwater levels to give a different prediction of cliff behaviour. Many such simulations can be carried out to establish a probabilistic prediction of cliff recession.

Empirical Modelling

Although there is much uncertainty about the impact of sea level rise and climate change, it is expected to result in increased recession rates (e.g. Samuals and

Brampton 1996). A number of simple empirical models are available to provide an indication of the possible changes:

(g) Historical projection

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.

(h) Geometric models;

Here, 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 foot of the cliff. 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 closure depth is the boundary of the profile beyond which there is little loss of sediment.

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

(i) Sediment Budget methods;

The Brunn 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 Brunn 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 adaption of the Bruun Rule for eroding cliffs (Bray and Hooke 1997).

(j) Shore Platform Geometrical Model;
With no dissipative beach, 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. Comparison of the model results against current conditions indicates that recession could accelerate significantly at all sites, although the estimated increases vary between models. Bray and Hooke (1997) concluded that reliable extrapolations of historical recession are the most important elements in the model predictions, irrespective of the selected sea level rise figures.

Appendix B

Defences Technical Report

Introduction

Aim

This report sets out the philosophy behind the methodology for the analysis of coastal defences.

Definitions

The failure of coast protection defences will lead to erosion of the coastline that they protect. Failure occurs only when the defence is breached – this differs from coastal flood defences which can fail due to excessive overtopping as well as breaching. The most common failure modes of coast protection defences are toe erosion and loss of beach.

Failure is defined as the point at which a defence is not providing the required level of protection. It may be that a defence structure is still present and structurally intact, but it is not providing the necessary overtopping protection due to its poor condition, perhaps a lack of roughness on the front face. In other instances, such as toe erosion, total collapse of the defence will occur at the point of failure. In many cases, some part of the defence structure will remain, providing some degree of residual protection and thus delaying the onset of erosion.

Approach

The approach that has been adopted is to consider how defence structures fail and then design a series of tests to investigate these various failure modes. A number of tests have been established and these can be performed at different levels of analysis with different levels of data. Some coast protection defences will have more data associated with them than others – this may be because of erosion problems in the area, valuable local assets or because of a high degree of local knowledge for some other reason. It is important that the analysis makes the most of all the information that is available so that the risk assessment is as full and accurate as possible. It is, however, also important for the effort involved to be proportionate with respect to the level of analysis being undertaken.

General Approach

Background
The event tree representing the failure modes of coast protection defences is shown in Figure 2.1. It illustrates that there are two chains of events that can lead to breaches, namely:

- Structural damage – due to failure of the defence structure and components;
- Geotechnical failure – due to changes in ground conditions.

There are two factors that influence these types of failures. Assuming a defence has been correctly designed and constructed, these are changes in the forcing conditions, ie waves, water levels and beach levels, and changes in structural condition, ie deterioration. These factors will affect defences of different structural forms in different ways. This is considered in more detail in the following sections and summarised in Table 2.1.

Structural Damage
There are three forms of structural damage that can lead to defence failure, namely:

- damage to the seaward face;
- damage to the landward face;
- damage to the crest.

Each of these types of damage is discussed in more detail below.

Seaward Damage
Damage to the seaward face of a coast protection defence can be caused by:

- Toe erosion - falling beach levels can cause deteriorating defences and structural failure. Low beaches allow deeper water at the defence and thus more severe forcing conditions act on the defence structure. This can lead to increased deterioration, component failure, additional overtopping and the loss of core material underneath any toe structure that becomes exposed. It can also cause instability of the entire defence, particularly in defence forms that are highly dependant on their toe structure, such as vertical seawalls;

- Component failure – this is caused mainly by poor condition/ lack of maintenance but potentially also by falling beach levels which lead to the hydraulic conditions at the defence to be more severe than anticipated. Depending on the structural form, this can lead to reduced hydraulic performance or even collapse of entire defence structure;
- Joint failure – this is caused by poor condition/ lack of maintenance and can lead to the wash-out of core material through the joints in a defence structure.
- Loss of core – this can be caused either by joint or component failure and/or toe erosion. Joint and component failure can cause the wash-out of core material through the joints and external faces of a defence respectively, whilst toe erosion can cause the loss of this material underneath an exposed toe structure. The loss of core material reduces the hydraulic performance of the defence – it can lead to the creation of internal voids and the collapse of the outer layers of the structure.

Landward & Crest Damage
Both of these types of damage are caused by excessive overtopping. The damage will be particularly severe if either of these faces is unprotected or if the protection can be easily eroded. Insufficient crest height is the main cause of excessive overtopping. It can be compounded by falling beach levels, which causes hydraulic conditions to be more severe than anticipated, and also by deterioration, such as reduced roughness on the seaward face of the defence. As previously noted, most coastal defences are not embankments and thus do not have landward faces. A high proportion of coastal defences do, however, have some form of crest structure.

Geotechnical Failure
There are 2 types of geotechnical failure, namely:

- seaward – failure on the seaward face of the defence;
- landward – failure on the landward face of the defence. Note, this failure mode primarily relates to embankment-type structures. Most coast protection defences are generally walls, revetments or beaches – there are relatively few embankments as this structural form is mostly used for flood defences.

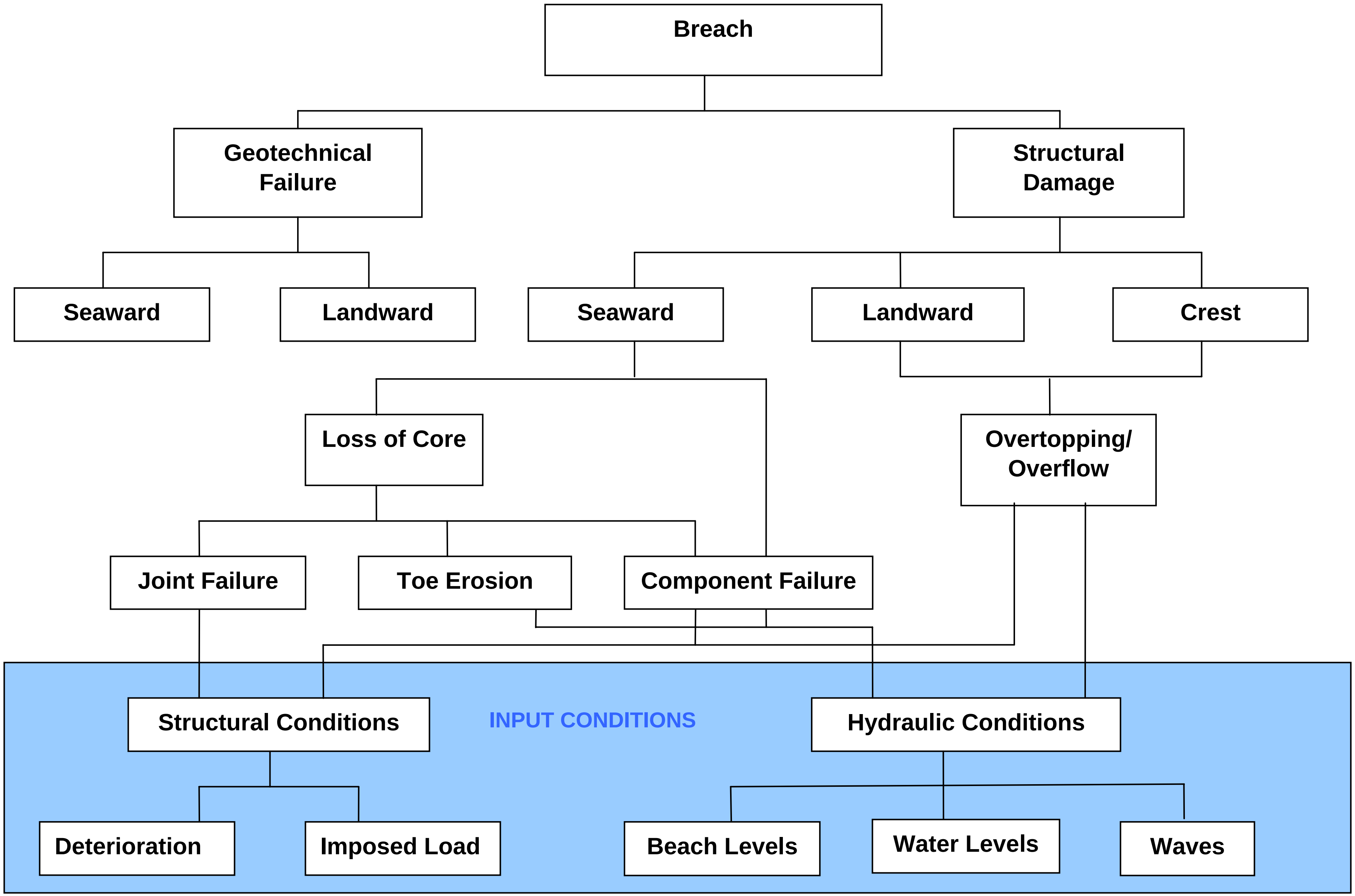


Figure 2.1 Event Tree of Coast Protection Defence Failure

Failure Mode	Triggers		
	Dominant	**Other**	**Comment**
Toe Erosion	Beach levels	Beach volatility	Toe dependency of structure and beach composition also influential
Joint Failure	Condition	Higher loading	Known at design stage
		Degree of exposure	Coastal conditions more severe than anticipated
Component Failure	Condition	Higher loading	Coastal conditions more severe than anticipated.
		Degree of exposure	Known at design stage
		Toe dependency	Varies with structural form
Loss of Core	Toe Erosion	Component Failure	Depends on all these triggers
	Joint Failure	Condition	
Geotech Failure – Seaward	Beach Levels	Beach Volatility	
Geotech Failure – Landward	Overtoppping	Protection to crest/ rear face	Only applies to embankments – few coastal defences of this form
Geotech Failure - other	Settlement	Piping	Settlement - lack of bearing strength; Piping - steep hydraulic gradients; Liquifaction - excess pore water pressure. All analyses need detailed geotechnical data - unlikely to be known for most defences.
		Liquifaction	

Table 2.1 Summary of Factors Influencing Coast Protection Defence Failure

Geotechnical failure modes include:

- Rotation – where the rotation moment from a defence exceeds the resistance provided by the ground conditions, for instance where erosion has reduced the volume of beach material supporting the defence;
- Sliding – where the sliding force from a defence exceeds the resistance provided by the ground conditions. Sliding usually occurs along existing failure planes, such as where erosion has reduced the volume of beach material at a defence;
- Settlement – where the load from a defence exceeds the bearing capacity of the ground;
- Piping – where steep hydraulic gradients are present across a defence structure;
- Liquifaction – where excessive pore water pressure is present at a defence.

The latter three failure modes require detailed geotechnical information – it is unlikely that this information will be available for most defences.

Classification of Defence Forms

Different failure modes affect defences of different structural forms in different ways and thus require different assessment methods. An important first step in any coastal defence assessment system is therefore to classify individual defences according to their structural forms. This will ensure that the defence is assessed in the most suitable manner, with tests and thresholds specific to the specific defence form.

Once a defence has been established as a coast protection defence rather than a coastal flood protection defence, a more detailed assessment of its structural form can be made using the classification system illustrated in Figure 2.2. There are different categories for defences with vertical and sloping front faces and also for the width of the defence structure. The classification can be made by consideration of the defence type as recorded in the NFDDD as well as site inspections and local knowledge.

Not all failure modes can be analysed by such a testing regime but for the majority of defences some insight can be gained through such analysis. The degree of insight that is obtained depends ion the level of analysis that is required and also on the amount of information that is available for a defence.

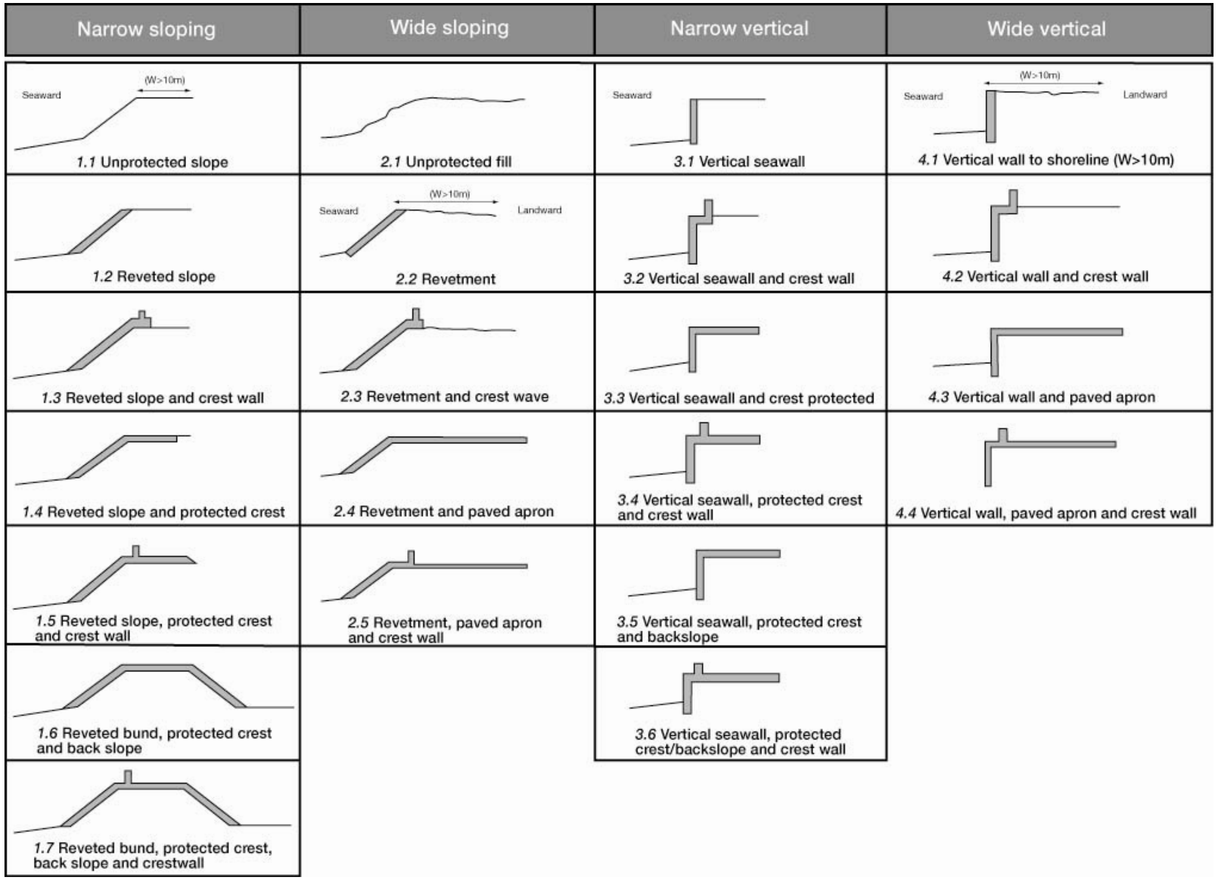


Figure 2.2 Structure Classification System

Assessment Procedure

Overview
The system that has been established to analyse the potential failure of coastal defences has two basic components. These are:

- A classification system to categorise the type of defence being analysed;
- A testing regime to investigate potential failure modes.

Further details of these components are provided below.

Data Sources
An important consideration in establishing a testing system is the data that will be available for the tests.

For the purposes of this project it is anticipated that basic data on coastal defences will be available from the NFCDD. It is acknowledged that in its present form there are many inaccuracies and omissions in the NFCDD, however for the purposes of this project it has been assumed that at some point in the future the database will be correctly and completely populated and will be the central national repository for information on coastal defences. As part of this project, a number of additional fields which would ideally be included within a future expanded version of NFCDD were identified. It is also anticipated that most of the users of the testing system will have some degree of local knowledge of individual defences and the prevailing site conditions - the tests have been designed to maximise the use of this knowledge where it is available. Furthermore, it is recognised that in some instances particularly detailed information exists for a defence and thus detailed techniques have been developed for these cases. Alternatively, for other defences it may be the case that the only information that exists in the present day is that which is available from site visits alone and perhaps also NFCDD – basic testing procedures thus need to be developed for such instances.

Methodology
Defence Classification System
The first stage of the testing regime is the classification of the form of the defence in accordance with the system illustrated in Figure 2.2. It should be noted that for the simpler versions of the testing procedures, it may be not be necessary to

classify the defence type as this will not make any difference the way in which these levels of analysis are conducted.

Testing Regime

The second stage of the testing system is the assessment procedure to investigate the potential coastal defence failure. A range of techniques has been developed, the simplest being based on a single site visit whilst the most complex requires detailed structural investigation and analysis. The intermediate techniques comprise a simple qualitative assessment and two levels of quantitative analysis, both simple and more detailed.

Full details of the techniques and individual tests developed for the testing regime are provided in Part 2 of this document, Appendix B.

Ergon House
Horseferry Road
London SW1P 2AL

www.defra.gov.uk

defra
Department for Environment
Food and Rural Affairs