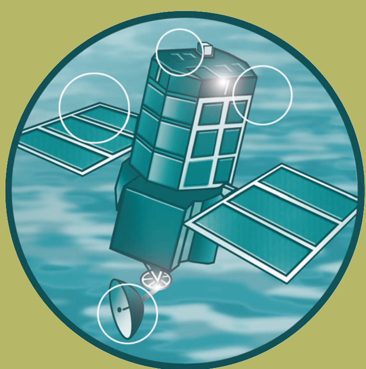
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Risk assessment of coastal erosion Part Two - Tools

R&D Technical Report FD2324/TR2



Environment Agency

defra
Department for Environment Food and Rural Affairs

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Risk Assessment of Coastal Erosion Part Two - Tools

R&D Technical Report FD2324/TR2

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

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Appendix A

Techniques for Erosion

1 Introduction

The methodology for assessing risk has two components, including, (i) natural erosion, and (ii) failure of coastal defence. Each component has a number of factors that require consideration and a range of associated techniques, depending upon the degree of sophistication of the analysis.

At the broadest level, there are several degrees of complexity which enable the determination of the techniques to obtain results might range from very detailed to coarse, and using information ranging from qualitative or subjective, through to quantifiable and even expertly applied models. Decision on the appropriate use of these techniques relate to the nature of the problems, the importance (value) of assets, the data available and the accuracy of output required.

1.1 Definitions

For the purposes of this project the following definitions have been assumed (refer to Appendix D for more definitions):

- Erosion – unconstrained erosion of all coastal landforms and including coastal instabilities such as landslips.
- Defence Failure – total failure of a defence structure.
- Erodible Landforms – any coastal backshore landform which does not front a flood area. These are predominantly cliffs but also include slopes, gently rising ground and significant dune structures.

1.2 General Framework

There is a general framework that can be used for assessing the probability of coastal erosion, around which the different techniques have been developed depending upon data and level of assessment appropriate, but all lead to the same form of output.

In all cases, accounting for erosion has two components;

- the instability and erosion process itself, i.e. the mechanisms and rate at which it might occur (definition of the hazard);

- any resistance to instability and erosion, i.e. coastal protection and slope stability measures (modification of the hazard).

Both of these are variable but in different ways. With regard to erosion there is uncertainty over the time as to when the landform will erode, by how much and if this would be instantaneous or gradual. With regard to resistance to instability, there is the impact of failure of coastal defences and sea level rise.

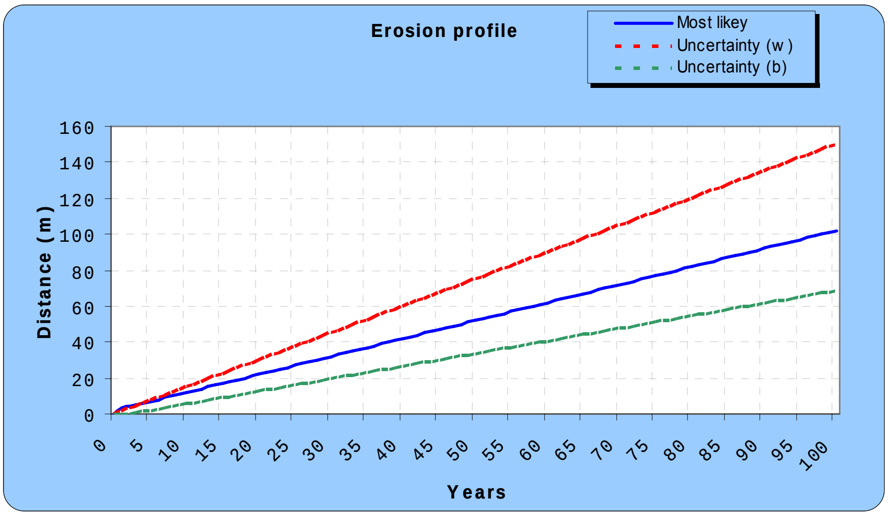
Even different types of cliff will be affected in different ways and to varying degrees by these two components. However, the overarching principles can be applied to any situation, irrespective of scale or level of information available. It is the use of techniques that input to this that accommodate the variability.

Supporting information relating to erosion that sits behind this general framework, which underpins these techniques, is documented in Annex D.

1.3 Form of Output

Irrespective of the simplicity or complexity of any given techniques, each should lead to the same basic output; a recession timeline. The principal difference between the output from various techniques is its accuracy and the level of confidence that can be attributed to it.

The following chart illustrates the output that the User is required to produce, with the blue line indicating the best assessment, and the degree of uncertainty shown by the red and green lines:



So, in the above example, based upon the User's assessment of cliff recession, the cliffs are expected to erode inland by an average distance of 102m over the next 100 years, although there is potential that the cliffs could eroded by a little as 68.6m, or as much as 150m over the next 100 years.

In all cases the User will deliver the Risk Assessment Methodology in a simple spreadsheet form.

Year	Erosion Distance (metres)	Upper and Lower Bound (metres)	
0	0	0	0
1	3	1.5	0
2	4	3	0
	etc	etc	etc
18	20	27	11.2
19	21	28.5	11.9
20	22	30	12.6
21	23	31.5	13.3
22	24	33	14
	etc	etc	etc
47	49	70.5	31.5
48	50	72	32.2
49	51	73.5	32.9
50	52	75	33.6
51	53	76.5	34.3
	etc	etc	etc
98	100	147	67.2
99	101	148.5	67.9
100	102	150	68.6

1.4 Range of Techniques for determining recession

The remaining pages of this procedure outline five different techniques that can be applied to generate the defence failure timeline.

These have increasing levels of complexity, providing incremental improvements in the quality of output, but also necessitating higher levels of data input, knowledge and time. Proportionate effort is therefore a consideration in deciding upon the technique to adopt.

The description of each technique includes guidance on how it can be carried out (supported by detailed appendices), advice on appropriateness of use and limitations of the method.

A brief overview of the five techniques is contained in the table below.

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. Data not available for dune frontages.
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 SRC* 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 SRC* manual to calculate single recession rates.	Likely to provide most accurate output. Methods require extensive data and expert input.

*SRC = Lee E. M. & Clark A. R., 2002. The Investigation and Managemnet of Soft Rock Cliffs. Thomas Telford.

In using these analysis techniques, it will be possible to determine the instability and erosion risk at any point in time.

The above techniques focus on cliff recession, but are also applicable to slopes and gently rising ground (i.e. low landscapes but higher than floodplains). Dunes, where they do not directly front a flood plain, also need to be considered and Techniques 1 and 3 will be applicable. Due to the complex nature of these landforms however, with scope for reworking and scope for accreting, it is likely that the quality of output will be highly dependent upon site-specific understanding of their behaviour.

2 Technique 1 – Technical Judgement

1.1 Overview

At the most basic level, the output can be constructed from technical judgement.

1.2 Applications

It might be appropriate to apply this approach where:

- A quick answer is required.
- The User has a working knowledge of the recession characteristics of the particular length of coast.
- The assets being protected are of very low value.
- There is no other information relating to that length of coast.

1.3 Approach

2.3.1 *Coast Type*

The information required is knowledge of the characteristics of the length of coast being assessed and how it is expected to behave, i.e. progressive erosion, year-on-year recession, or via event erosion, such as landslides. There are a number of ways that the User may be able to provide this:

- On-site visual inspection and judgement by the User.
- Existing knowledge such as the cliff type and expected type of erosion.

2.3.2 *Time*

The information required is the best estimate of the time over which erosion is expected to occur. There are a number of ways that the User may be able to provide this:

- On-site visual inspection and judgement by the User.
- Existing knowledge of the geomorphology and geology, such as the cliff type, and expected type of erosion to make a judgement.

2.3.3 *Procedure*

1. From visual inspection or existing knowledge, make best estimate of the amount of erosion that will occur, based on the landform (eg. cliff type) and past behaviour.
2. Estimate upper and lower cases for erosion, ie. earliest and latest times.
3. Construct recession timeline from combining the above information

2.3.4 *Limitations*

This approach relies entirely on the knowledge of the User.

The results derived using this technique has the potential to be inaccurate because of the limited use of actual data.

3 Technique 2 – Futurecoast Assessment

1.1 *Overview*

This technique makes use of the information within Futurecoast.

1.2 *Applications*

It might be appropriate to apply this approach where:

- A large number of cliffs require analysis using a consistent baseline.
- There is limited additional information detailing the type of cliff erosion and expected rate of erosion.
- Precision of output is not essential.
- A quick answer is required
- The assets being protected are not of extremely high value.

1.3 *Approach*

The approach is to use information from the Futurecoast cliff database to answer a series of questions presented in the LEVEL1(FUTURECOAST) guidance sheet, to provide the User with an indication of the cliff erosion timeline and a level of confidence associated with the outputs.

3.3.1 *Futurecoast*

The information required is the provided in the Futurecoast Cliff Database, reference "Data and Supporting Information\Cliff Behaviour Assessment\Methodology and Cliff Classification". The assessment provides a systematic classification of coastal cliffs together with consideration of their likely activity over the next 100 years.

3.3.2 *LEVEL1(FUTURECOAST)*

A step-by-step guide to the Technique 2 procedure is provided in the Excel spreadsheet LEVEL1(FUTURECOAST) (refer to Figure A.1, Appendix A). This spreadsheet contains a series of flow charts that can be used in different situations; progressive recession (i.e. erosion); cliffs subject to episodic retreat; and to account for the potential impacts of relative sea-level rise on the future recession rates.

3.3.3 Procedures

1. Use Futurecoast cliff database and LEVEL1(FUTURECOAST) Level 1 front worksheet, to determine which flow chart is required for analysis.
2. Use Futurecoast cliff database to provide the inputs for the questions asked in the relevant flow chart. Refer to Box A.1, Appendix A for a definition of cliff-type. Refer only to the cliff sections with an *, which refers to the prediction of cliff behaviour assuming total removal of exiting coastal defences.
3. Enter the outputs (answers to questions) into the parameters table.
4. Derive average, lower and upper estimates of cliff recession (as per Table A.1 and A.2, Appendix A, and formulas in Box A.2 and A.3, Appendix A).
5. If adjusting the average rate of recession for sea level rise, add this figure to the recession rate provided by Futurecoast (Future potential change COLUMN 3).
6. Produce time-distance plot using the outputs from the relevant flow chart.

3.3.4 Limitations

Quality of source data – the data included in the Futurecoast is based upon geological mapping and broad visual inspection (aerial photographs), which contains assumptions. The data also covers large areas and will not have specific details which can vary along the coast. The results will therefore have a high uncertainty (refer to Appendix D).

Using the Brunn Rule to assess the impacts of sea level rise on the rate of cliff recession, will provide only a broad estimate.

The approach is limited to cliffed coastlines only.

4 Technique 3 – Site Specific Assessment

1.1 Overview

This level of analysis is based upon using real, site specific data, i.e. that which supersedes the information provided by the Futurecoast cliff database.

1.2 Applications

It might be appropriate to apply this approach where:

- There is a good level of information about the landform geology and geomorphology (e.g. cliff type) and recession potential.
- The User would like to undertake more site specific analysis than can be supported by the Futurecoast cliff database.
- The landform is not a cliff.

1.3 Approach

Technique 3 uses the same spreadsheets used for Technique 1, but incorporates engineering judgement and real data. The approach is to use this information and real data to answer a series of questions presented in the LEVEL1(FUTURECOAST) guidance sheet, to provide the User with an indication of the cliff erosion timeline and a level of confidence associated with the outputs.

Where the landform is not a cliff (e.g. sloping or gently rising ground) the same principles apply and this same technique can be adopted although the necessary data will need to be collected.

4.3.1 *Real Data*

Real data will be held by the User or can be collected via a range of methods. The outputs from three key questions will provide the data necessary to complete a time-distance plots found in LEVEL1(FUTURECOAST). The questions and the recommendations on how to answer them, are provided in LEVEL2(CHART) (Figure C.1, Appendix C), for example:

- Question form LEVEL2(CHART): What are the historical trends and patterns of recession?

- Answer: Establish recession rates from maps and/or aerial photographs (SRC 119-123).

LEVEL2(CHART) refers to the Soft Rock Cliffs Manual (Lee E.M. & Clark A.R., 2002. The Investigation and Management of Soft Rock Cliffs. Thomas Telford). Guidance on the techniques that can be used to obtain real data is supplied in the SRC manual.

4.3.2 *LEVEL1(FUTURECOAST)*

A step-by-step guide to the Technique 2 procedure is provided in the Excel spreadsheet LEVEL1(FUTURECOAST) (refer to Figure A.1, Appendix A). This spreadsheet contains a series of flow charts that can be used in different situations; progressive recession (i.e. erosion); cliffs subject to episodic retreat; and to account for the potential impacts of relative sea-level rise on the future recession rates.

1. Obtain real data using a combination of existing data that is more up-to-date than Futurecoast, LEVEL2(CHART) (Figure C.1, Appendix C)and the SRC manual.
2. Follow the flow chart in LEVEL1(FUTURECOAST), using the real data. Refer to Box A.1, Appendix A for a definition of cliff-type and Table B.1, Appendix B, for a reference as to where data from the Futurecoast cliff data base should be replaced with real data.
3. Enter the outputs (answers to questions) into the parameters table.
4. Derive average, lower and upper estimates of coastline recession (as per formulas in Box A.2 and A.3, Appendix A).
5. If adjusting the average rate of recession for sea level rise, add this figure to the recession rate calculated in previous actions.
6. Produce time-distance plot using the outputs from the relevant flow chart.

4.3.3 *Limitations*

Minimum data requirements to apply the methods, although these need not be too onerous and in several instances there should be a reasonable amount of information available to improve upon Technique 2.

Some information may not be readily available to the User and they therefore need to collect new data, which will take time and cost money.

5 Technique 4 – Single Rate Recession Method

1.1 Overview

This technique involves using real site specific data to calculate the rate of cliff recession.

1.2 Applications

It might be appropriate to apply this approach where:

- There is a good level of information available about the cliffs (or slopes/gently rising ground).
- The landforms are of complex or usual nature that warrants bespoke methods to be applied to determine the risk of their erosion.
- The assets being protected are of high value.
- A high level of expertise can be brought to the analysis.
- Where the User requires and improved degree of precision and reliability compared with the outputs of Techniques 1 – 3.

1.3 Approach

Technique 4 involves the development of a behavioural model based on site/area specific cliff investigations, and the use of currently available predictive models. The approach is to use real data to answer a series of questions presented in the LEVEL2(CHART) guidance sheet (Figure C.1, Appendix C), to provide the User with an indication of the recession timeline and a level of confidence associated with the outputs. The Soft Rock Cliffs Manual (Lee E.M. & Clark A.R., 2002. The Investigation and Management of Soft Rock Cliffs. Thomas Telford) provides information on the techniques that are available to the User to use the single rate recession methods, a summary is provided below.

- Extrapolation of Trends (SRC page reference 155-160): use of historical data.
- Expert Judgement (SRC 163-169): use of past experience, expert judgement and existing technical literature.
- Empirical Models (SRC 188-191): incorporation of the impact of sea level rise.

5.3.1 *Procedure*

1 Obtain real data.
2 Follow the flow chart in LEVEL2(CHART) and answer the relevant questions.
3 Develop a behaviour model from the available information.
4 Follow the flow chart in LEVEL2(CHART) and answer the relevant questions.
5 Develop a prediction model based on the behaviour model
6 Refer to single rate recession methods recommended by the SRC.
7 Produce time-distance plot

5.3.2 *Limitations*

Some information may not be readily available to the User and they therefore need to collect new data, which will take time.

6 Technique 5 – Probabilistic Recession Method

1.1 *Overview*

The most sophisticated techniques, which considers probabilistic analysis of cliff recession.

1.2 *Applications*

It might be appropriate to apply this approach where:

- There is a good level of information available about the landform.
- The cliffs (or slopes/gently rising ground) are of complex or usual nature that warrants bespoke methods to be applied to determine the risk of their erosion.
- The assets being protected are of high or exceptionally high value, e.g. nuclear power station.
- A high level of expertise can be brought to the analysis.
- Where the User requires and improved degree of precision and reliability compared with the outputs of Techniques 1– 4.

1.3 *Approach*

Technique 5 involves the development of a behaviour model based on site/area specific investigations, and the use of currently available predictive models. The approach is to use real data to answer a series of questions presented in the LEVEL2(CHART) guidance sheet (Figure C.1, Appendix C), to provide the User with an indication of the recession timeline and a level of confidence associated with the outputs. The Soft Rock Cliffs Manual (Lee E.M. & Clark A.R., 2002. The Investigation and Management of Soft Rock Cliffs. Thomas Telford) provides information on the techniques that are available to the User to use the single rate recession methods, a summary is provided below.

- Regression Analysis (SRC page reference number 155-160): use of historical data.
- Historical Event Frequency (SRC 170-173): consideration that the probability of an event happening can be based on the frequency at which that event has taken place in the past.

- Expert Judgement (SRC 160-163; 173-174): use past experience, expert judgement and existing references.
- Probabilistic Stability Analysis (SRC 169-170): computer modelling of slope stability versus. slope failures.
- Simulation Models (SRC 174-181): implementing above.
- Process Simulation Models (SRC 181-188): development of predictive models based on the interactions between the nearshore, foreshore and cliff processes.

6.3.1 *Procedure*

1. Obtain real data.
2. Follow the flow chart in LEVEL2(CHART) and answer the relevant questions.
3. Develop a behaviour model from the available information.
4. Follow the flow chart in LEVEL2(CHART) and answer the relevant questions.
5. Develop a prediction model based on the behaviour model
6. Refer to probabilistic rate recession methods recommended by the SRC.
7. Produce time-distance plot.

6.3.2 *Limitations*

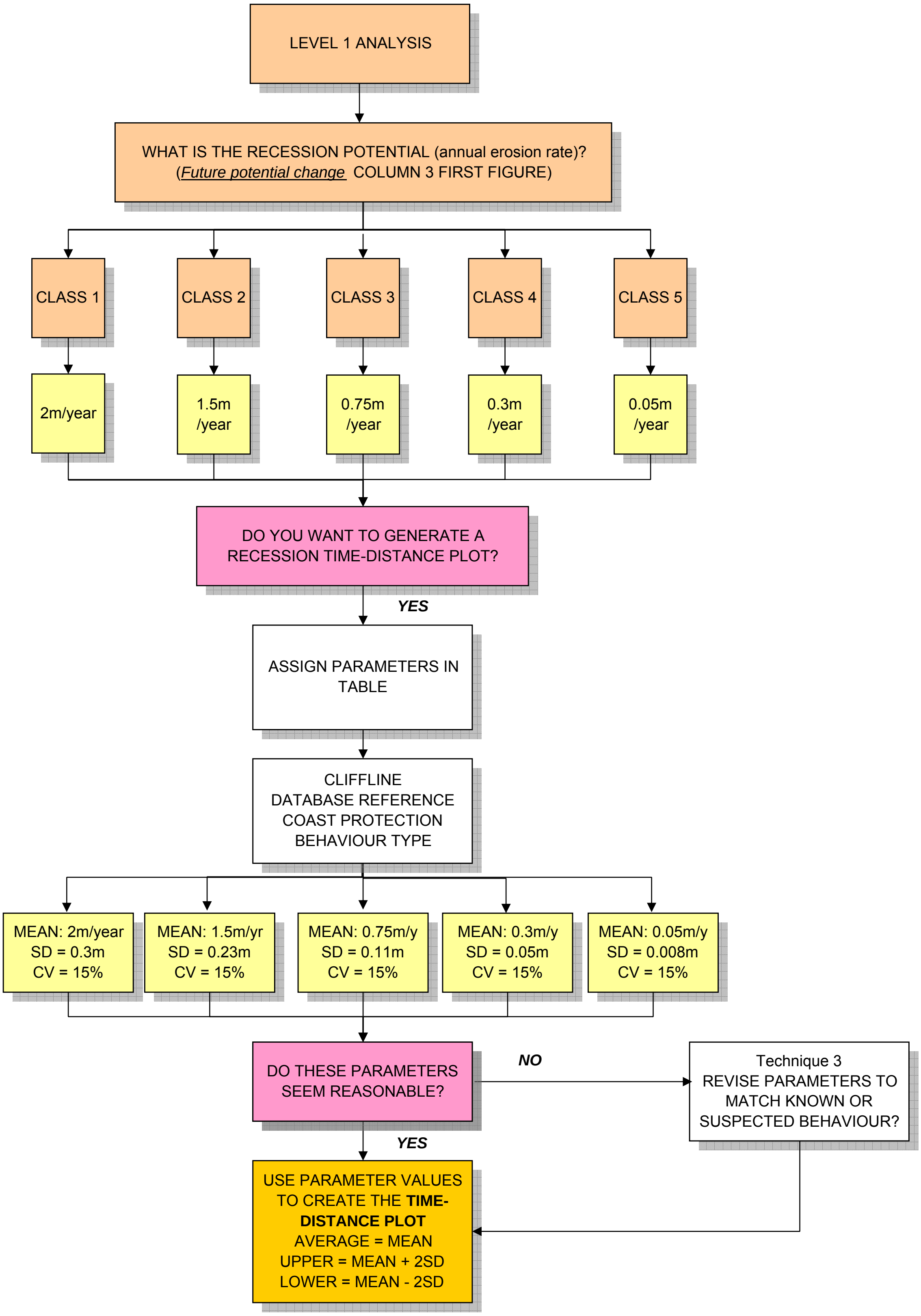
Probabilistic failure analysis models have generally been established for cliff recession, although there is also very little detailed information on past defence failures to be able to use to calibrate any such models.

Some information may not be readily available to the User and they therefore need to collect new data, which will take time.

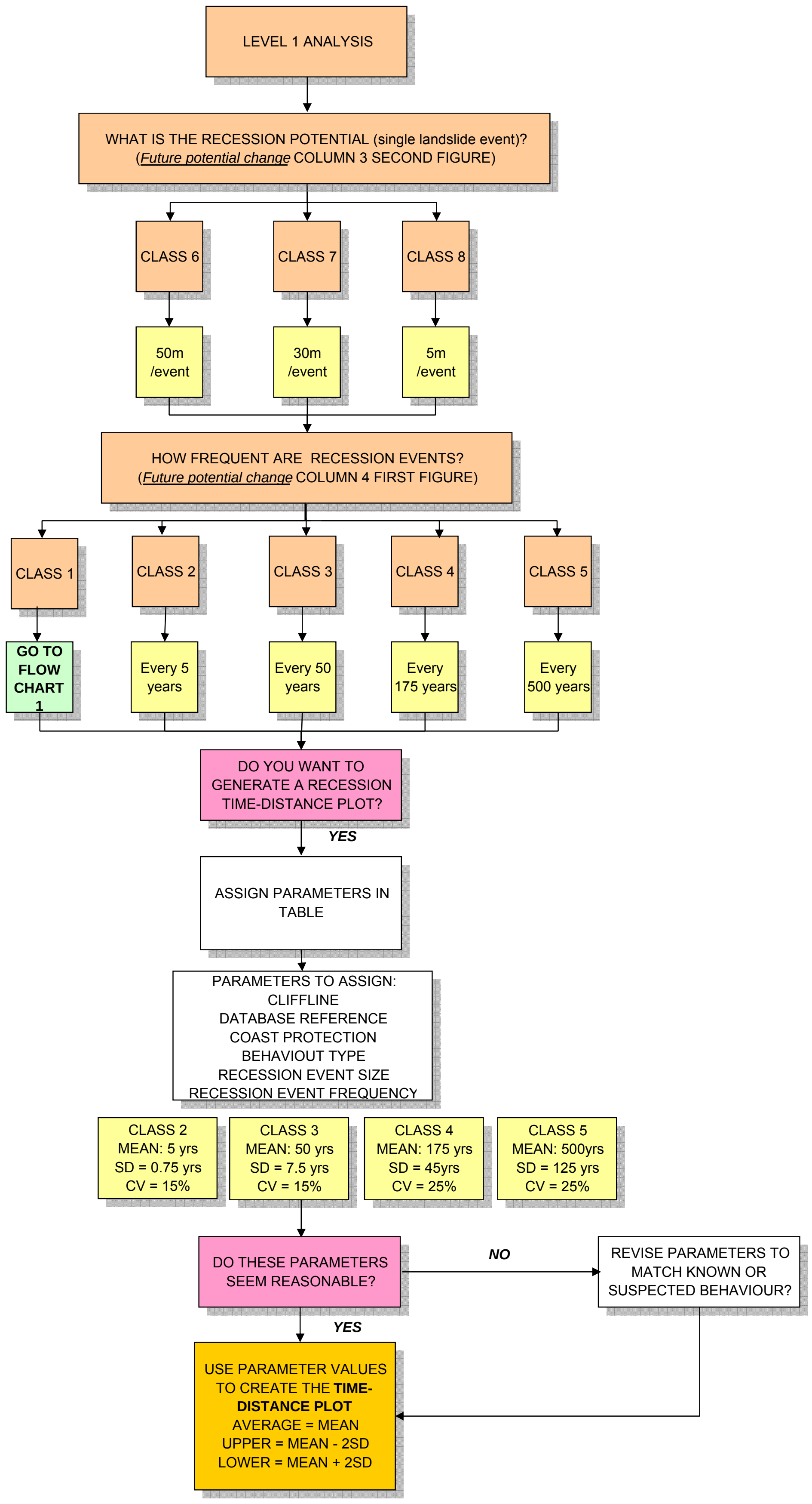
This approach may need to be undertaken by individuals with prior experience in such assessments.

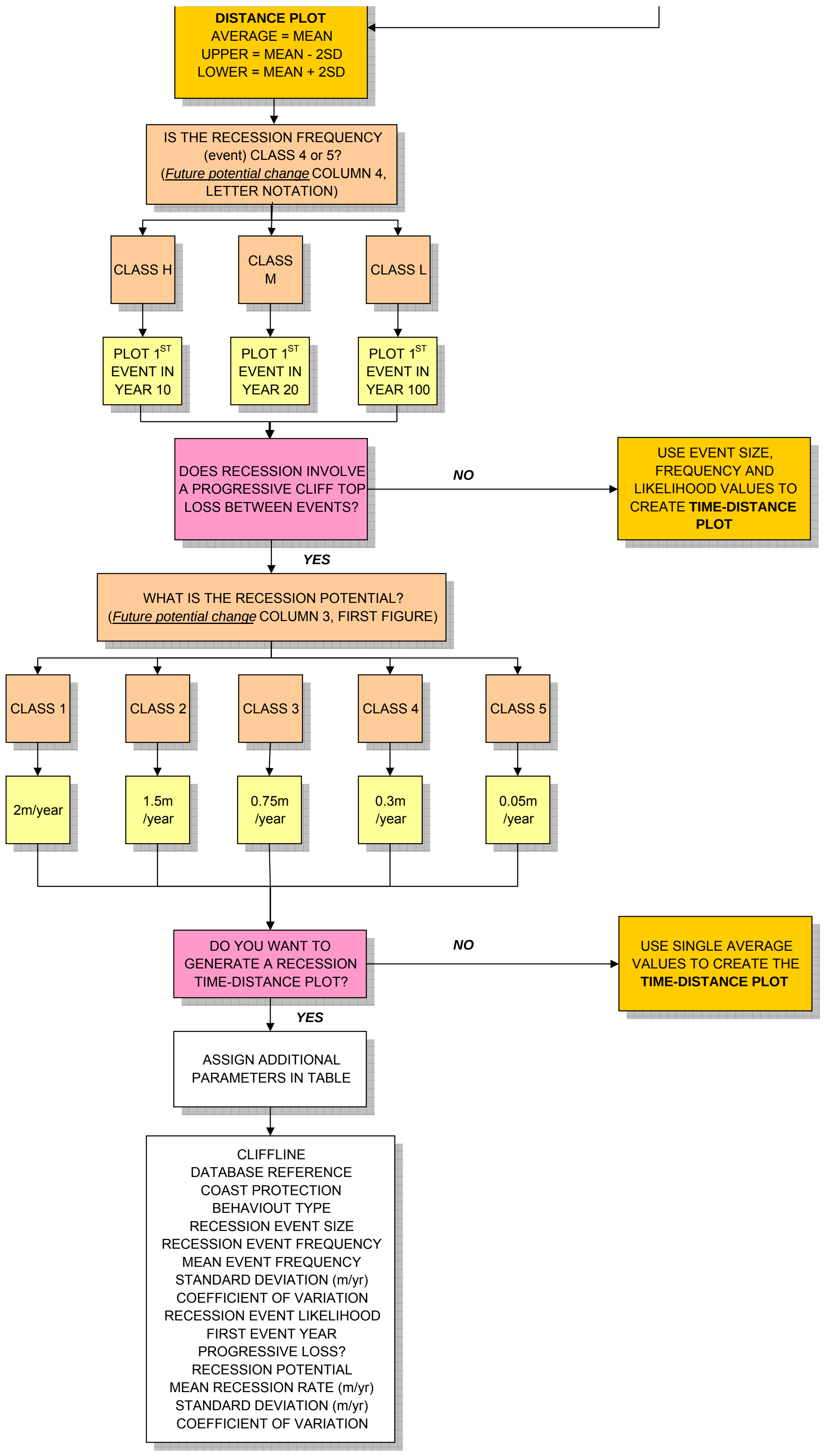
Annex A – Futurecoast Assessment

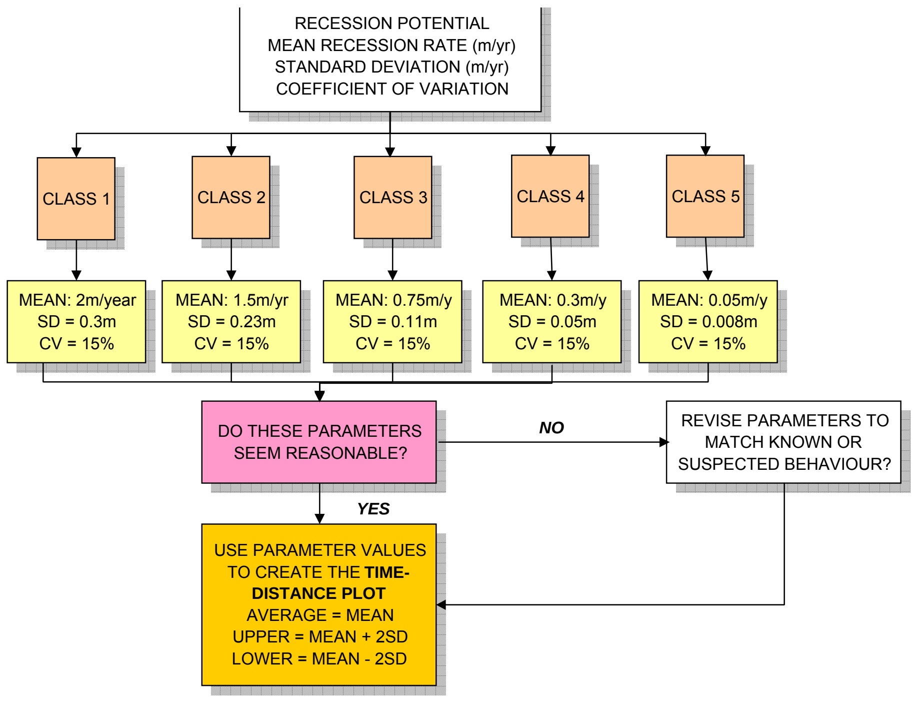
FLOW CHART 1: CREATION OF A TIME-DISTANCE PLOT FROM THE FUTURECOAST DATABASE FOR UNPROTECTED CLIFFS AFFECTED BY PROGRESSIVE RECESSION



FLOW CHART 2: CREATION OF A TIME-DISTANCE PLOT FROM THE FUTURECOAST DATABASE FOR UNPROTECTED CLIFFS AFFECTED BY EPISODIC RECESSION




DISTANCE PLOT
AVERAGE = MEAN
UPPER = MEAN - 2SD
LOWER = MEAN + 2SD
IS THE RECESSION FREQUENCY (event) CLASS 4 or 5? (Future potential change COLUMN 4, LETTER NOTATION)
CLASS H
CLASS M
CLASS L
PLOT 1ST EVENT IN YEAR 10
PLOT 1ST EVENT IN YEAR 20
PLOT 1ST EVENT IN YEAR 100
DOES RECESSION INVOLVE A PROGRESSIVE CLIFF TOP LOSS BETWEEN EVENTS?
NO
USE EVENT SIZE, FREQUENCY AND LIKELIHOOD VALUES TO CREATE TIME-DISTANCE PLOT
YES
WHAT IS THE RECESSION POTENTIAL? (Future potential change COLUMN 3, FIRST FIGURE)
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
2m/year
1.5m /year
0.75m /year
0.3m /year
0.05m /year
DO YOU WANT TO GENERATE A RECESSION TIME-DISTANCE PLOT?
NO
USE SINGLE AVERAGE VALUES TO CREATE THE TIME-DISTANCE PLOT
YES
ASSIGN ADDITIONAL PARAMETERS IN TABLE
CLIFFLINE
DATABASE REFERENCE
COAST PROTECTION
BEHAVIOUT TYPE
RECESSION EVENT SIZE
RECESSION EVENT FREQUENCY
MEAN EVENT FREQUENCY
STANDARD DEVIATION (m/yr)
COEFFICIENT OF VARIATION
RECESSION EVENT LIKELIHOOD
FIRST EVENT YEAR
PROGRESSIVE LOSS?
RECESSION POTENTIAL
MEAN RECESSION RATE (m/yr)
STANDARD DEVIATION (m/yr)
COEFFICIENT OF VARIATION


RECESSION POTENTIAL
MEAN RECESSION RATE (m/yr)
STANDARD DEVIATION (m/yr)
COEFFICIENT OF VARIATION
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
MEAN: 2m/year
SD = 0.3m
CV = 15%
MEAN: 1.5m/yr
SD = 0.23m
CV = 15%
MEAN: 0.75m/y
SD = 0.11m
CV = 15%
MEAN: 0.3m/y
SD = 0.05m
CV = 15%
MEAN: 0.05m/y
SD = 0.008m
CV = 15%
DO THESE PARAMETERS SEEM REASONABLE?
NO
REVISE PARAMETERS TO MATCH KNOWN OR SUSPECTED BEHAVIOUR?
YES
USE PARAMETER VALUES TO CREATE THE TIME-DISTANCE PLOT
AVERAGE = MEAN
UPPER = MEAN + 2SD
LOWER = MEAN - 2SD

FLOW CHART 3: ADJUSTMENT OF THE FUTURECOAST RECESSION RATES TO TAKE ACCOUNT OF RELATIVE SEA-LEVEL RISE

IS SEA-LEVEL RISE EXPECTED ALONG THE SHORELINE?

NO → USE TIME-DISTANCE PLOTS GENERATED USING THE FUTURECOAST DATABASE (**GO TO FLOW CHARTS 1-2**)

YES ↓

WHAT IS THE HISTORIC RATE OF SEA-LEVEL RISE? (SEE WOODWORTH ET AL 1999)

REFERENCE

Woodworth, P. L., Tsimplis, M. N., Flather, R. A. and Shennan, I., 1999. A review of the trends observed in British Isles mean sea level data measured by tide gauges. Geophysics Journal International, 136, 651-670.

WHAT IS THE PREDICTED RATE OF *RELATIVE* SEA-LEVEL RISE? (SEE UKCIP02)

REFERENCE

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S. 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

CALCULATE THE DIFFERENCE BETWEEN THE FUTURE (S2) AND HISTORIC (S1) SEA-LEVEL RISE? (S2-S1 mm)

WHAT IS THE CLIFF HEIGHT? (COLUMN 5)

ESTIMATE THE GRADING OF BEACH BUILDING MATERIALS (COLUMN 13, LETTER NOTATION)

GRADE f	GRADE m	GRADE c
GO TO BRUUN MODEL 1	**GO TO BRUUN MODEL 2**	**GO TO BRUUN MODEL 3**

SELECT THE APPROPRIATE **S2-S1 CURVE** ON THE MODEL

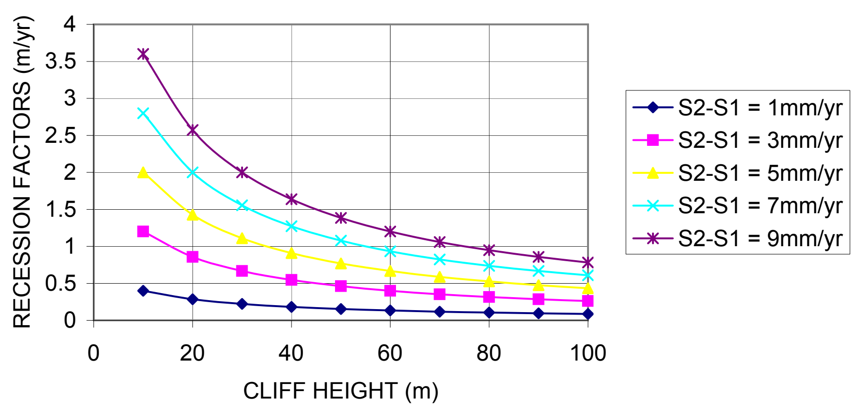
ESTIMATE THE RECESSION FACTOR FOR THE COMBINATION OF **CLIFF HEIGHT** AND **S2-S1 CURVE**

ADD THE RECESSION FACTOR TO THE MEAN RECESSION RATE FROM THE FUTURECOAST DATABASE

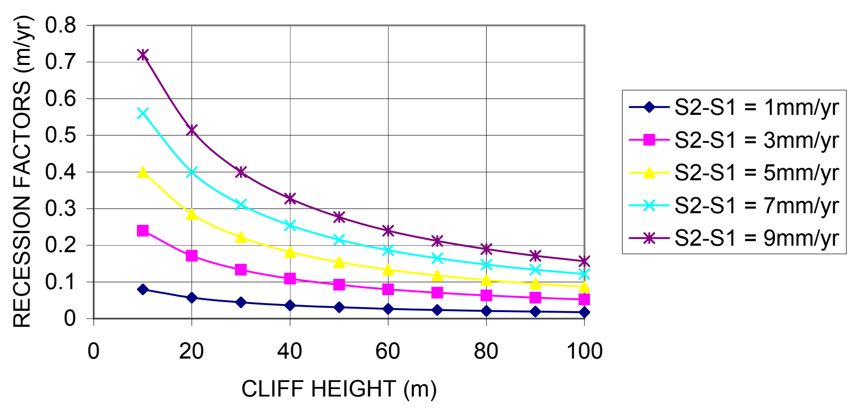
CREATE THE MODIFIED **TIME-DISTANCE PLOT**

PROGRESSIVE RECESSION (**GO TO FLOW CHART 1**)	EPISODIC RECESSION (**GO TO FLOW CHART 2**)

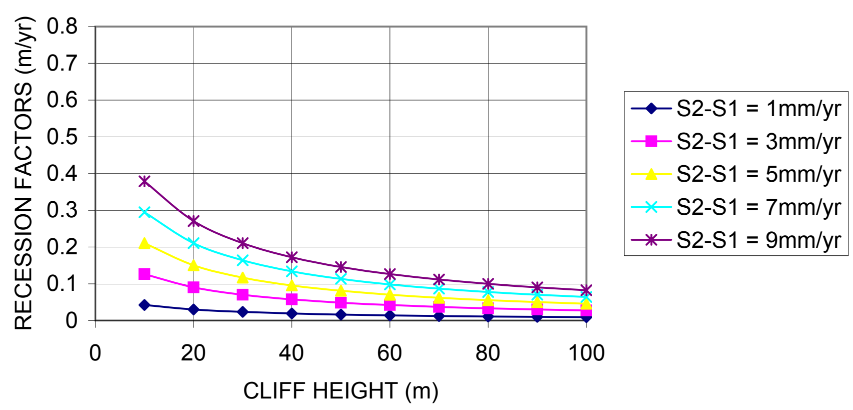
BRUUN MODEL 1: RECESSION FACTORS (P = 0.1)



BRUUN MODEL 2: RECESSION FACTORS (P = 0.5)



BRUUN MODEL 3: RECESSION FACTORS (P = 0.95)



THE ABOVE **BRUUN MODELS** ASSUME:
CLIFF-BEACH CLOSURE DISTANCE = 1000m
CLOSURE DEPTH = 15m
IF THE LOCAL CONDITIONS ARE SIGNIFICANTLY DIFFERENT, THEN IT WILL BE NECESSARY TO MODIFY AND RE-RUN THE BRUUN MODEL

REFERENCE

CHAPTER 5 IN: LEE E.M. & CLARK A.R. 2002. THE INVESTIGATION AND MANAGEMENT OF SOFT ROCK CLIFFS. THOMAS TELFORD.

EXAMPLE 1: USE OF THE FUTURECOAST DATABASE TO GENERATE A PROBABILISTIC TIME-DISTANCE PLOT

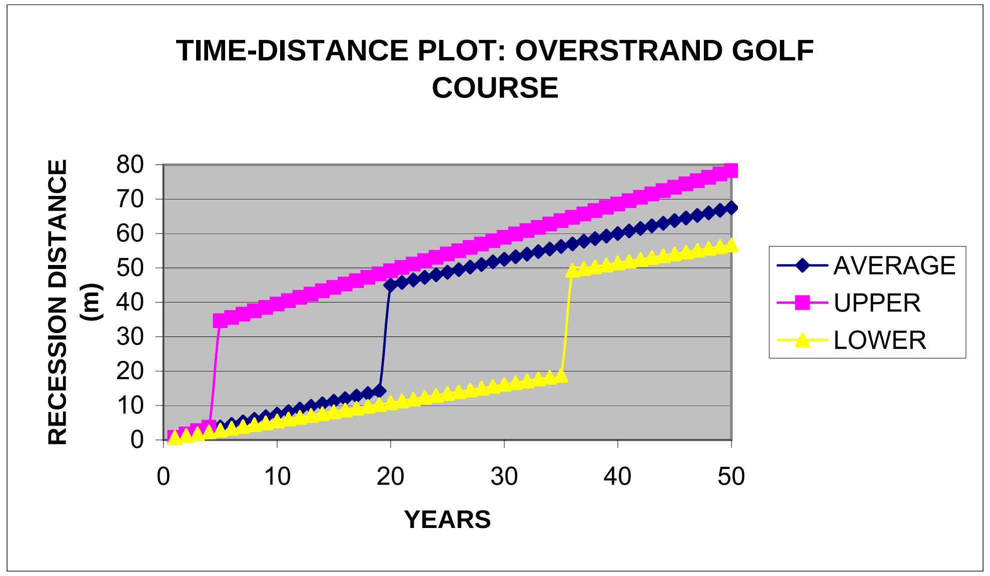
PARAMETERS TABLE	
CLIFFLINE	SIDESTRAND
COAST PROTECTION	NONE
BEHAVIOUT TYPE	TYPE 2; Progressive retreat
RECESSION POTENTIAL	CLASS 3
MEAN RECESSION RATE (m/yr)	0.75
STANDARD DEVIATION (m/yr)	0.11
COEFFICIENT OF VARIATION	15%

NOTE:
There is a 95% chance that the recession distance will lie between the Upper and Lower Estimates.

YEAR	AVERAGE ESTIMATE	UPPER ESTIMATE	LOWER ESTIMATE
1	0.75	0.97	0.53
2	1.5	1.94	1.06
3	2.25	2.91	1.59
4	3	3.88	2.12
5	3.75	4.85	2.65
6	4.5	5.82	3.18
7	5.25	6.79	3.71
8	6	7.76	4.24
9	6.75	8.73	4.77
10	7.5	9.7	5.3
11	8.25	10.67	5.83
12	9	11.64	6.36
13	9.75	12.61	6.89
14	10.5	13.58	7.42
15	11.25	14.55	7.95
16	12	15.52	8.48
17	12.75	16.49	9.01
18	13.5	17.46	9.54
19	14.25	18.43	10.07
20	15	19.4	10.6
21	15.75	20.37	11.13
22	16.5	21.34	11.66
23	17.25	22.31	12.19
24	18	23.28	12.72
25	18.75	24.25	13.25
26	19.5	25.22	13.78
27	20.25	26.19	14.31
28	21	27.16	14.84
29	21.75	28.13	15.37
30	22.5	29.1	15.9
31	23.25	30.07	16.43
32	24	31.04	16.96
33	24.75	32.01	17.49
34	25.5	32.98	18.02
35	26.25	33.95	18.55
36	27	34.92	19.08
37	27.75	35.89	19.61
38	28.5	36.86	20.14
39	29.25	37.83	20.67
40	30	38.8	21.2
41	30.75	39.77	21.73
42	31.5	40.74	22.26
43	32.25	41.71	22.79
44	33	42.68	23.32
45	33.75	43.65	23.85
46	34.5	44.62	24.38
47	35.25	45.59	24.91
48	36	46.56	25.44
49	36.75	47.53	25.97
50	37.5	48.5	26.5

EXAMPLE 2: USE OF THE FUTURECOAST DATABASE TO GENERATE A PROBABILISTIC TIME-DISTANCE PLOT WITH EPISODIC LARGE EVENTS

PARAMETERS TABLE	
CLIFFLINE	OVERSTRAND GOLF COURSE
COAST PROTECTION	NONE
BEHAVIOUT TYPE	TYPE 4; COMPLEX CLIFF
RECESSION EVENT SIZE	CLASS 7
VOLUME PER EVENT	30
RECESSION EVENT FREQUENCY	CLASS 3
MEAN EVENT FREQUENCY	50
STANDARD DEVIATION (m/yr)	7.5
COEFFICIENT OF VARIATION	15%
RECESSION EVENT LIKELIHOOD	MEDIUM (ASSUMED)
FIRST EVENT YEAR	20
PROGRESSIVE LOSS?	YES
RECESSION POTENTIAL	CLASS 3
MEAN RECESSION RATE (m/yr)	0.75
STANDARD DEVIATION (m/yr)	0.11
COEFFICIENT OF VARIATION	15%

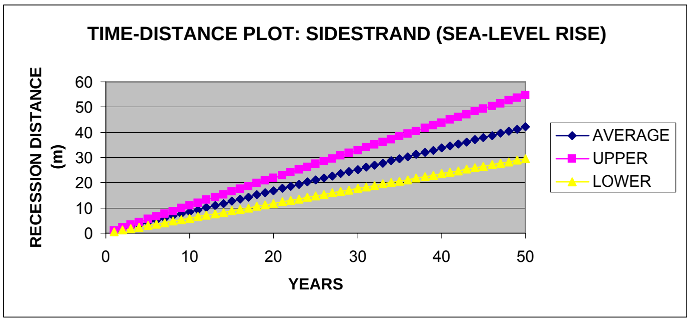


NOTE:
There is a 95% chance that the recession distance will lie between the Upper and Lower Estimates.

	AVERAGE ESTIMATE			UPPER ESTIMATE			LOWER ESTIMATE		
YEAR	EVENTS	PROGRESSIVE	OVERALL	EVENTS	PROGRESSIVE	OVERALL	EVENTS	PROGRESSIVE	OVERALL
1		0.75	0.75		0.75	0.75		0.75	0.75
2		1.5	1.5		1.72	1.72		1.28	1.28
3		2.25	2.25		2.69	2.69		1.81	1.81
4		3	3		3.66	3.66		2.34	2.34
5		3.75	3.75	30	4.63	34.63		2.87	2.87
6		4.5	4.5	30	5.6	35.6		3.4	3.4
7		5.25	5.25	30	6.57	36.57		3.93	3.93
8		6	6	30	7.54	37.54		4.46	4.46
9		6.75	6.75	30	8.51	38.51		4.99	4.99
10		7.5	7.5	30	9.48	39.48		5.52	5.52
11		8.25	8.25	30	10.45	40.45		6.05	6.05
12		9	9	30	11.42	41.42		6.58	6.58
13		9.75	9.75	30	12.39	42.39		7.11	7.11
14		10.5	10.5	30	13.36	43.36		7.64	7.64
15		11.25	11.25	30	14.33	44.33		8.17	8.17
16		12	12	30	15.3	45.3		8.7	8.7
17		12.75	12.75	30	16.27	46.27		9.23	9.23
18		13.5	13.5	30	17.24	47.24		9.76	9.76
19		14.25	14.25	30	18.21	48.21		10.29	10.29
20	30	15	45	30	19.18	49.18		10.82	10.82
21	30	15.75	45.75	30	20.15	50.15		11.35	11.35
22	30	16.5	46.5	30	21.12	51.12		11.88	11.88
23	30	17.25	47.25	30	22.09	52.09		12.41	12.41
24	30	18	48	30	23.06	53.06		12.94	12.94
25	30	18.75	48.75	30	24.03	54.03		13.47	13.47
26	30	19.5	49.5	30	25	55		14	14
27	30	20.25	50.25	30	25.97	55.97		14.53	14.53
28	30	21	51	30	26.94	56.94		15.06	15.06
29	30	21.75	51.75	30	27.91	57.91		15.59	15.59
30	30	22.5	52.5	30	28.88	58.88		16.12	16.12
31	30	23.25	53.25	30	29.85	59.85		16.65	16.65
32	30	24	54	30	30.82	60.82		17.18	17.18
33	30	24.75	54.75	30	31.79	61.79		17.71	17.71
34	30	25.5	55.5	30	32.76	62.76		18.24	18.24
35	30	26.25	56.25	30	33.73	63.73		18.77	18.77
36	30	27	57	30	34.7	64.7	30	19.3	49.3
37	30	27.75	57.75	30	35.67	65.67	30	19.83	49.83
38	30	28.5	58.5	30	36.64	66.64	30	20.36	50.36
39	30	29.25	59.25	30	37.61	67.61	30	20.89	50.89
40	30	30	60	30	38.58	68.58	30	21.42	51.42
41	30	30.75	60.75	30	39.55	69.55	30	21.95	51.95
42	30	31.5	61.5	30	40.52	70.52	30	22.48	52.48
43	30	32.25	62.25	30	41.49	71.49	30	23.01	53.01
44	30	33	63	30	42.46	72.46	30	23.54	53.54
45	30	33.75	63.75	30	43.43	73.43	30	24.07	54.07
46	30	34.5	64.5	30	44.4	74.4	30	24.6	54.6
47	30	35.25	65.25	30	45.37	75.37	30	25.13	55.13
48	30	36	66	30	46.34	76.34	30	25.66	55.66
49	30	36.75	66.75	30	47.31	77.31	30	26.19	56.19
50	30	37.5	67.5	30	48.28	78.28	30	26.72	56.72

EXAMPLE 3: USE OF THE FUTURECOAST DATABASE TO CREATE A PROBABILISTIC TIME-DISTANCE PLOT TAKING ACCOUNT OF RELATIVE SEA-LEVEL RISE

PARAMETERS TABLE	
CLIFFLINE	SIDESTRAND
S1 HISTORIC SEA-LEVEL RISE (m/yr)	0.0018
S2 FUTURE SEA-LEVEL RISE (m/yr)	0.005
S2-S1	0.003
CLIFF HEIGHT	50
BEACH BUILDING MATERIALS	m
PROPORTION OF SEDIMENTS (P)	0.5
BRUUN MODEL	2
ESTIMATED RECESSION FACTOR	0.09
COAST PROTECTION	NONE
BEHAVIOUR TYPE	TYPE 2; Progressive retreat
RECESSION POTENTIAL	CLASS 3
HISTORIC MEAN RECESSION RATE (m/yr)	0.75
ADJUSTED MEAN RECESSION RATE (m/yr)	0.84
STANDARD DEVIATION (m/yr) (MEAN x CV)	0.13
COEFFICIENT OF VARIATION	15%



NOTE:
There is a 95% chance that the recession distance will lie between the Upper and Lower Estimates.

YEAR	AVERAGE ESTIMATE	UPPER ESTIMATE	LOWER ESTIMATE
1	0.84	1.10	0.59
2	1.68	2.19	1.18
3	2.53	3.29	1.77
4	3.37	4.38	2.36
5	4.21	5.48	2.95
6	5.05	6.57	3.54
7	5.90	7.67	4.13
8	6.74	8.76	4.72
9	7.58	9.86	5.31
10	8.42	10.95	5.90
11	9.27	12.05	6.49
12	10.11	13.14	7.08
13	10.95	14.24	7.67
14	11.79	15.33	8.25
15	12.63	16.43	8.84
16	13.48	17.52	9.43
17	14.32	18.62	10.02
18	15.16	19.71	10.61
19	16.00	20.81	11.20
20	16.85	21.90	11.79
21	17.69	23.00	12.38
22	18.53	24.09	12.97
23	19.37	25.19	13.56
24	20.22	26.28	14.15
25	21.06	27.38	14.74
26	21.90	28.47	15.33
27	22.74	29.57	15.92
28	23.58	30.66	16.51
29	24.43	31.76	17.10
30	25.27	32.85	17.69
31	26.11	33.95	18.28
32	26.95	35.04	18.87
33	27.80	36.14	19.46
34	28.64	37.23	20.05
35	29.48	38.33	20.64
36	30.32	39.42	21.23
37	31.17	40.52	21.82
38	32.01	41.61	22.41
39	32.85	42.71	23.00
40	33.69	43.80	23.58
41	34.53	44.90	24.17
42	35.38	45.99	24.76
43	36.22	47.09	25.35
44	37.06	48.18	25.94
45	37.90	49.28	26.53
46	38.75	50.37	27.12
47	39.59	51.47	27.71
48	40.43	52.56	28.30
49	41.27	53.66	28.89
50	42.12	54.75	29.48

Simple cliff systems; comprising a single sequence of sediment inputs (from falls or slides) and outputs with limited storage. Examples include: 'soft' unconsolidated sands and gravels found on the Suffolk coast or 'harder' rock cliffs, such as the Chalk cliffs of East Sussex;

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. Examples include: rotational failures on the London Clay cliffs of north Kent; mudslides on the north Norfolk and east Dorset coasts.

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. Examples include the Durham cliffs comprising mudslide systems developed in till over limestone cliffs prone to rockfalls and the cliffs at Flamborough Head where tills overlie near vertical Chalk cliffs.

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 cliffs of Christchurch Bay and the west Dorset cliffs, and cliffs affected by seepage such as Chale Cliff, Isle of Wight;

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 Landslip Nature Reserve, East Devon and East Cliff, Lyme Regis and the 'slope-over-wall' cliffs of south-west England.

Box A.1 Definition of Cliff Types

Probability distribution parameter	Example	Futurecoast cliff database reference
Cliffline	SIDESTRAND	Characteristics COLUMN 1
Coast Protection	NONE	Non-applicable
Behaviour Type	TYPE 2; Progressive retreat	Characteristics COLUMN 2
Recession Potential	CLASS 3	Future potential change COLUMN 3 FIRST FIGURE
Mean recession rate (m/yr)	0.75	Refer to Flow Chart 1, level 4 from top
Standard deviation (m/yr)	0.11	Refer to Flow Chart 1, level 8 from top
Coefficient Of Variation	15%	Refer to Flow Chart 1, level 8 from top

Table A.1: Flow Chart 1

Probability distribution parameter	Example	Futurecoast cliff database reference
Cliffline	OVERSTRAND GOLF COURSE	Characteristics COLUMN 1
Coast protection	NONE	Non-applicable
Behaviour type	TYPE 4; COMPLEX CLIFF	Characteristics COLUMN 2
Recession event size	CLASS 7	Future potential change COLUMN 3 SECOND FIGURE
Volume per event	30	Refer to Flow Chart 2, level 4 from top
Recession event frequency	CLASS 3	Future potential change COLUMN 4 FIRST FIGURE
Mean event frequency	50	Refer to Flow Chart 2, level 7 from top
Standard deviation (m/yr)	7.5	Refer to Flow Chart 2, level 11 from top
Coefficient of variation	15%	Refer to Flow Chart 2, level 11 from top
Recession event likelihood	MEDIUM (ASSUMED)	Future potential change COLUMN 4, LETTER NOTATION
First event year	20	Refer to Flow Chart 2, level 16 from top
Progressive loss?	YES	Future potential change COLUMN 3 FIRST FIGURE
Recession potential	CLASS 3	Future potential change COLUMN 3, FIRST FIGURE
Mean recession rate (m/yr)	0.75	Refer to Flow Chart 2, level 25 from top
Standard deviation (m/yr)	0.11	Refer to Flow Chart 2, level 25 from top
Coefficient of variation	15%	Refer to Flow Chart 2, level 25 from top

Table A.2: Flow Chart 2

Average estimate = mean recession rate

Upper estimate = mean recession rate + standard deviation multiplied by 2

Lower estimate = mean recession rate – standard deviation multiplied by 2.

Box A.2: Formulas required to calculate time –distance plots for Flow Chart 1.

Average estimate, events = volume per event

Average estimate, progressive = mean recession rate

Average estimate, overall = Average estimate, events + Average estimate, progressive

Upper estimate = cumulative progressive rate + (mean recession rate + standard deviation multiplied by 2)

Lower estimate = cumulative progressive rate + (mean recession rate - standard deviation multiplied by 2)

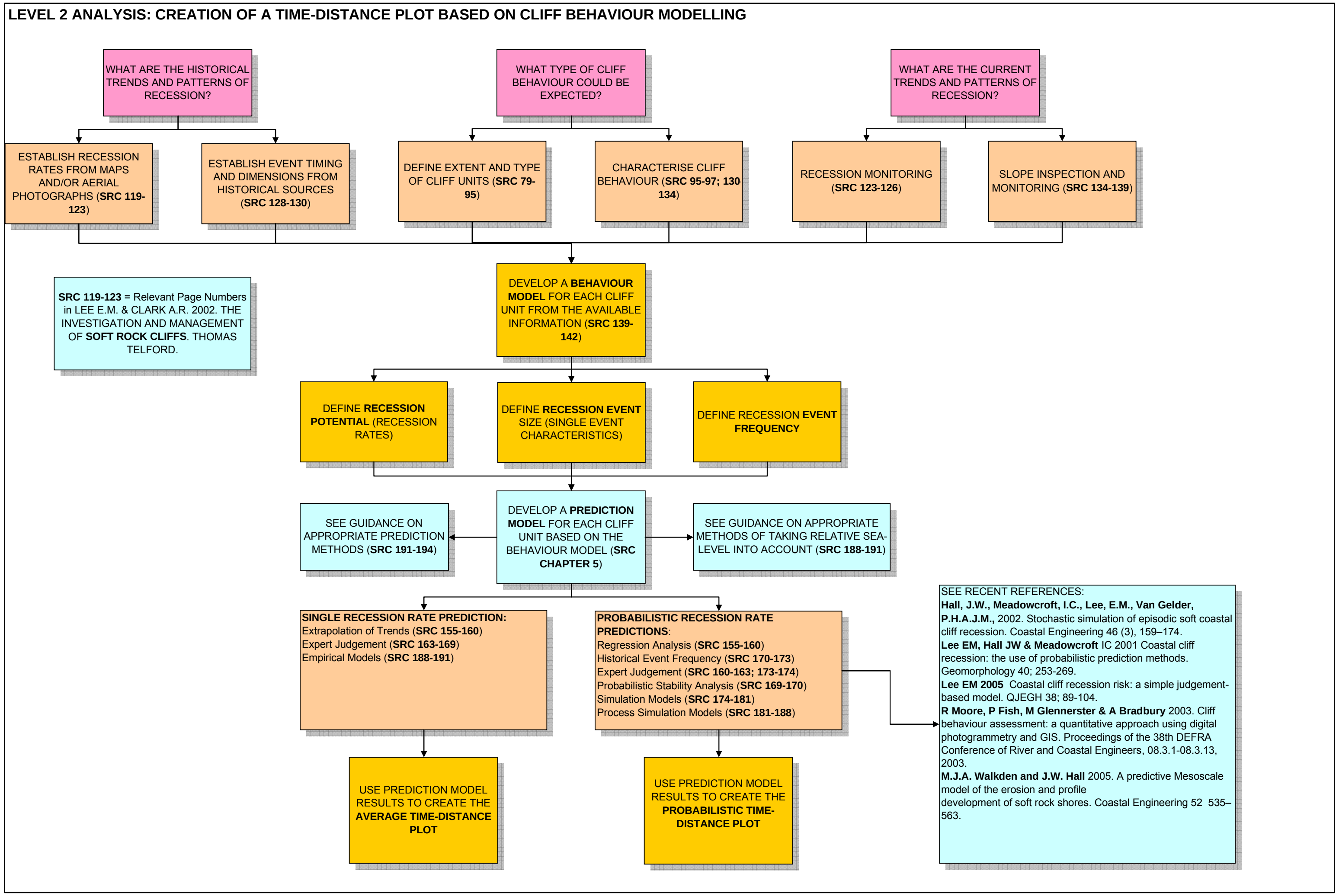
Box A.3: Formulas required to calculate time-distance plots for Flow Chart 2.

Annex B – Site Specific Assessment

Probability distribution parameter	Example	Futurecoast cliff database reference	Question from Level 3	Question from Level 3
Level 1				
Cliffline	SIDESTRAND	Characteristics COLUMN 1	User	User
Coast Protection	NONE	Only use in Example 3	Non-applicable	Non-applicable
Behaviour Type	TYPE 2; Progressive retreat	Characteristics COLUMN 2	What type of cliff behaviour could be expected?	Define extent and type of cliff units (src 79- 95)
				Characterise cliff behaviour (src 95-97; 130-134)
Recession Potential	CLASS 3	Future potential change COLUMN 3 FIRST FIGURE	What are the historical trends and patterns of recession?	Establish recession rates from maps and/or aerial photographs (src 119-123)
Mean recession rate (m/yr)	0.75	Refer to Flow Chart 1, level 4 from top		
Standard deviation (m/yr)	0.11	Refer to Flow Chart 1, level 8 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate
Coefficient Of Variation	15%	Refer to Flow Chart 1, level 8 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate

Probability distribution parameter	Example	Futurecoast cliff database reference	Question from Level 3	
Level 2				
Cliffline	OVERSTRAND GOLF COURSE	Characteristics COLUMN 1	User	User
Coast Protection	NONE	Only use in Example 3	Non – applicable	Non – applicable
Behaviour type	TYPE 4; COMPLEX CLIFF	Characteristics COLUMN 2	What type of cliff behaviour could be expected?	Define extent and type of cliff units (src 79- 95)
				Characterise cliff behaviour (src 95-97; 130-134)
Recession event size	CLASS 7	Future potential change COLUMN 3 SECOND FIGURE	What are the historical trends and patterns of recession?	Establish recession rates from maps and/or aerial photographs (src 119-123)
				Establish event timing and dimensions from historical sources (src 128-130)
Volume per event	30	Refer to Flow Chart 2, level 4 from top		Establish event timing and dimensions from historical sources (src 128-130)
Recession event frequency	CLASS 3	Future potential change COLUMN 4 FIRST FIGURE		Establish event timing and dimensions from historical sources (src 128-130)
Mean event frequency	50	Refer to Flow Chart 2, level 7 from top	As above	As above
Standard deviation (m/yr)	7.5	Refer to Flow Chart 2, level 11 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate
Coefficient of variation	15%	Refer to Flow Chart 2, level 11 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate
Recession event likelihood	MEDIUM (ASSUMED)	Future potential change COLUMN 4, LETTER NOTATION	What are the current trends and patterns of recession?	Recession monitoring (src 123-126)
				Slope inspection and monitoring (src 134-139)
First event year	20	Refer to Flow Chart 2, level 16 from top	?	?
Progressive loss?	YES	Future potential change COLUMN 3 FIRST FIGURE	What are the historical trends and patterns of recession?	Establish recession rates from maps and/or aerial photographs (src 119-123)
Recession potential	CLASS 3	Future potential change COLUMN 3, FIRST FIGURE	What are the historical trends and patterns of recession?	Establish recession rates from maps and/or aerial photographs (src 119-123)
Mean recession rate (m/yr)	0.75	Refer to Flow Chart 2, level 25 from top		
Standard deviation (m/yr)	0.11	Refer to Flow Chart 2, level 25 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate
Coefficient of variation	15%	Refer to Flow Chart 2, level 25 from top	Calculate using Mean Recession Rate	Calculate using Mean Recession Rate

Annex C – Single Rate and Probabilistic Recession Method



Annex D – Supporting Information

1.1 Definitions

- Coastal protection – includes all interventions along the coast, such as defence structures, stabilisation measures and cliff drainage;
- Hazard – the process of coastal cliff/slope erosion and instability;
- Risk – the impact of an erosion hazard on built and natural assets;
- Timescale – the 100 year case is being assumed.
- SRC – Soft Rock Cliff Manual (Lee E.M. & Clark A.R., 2002. The Investigation and Management of Soft Rock Cliffs. Thomas Telford).

1.2 Uncertainty

Recession can take place in two ways, linear or non-linear. Linear recession refers to continuous, year-on-year, erosion.

- Expressing 'linear' recession is relatively simple; it is a rate with some level of variability in terms of magnitude attached to it. For example, the rate might typically be 0.5m/yr, but variability attached to that is say 0.3m in some years and 0.7m in others, although also recognising that by definition these average out once a period of several years is considered. This is different from uncertainty, which also needs to be considered, i.e. the rate might average out at only 0.4m/yr or 0.6m/yr.
- Non-linear recession refers to instability and erosion taking place as a result of larger-scale failures every few years, e.g. losing a 20m wide slice every 40 years followed by a period of relative inactivity before the next failure. At the extreme, reactivation of large coastal undercliffs (e.g. Ventnor and Lyme Regis) could result in significant losses to assets located hundreds of metres inland of the shoreline.

In terms of determining the risks from this, the questions that need to be addressed are the mechanisms, damage intensity and frequency of such events, and the time taken since the last event (hence the likely time to the next one).

In both of the above cases there will be other factors (conditional probabilities) that influence the instability and recession potential, e.g. beach levels, storms, rainfall, but these need to be addressed within the techniques providing at the answer, not within the higher level analysis.

There will inevitably be uncertainty associated with the magnitude of an event (eg could the next one be 15m or 25m?) and the timing (could the next one follow after just 30 years or not happen for 50 years?). For such events, the probability of the next occurrence will increase year-on-year as the likelihood will increase for every year that this doesn't occur. However, for very long frequency events (e.g. greater than 100 years) then the probability remains the same year-on-year.

1.3 'Modified' recession

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 rapid (probably non-linear) catch up process, ie the cliff (or slope or other landform) reassuming its position had defences not existed by initially eroding at a rate much faster than the natural rate;
- an initially slow retreat rate, with the residual effects of the failed defences still offering some limited protection and not allowing full 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 time and rates associated 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. It is also worth considering whether, as a default, some assumptions can be made for high level analysis, at least for case (a), whereas we might simply assume case (b) will not exist (worst case).

The overarching analysis can be applied to any situation, irrespective of scale or level of information available. It is the techniques that input to this that accommodate the variability.

Appendix B

Techniques for Defences

1 Introduction

1.1 *Overview*

The methodology for assessing risk has three components, of which failure of the coastal defence is one. Each component has a number of factors that require consideration and a range of associated techniques, depending upon the degree of sophistication of the analysis.

At the broadest level, there are several degrees of complexity which enable determination of the level of techniques to obtain results – these range from very detailed to coarse, and using information ranging from qualitative or subjective, through to quantifiable and even expertly applied models.

This methodology for determining coastal defence failure potential therefore provides a hierarchy of techniques to allow for proportionate effort. These are quite simply, more or less sophisticated techniques that can be applied to generate the solution. Decision on the appropriate use of any of these techniques relate to the nature of the problems, the importance (value) of assets, the data available and the accuracy of output required.

1.2 *Definitions*

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

- Coast Protection –includes all interventions along the coast, such as defence structures and stabilisation measures.

- Defence Failure – the total failure of a defence structure which leads to the onset of erosion.

1.3 *General Framework*

There is a general framework that can be used for assessing the probability of defence failure. The different techniques have been developed around this depending upon data and level of assessment appropriate - but all lead to the same form of output.

In all cases, taking account of the influence of defences has two components,

- a general deterioration over time, ie due to general wear and tear at some point in the future the defence will cease to be effective

- a failure of the defence due to design conditions being exceeded, eg destroyed by a storm, or undermined by falling beach levels (forcing conditions).

Both of these are variable but in different ways. With regard to deterioration there is uncertainty over the time at which the defence will fall apart, and indeed if this would be instantaneous or gradual. With regard to failures resulting from changes in forcing conditions, then there is an annual probability of exceedence, i.e. an extreme storm could occur this year, next year or not for ten years etc.

Different forms of defence structure will also be affected in different ways and to varying degrees by these two components. However, the overarching principles can be applied to any situation, irrespective of scale or level of information available. It is the use of techniques that input to this that accommodate the variability.

Factors including climate change and alongshore interactions can also be incorporated into any of the techniques by the User making appropriate allowances.

In the matter of climate change, it is expected that the User would consider this through adjustment of water levels and wave climate over time in line with published predictions.

Alongshore influences upon defence failure, for example structures restricting the supply of sediment to a frontage, can almost entirely be accommodated through the consideration of foreshore levels. For example, if such restrictions do apply then the User needs to account for that in the foreshore levels or assessment of foreshore volatility that they adopt in performing their analysis.

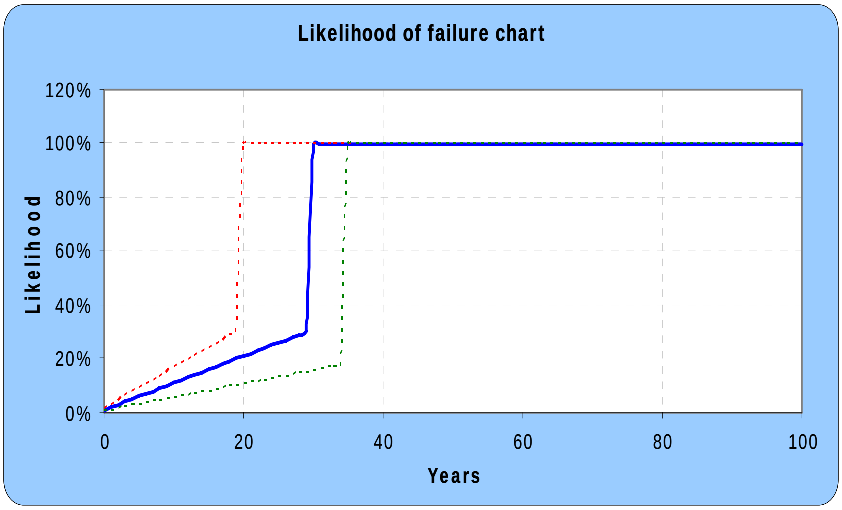
In both of the above cases, for more sophisticated methods where detailed studies have been undertaken then these factors should be inherent in the results of that work; where this is not the case then the User needs to make a judgement, if necessary seeking appropriate expert advice.

The philosophy behind this general framework, which underpins these techniques, is documented in the main RACE technical report.

2 Form of Output

Irrespective of the simplicity or complexity of any given techniques, each should lead to the same basic output; a timeline to defence failure. The principal difference between the outputs from various techniques is their accuracy and the level of confidence that can be attributed to them.

The following chart illustrates the output that the User is required to produce. The blue line indicates the best assessment, and the degree of uncertainty shown by the red and green lines, which are considered to approximate to 5% and 95% confidence limits.



So, in the above example, based upon the User's assessment of the condition of the defence and potential deterioration, they expect it is most likely to stand up for another 30 years, but it might collapse after 20 years, or could last 35 years. During the period leading up to that, the User has assessed that there is a 1% chance of storm conditions exceeding design conditions year-on-year and leading to its 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 definitely 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.

In all cases the User will deliver the information to the Risk Assessment Methodology in a simple spreadsheet form:

Year	Chance of Failure (5)	Upper and Lower Bound (5)	
0	0.01	0.02	0.01
1	0.02	0.03	0.01
2	0.03	0.05	0.02
	etc	etc	etc
	…	…	…
17	0.18	0.27	0.09
18	0.19	0.29	0.10
19	0.20	0.30	0.10
20	0.21	1.00	0.11
21	0.22	1.00	0.11
	etc	etc	etc
	…	…	…
28	0.29	1.00	0.15
29	0.30	1.00	0.15
30	1.00	1.00	0.16
31	1.00	1.00	0.16
32	1.00	1.00	0.17
	etc	etc	etc

3 Range of Techniques

The remaining pages of this procedure outline five different techniques that can be applied to generate the defence failure timeline.

These have increasing levels of complexity, providing incremental improvements in the quality of output, but also necessitating higher levels of data input, knowledge and time. Proportionate effort is therefore a consideration in deciding upon the technique to adopt.

The description of each technique includes guidance on how it can be carried out (supported by the detailed annexes attached), advice on appropriateness of use and limitations of the method.

A brief overview of the five techniques is contained in the table below.

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.

4 Technique 1 - Engineering Judgement

4.1 Applications

At the most basic level, the output can be constructed from engineering judgement by an experienced engineer. It might be appropriate to apply this approach where:

- A quick answer is required.
- The defence is of a very simple form.
- The User has a working knowledge of the particular defence and/or experience of similar defences.
- The assets being protected are of very low value.
- There is no other information relating to the structure.

4.2 Approach

4.2.1 Defence deterioration

The information required is the best estimate of the time that the structure is expected to remain standing and functioning. There are a number of ways that the User may be able to provide this:

- On-site visual inspection of the defence and judgement by an experienced engineer;
- Existing knowledge of the structure such as its form of construction, age and present state to make a judgement.

4.2.2 Forcing conditions

Where no information exists on storm conditions or the capacity of the structure to withstand these, then the likelihood of exceedence can be estimated. The chance that a storm of magnitude greater than the estimated design standard for the defence will occur in any given year can be obtained from the formula or table in Appendix A. If the design standard of the defence is not known then the User can make a best estimate together with upper and lower estimates.

4.2.3 Procedure

1) From visual inspection or existing knowledge, make best estimate of probable remaining life of structure.
2) Estimate upper and lower cases for failure, i.e. earliest and latest times.
3) Estimate probable design standard for defence, i.e. the conditions that the defence was probably designed to withstand (e.g. 1 in 100).
4) Determine annual likelihood of exceedence from formula or table A1. Consider upper and lower cases if uncertain over defence standard (e.g. 1 in 50 and 1 in 200).
5) Construct defence failure timeline from combining the above information.

4.2.4 *Limitations*

This approach will take no account of possible foreshore volatility or lowering which could significantly impact the likelihood of failure, unless the User specifically makes provision for that as part of their expert judgement in constructing the defence failure timeline.

5 Technique 2 – Qualitative Assessment

5.1 *Overview*

This technique makes use of qualitative information within the National Flood and Coastal Defence Database (NFCDD). Note that a spreadsheet has been developed to automate the analyses to be undertaken for this technique, a copy is included in Part Two, Appendix D.

5.2 *Applications*

It might be appropriate to apply this approach where:

- A large number of defences require analysis using a consistent baseline, e.g. national or regional assessment.
- There is limited additional information detailing the physical parameters of the defence or the loading upon it.
- Precision of output is not essential.
- The defences are not of a complex form.
- The assets being protected are not of extremely high value.

5.3 *Approach*

The approach is to use largely qualitative information from the NFCDD and ask a series of questions which provide the user with an indication of the defence failure timeline and the level of confidence they may have in their output.

5.3.1 *Defence deterioration*

The information required is the best estimate of the structure's residual life. This is a field reported in NFCDD but it may be possible to improve upon this data using other guidance. For example, from the PAMS project it should be possible to produce deterioration curves for different structure types, based upon a consideration of a structure's durability and thus performance over time. These curves are not available at the time of this report but the User can still use simple existing guidance to relate condition to estimated residual life, e.g. tabulated estimates (see Annex B, Table B1).

An estimate of upper and lower cases (earliest and latest times) can be established through consideration of other information contained within NFCDD, including component failure and loss of core, and applying a series of tests to that data, as described in Annex B. These consider a range of circumstances which may affect the timing of the defence failure.

5.3.2 *Forcing conditions*

With a knowledge of the intended design standard of the defence from NFCDD, the chance that a storm of magnitude greater than that standard will occur in any given year can be obtained from Table A1 in Annex A (as described for Technique 1).

An estimate of upper and lower bounds on the annual probability of failure is again established through consideration of other information contained within NFCDD, including potential for toe erosion and overtopping. The tests used to determine this are presented in Annex B. Depending upon the outcome of these tests, in some instances it will be appropriate to modify the best estimate timeline to reflect a potentially greater risk of failure.

5.3.3 *Extrapolation of test data*

One constraint of information within NFCDD is that it is time-bound to the present day. In order to construct the timeline of defence failure it is necessary to extrapolate to future dates and generate some assumptions on changes to the NFCDD data. The approach to doing this is reported in Annex B.

5.3.4 *Procedure*

1) Use NFCDD condition data to provide estimate of defence deterioration for the defence type and thus likely time to failure (e.g. see Table B1, although in time this will likely be superseded by output from the PAMS project).
2) Use NFCDD design standard data to determine annual likelihood of exceedence from Annex A.
3) Construct initial defence failure timeline from combining the above information.
4) Use other NFCDD datasets to apply the indicative tests described in Annex B.
5) Modify defence failure timeline and calculate possible upper and lower cases using the output from the indicative tests.

5.3.5 *Limitations*

This output remains an approximation based upon indicative tests using qualitative data. While some account is made of site-specific conditions the conversion of this to quantified risk is limited by assumptions on the response of generic defence forms. Information in the database is also present-day and does not represent future change in any of these parameters, which again is assumed based upon generic situations.

At the time of producing this report, many of the fields in NFCDD are still to be populated for all coastal defences.

6 Technique 3 – Broad Numerical Analysis

This level of analysis is based upon using information on defence structures from the National Flood and Coastal Defence Database (NFCDD), combined with additional site specific data, i.e. knowledge of changing beach levels and basic hydrodynamic parameters. Note that a spreadsheet has been developed to automate the analyses to be undertaken for this technique, a copy is included in Part Two, Appendix D.

6.1 Applications

It might be appropriate to apply this approach where:

- A large number of defences require analysis using a consistent baseline, e.g. national or regional assessment.
- There is limited additional information detailing the physical parameters of the defence but local knowledge on local conditions, i.e. beach levels and water levels.
- The defences are not of a complex form.
- The assets being protected are not of extremely high value.

6.2 Approach

This technique is not focussed upon delivering calculations of structural performance, which is covered by Technique 4. Rather the approaches described here are an extension of the indicative tests described for Technique 2, but moving from a qualitative to a quantitative assessment.

6.2.1 Defence deterioration

The information required is the best estimate of the structure's residual life. At this level the approach is as described for Technique 2. This is described in Annex B.

6.2.2 Forcing conditions

With basic information on beach levels and their potential for change, a quantified assessment can be made of the likelihood of toe failure, by combining this with the defence toe level information held within NFCDD. The beach data can also be extrapolated to estimate future changes so that cumulative probability of failure can be determined.

Additional information on extreme water levels can be combined with basic structure information from NFCDD to make more informed assessments. Where wave data is not available, depth-limited conditions can be readily calculated, these applying to the majority of the open coast of England and Wales. Extrapolation is again possible through taking into account current sea level rise estimates, together with the assumptions of beach level changes, to provide the defence failure timeline.

The details of these methods are described in Annex C.

6.2.3 *Procedure*

1) Use NFCDD condition data to provide estimate of defence deterioration for the defence type and thus likely time to failure (e.g. see Table B1, although in time this will likely be superseded by output from the PAMS project).
2) Use other NFCDD datasets to apply the indicative tests described in Annex B and calculate possible upper and lower (earliest and latest) cases using the output from the indicative tests.
3) Use NFCDD information on physical form of the defence, combined with additional information on foreshore levels and hydrodynamic parameters to determine annual likelihood of failure, using approaches described in Annex C.
4) Construct defence failure timeline from combining the above information.

6.2.4 *Limitations*

Although the annual likelihood of failure is vastly improved over Techniques 1 and 2, the defence deterioration remains an approximation based upon indicative tests using qualitative data. The application of methods to calculate failure due to the forcing conditions does also require a basic level of engineering knowledge regarding these aspects to ensure appropriate application.

At the time of producing this report, many of the fields in NFCDD are still to be populated for all coastal defences.

7 Technique 4 – Detailed Calculation of Failure Potential

7.1 *Overview*

These techniques involve using site specific information to calculate the failure potential of a coastal defence.

7.2 *Applications*

It might be appropriate to apply this approach where:

- The assets being protected are of high value.
- There is a good level of information about the defence and the environmental parameters.
- The defences are of a complex or unusual nature that warrant bespoke methods to be applied to determine the risk of their failure.
- A high level of expertise can be brought to the analysis.

7.3 *Approach*

These approaches are all numerically based and aimed at calculating a quantified result. They are all generally either deterministic or quasi-probabilistic, that is to say include probabilistic elements (e,g, overtopping) or have an overall probability of failure associated with them, as opposed to being a completely probabilistic model as described for Technique 5.

There are some general assumptions that exist for this techniques; that there is site specific information on foreshore conditions and hydrodynamic conditions (forces) that can be used to make an assessment of the structure, and that the primary physical attributes of the structure are specifically known, i.e. its profile and general materials. Some of this information may already be established from existing studies and reports, while elsewhere there may be a need to conduct additional surveys of the defence or studies of environmental parameters.

There may be three approaches that apply for this technique:

- Use of existing analysis.
- Adaptation of design methods.
- Bespoke methods developed to calculate likelihood of defence failure.

7.3.1 *Use of existing analysis*

In several instances local operating authorities may already have previous assessments of their coastal defences and this information may be used directly to generate the defence failure timeline. The specific details of how to do this are dependent upon the form of that analysis and how the results have been reported, therefore additional guidance on this cannot be provided here.

7.3.2 *Adaptation of design methods*

There are numerous approaches that exist for the design of coastal structures, varying in degrees of complexity and dependent upon structure type. These tend to be well reported in publications such as the Manual on the Use of Rock in Coastal and Shoreline Engineering, (CUR-CIRIA 1991) or Seawall Design (Thomas &Hall, CIRIA 1992), so not repeated here.

Irrespective of the methods employed, the approach is one of reversal of the design assessment. In design information on the environmental conditions (i.e. foreshore movement, waves and water levels) is used to determine the required materials and profile of the structure to be built to withstand events of a particular magnitude (e.g. return period storm event). In analysing risk, the materials and profile are already established, so it is using the same techniques to determine the likelihood that the structural integrity of a defence is exceeded, and thus the structure failing. As a minimum the basic tests that are usually applied are undermining, overtopping and structural damage. Through developing a profile of changing foreshore conditions and allowing for climate change, the trends and thus changes in this likelihood of exceedence over time can be determined.

7.3.3 *Bespoke methods*

In some circumstances, particularly where the coastal defence is of an unusual form, or where the User wants to analyse and combine failure mechanism in a particular way, it may be appropriate for the User to develop their own analytical method.

By virtue of their nature, there are no guidelines on what such methods should contain, other than the capacity to provide the required defence failure timeline as an output. There are, however examples, one such being that presented at Defra 2005 (McFarland, Edwards and Lombardo).

7.3.4 *Procedure*

1) Decide upon approach to be used. This will depend upon availability of information, complexity of the structure and the required level of accuracy.
2) Collect existing information (use results if they already exist).
3) If necessary, conduct studies of foreshore conditions, waves and water levels as required providing information required for the analysis. Analyse data.
4) If necessary, conduct basic topographical surveys of the defence structure to provide information required for the analysis.
5) Apply selected approach to generate timeline of defence failure

7.3.5 *Limitations*

Minimum data requirements to apply the methods, although these need not be too onerous and in several instances there should be a reasonable amount of information available to employ the most basic techniques.

Approaches do generally require a reasonable level of relevant coastal engineering experience to undertake and interpret results.

8 Technique 5 – Probabilistic Models

8.1 Overview

The most sophisticated techniques are those which consider probabilistic analysis of each element of the defence.

8.2 Applications

It might be appropriate to apply this approach where:

- The assets being protected are of exceptionally high value, e.g. a nuclear power station.
- The internal integrity of the structure is not known.
- The costs for survey or analysis are not prohibitive.
- A high level of expertise can be brought to the analysis.
- The defence is of a very unusual form and failure potential is not well understood.

8.3 Approach

Full probabilistic models involve calculating the failure probability for every component of the defence, combining these to establish the overall probability of failure of the defence.

These methods are extremely complex; require considerable knowledge of defence element failure mechanisms and a significant amount of structure specific data. It is very rare that such information already exists, therefore a full and intrusive structural survey will generally be required to establish the current condition of different elements of the defence if these techniques are to be adopted.

These type of models are written up and available in published works so not repeated here or within the Appendices, e.g. see Manual on the Use of Rock in Coastal and Shoreline Engineering, sections 2.2 and 2.3 (CUR-CIRIA 1991).

8.3.1 *Procedure*

1) Obtain expert advice on probabilistic design methods and determine appropriate approach to use for the assessment.
2) Undertake full and intrusive structural survey to establish data required for the model.
3) Carry out detailed studies into foreshore conditions and loading conditions e.g. waves and water levels.
4) Conduct probabilistic analysis using established techniques and the data obtained for that structure.
5) Construct defence failure timeline from the above information.

8.3.2 *Limitations*

Probabilistic failure analysis models have generally been established for design of structures, where there can be knowledge of the materials and methods that will go into its construction. But this information is rarely well known for existing structures. There is also very little detailed information on past defence failures to be able to use to calibrate any such models.

Requires expert knowledge of coastal defence structures to appropriately apply the methods.

ANNEXES TO SUPPORT APPLICATION OF TECHNIQUES

Annex A, Engineering Judgement

The annual likelihood of a storm event exceeding the design standard of a defence can be estimated using the following formula.

$P = 1-(1-1/T)^N$

(Where T is the design standard and N is the number of years.)

Alternatively this can be extracted from the following table:

Table A1 – Cumulative probability of conditions occurring which exceed the design standard of a defence

Number of Years	Design Standard of the Structure						
	5	**10**	**20**	**50**	**100**	**200**	**500**
1	0.20	0.10	0.05	0.02	0.01	0.005	0.002
2	0.36	0.19	0.10	0.04	0.02	0.01	0.004
3	0.49	0.27	0.14	0.06	0.03	0.01	0.006
5	0.67	0.41	0.23	0.10	0.05	0.02	0.01
7	0.89	0.52	0.30	0.13	0.07	0.03	0.01
10	0.96	0.65	0.40	0.18	0.10	0.05	0.02
15	0.99	0.79	0.54	0.26	0.14	0.07	0.03
20	1.00	0.88	0.64	0.33	0.18	0.10	0.04
30		0.96	0.78	0.45	0.26	0.14	0.06
50		0.99	0.92	0.64	0.39	0.22	0.09
75		1.00	0.98	0.78	0.53	0.31	0.14
100			0.99	0.87	0.63	0.39	0.18
150			1.00	0.95	0.78	0.53	0.26

Annex B

Qualitative Assessment

B Technique 2, Qualitative Assessment

B.1 *Aim*

These tests produce a first assessment of the risk of defence structure failure. Whilst the analysis is non-numeric, the technique produces an estimate of the probability of failure. This is done via a series of tests that investigate failure mechanisms for different defence forms as well as observations made during site visits. In order to account for changes to condition and loading during the life of a defence structure, the tests are repeated at different intervals over time.

B.2 *Data Required*

These tests will require the following information:

- NFCDD data;
- site visit observations.

Prior to commencing the screening tests, the defence data held in NFCDD should be reviewed to see if any revision is required as a result of the site inspection.

B.3 *Testing Methodology*

The flow chart shown in Figure B.1 illustrates the test procedure to be followed. It can be seen that at this level, sufficient data will exist only to undertake a basic assessment of the potential for landward/ seaward slips of the defence – tests to consider more complex geotechnical failure modes will have to be conducted in later, more detailed analysis stages when more information is be available.

The tests concern the defence failure modes illustrated in Annex E (Figure 2.1), which fall into the two categories of structural and geotechnical failure. The following sections set out the tests for each of these failure modes.

It should be noted that a spreadsheet has been developed to automate the testing process. The user has to enter the defence data and then the tests are undertaken automatically and a resultant defence failure timeline produced. As well as speeding up the assessment process, the spreadsheet demonstrates that this process can be automated and is suitable for turning into a computer programme, as will be required for full development of the technique for national use in the future.

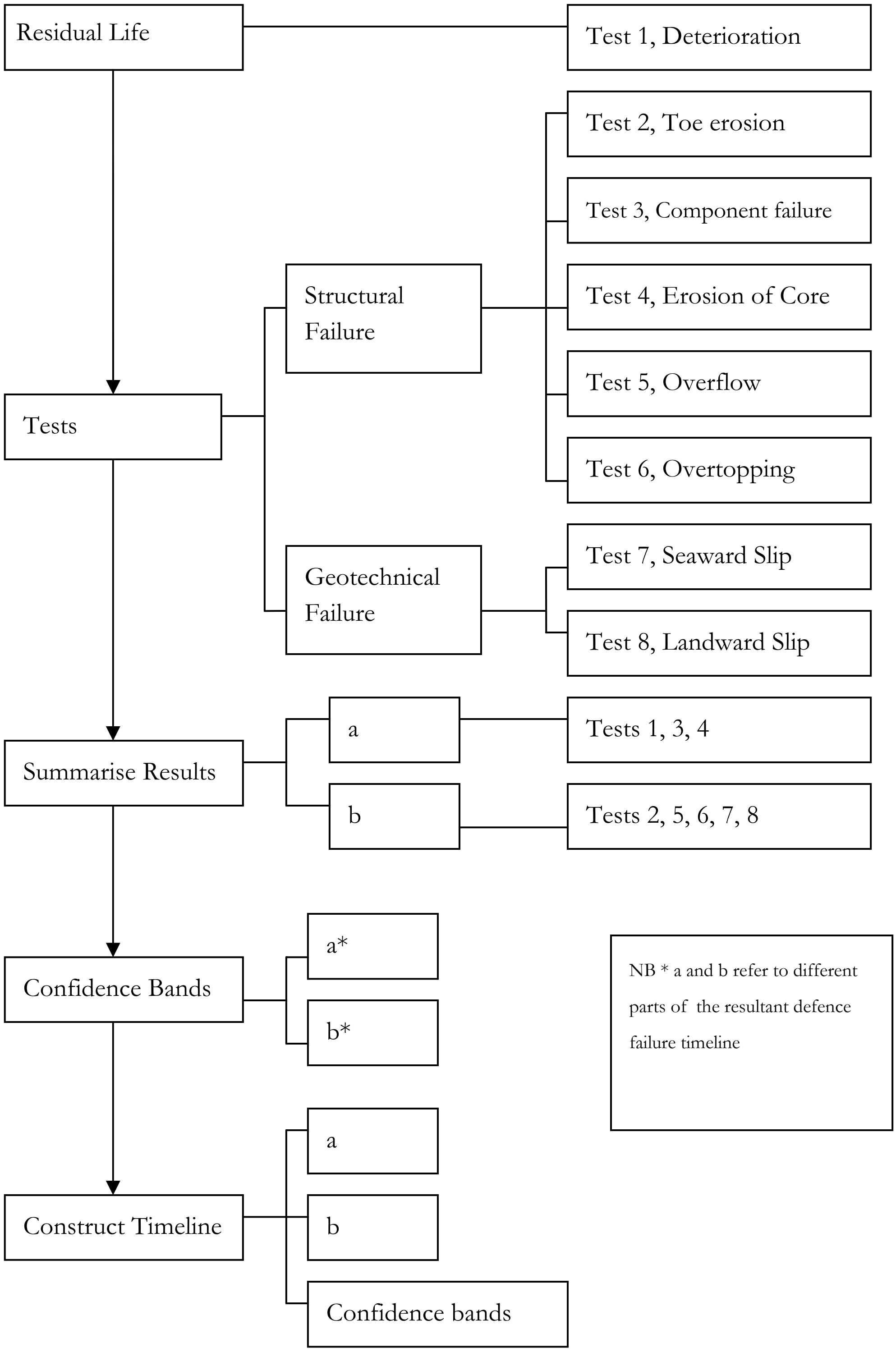


Figure B.1 Flowchart of Defence Failure Timeline

B.4 ***Screening Tests***

B.3.4 *Residual Life*

This test considers the residual life of the defence, i.e. how long it will continue to provide protection.

As part of the Shoreline Management Plan Guidance (Volume 2 – Procedures, Table D1) recently published by DEFRA, the residual life estimates given by the 'AssetCondition' parameter in NFCDD have been extended up to 35 years, as shown in Table B.1.

The condition of beaches can vary considerably over time. These are thus best assessed with a site visit.

Defence Description	**Existing Defence Condition Grade**				
	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**
Seawall (concrete/ masonry)	25 to 35	15 to 25	10 to 15	5 to 7	0
Revetment (concrete/ rock)	25 to 35	15 to 25	10 to 15	5 to 7	0
Timber structures	15 to 25	10 to 20	8 to 12	2 to 7	0
Gabions	10 to 25	6 to 10	4 to 7	1 to 3	0
NOTE Grade 5 is not used in the CPSE, but is included here as a measure of failure					

Table B.1 Estimates of Residual Life from SMP Guidance

Test 1: Residual life use Table B.1 to determine residual life

B.3.5 *Defence Failure Mechanisms*

These tests consider how to identify potential breaching of the defence through the two modes of structural and geotechnical failure. The analysis uses look-up tables for a range of tests related to the different failure modes.

The tests can be summarised as:

- Structural damage
  - general deterioration – already included in Test 1
  - toe erosion

- component failure
- loss of core
- joint failure
- overflow
- overtopping

- Geotechnical failure
  - seaward slip
  - landward slip

Each test can either be passed or failed. At the end of the analysis, individual test results are then combined to express the overall failure probability of the defence.

a) Structural Damage

(i) Test 2, Toe Erosion

This is a two stage test

1. If foreshore level > action beach level and

beach = post event accretion, stable, accreting

then = pass;

2 If foreshore level < action beach level then proceed to lookup Table B.2, where X = failure potential.

Beach Stability	Foreshore Level								
	High			Medium			Low		
	Foreshore Dependency								
	High	Medium	Low	High	Medium	Low	High	Medium	Low
Post event erosion	X	X	√	X	X	√	X	X	X
Post event accretion	√	√	√	√	√	√	√	√	√
Eroding	X	X	√	X	X	√	X	X	X
Stable	√	√	√	X	√	√	X	X	√
Accreting	√	√	√	√	√	√	√	√	√
Volatile	X	√	√	X	X	√	√	√	√
Variable	X	√	√	X	X	√	X	X	X
Seasonal Variation	X	√	√	X	X	√	X	X	X

Table B.2 Toe Erosion

(iii) Test 3 – Component Failure

This is a two stage test:

(1) If defence type[1] = armour layer, apron, bank, bastion, berm, breakwater, breastwork, bund, cliff, crest, dune, foreshore, groyne, high ground, natural, parapet, pile, ramp, revetment, rock armour, seawall, shingle bank, slipway, splash wall, tetrapod, toe, wall, wave reflection wall and

defence has no other main elements[2], then Table B.3, where X = potential failure

(2) If main other defence elements[2] = apron, breastwork, embankment, natural, regraded, splash wall, tetrapod, vegetated and wall then look-up Table B.3; else N/A.

NB In NFCDD, 1 = AssetElementType parameter and 2= AssetElementSub type parameter.

Asset Element Type		Revetment Type			Condition Grade	Exposure		
						High	Medium	Low
Armour layer	→	Asphalt	→		V good	√	√	√
Apron	→	Bituminised Aggregate	→		Good	√	√	√
Bank	→	Cobbles	→	→	Fair	X	√	√
Bastion	→	Concrete in-situ	→		Poor	X	X	√
Berm	→	Concrete precast dolos	→		V poor	X	X	X
Breakwater	→	Concrete precast tetrapod	→					
Breastwork	→	Concrete precast armourflex	→					
Bund	→	Concrete precast piles	→					
Cliff	→	Concrete precast other	→					
Crest	→	Concrete cladding	→					
Dune	→	Fabric	→					
Foreshore	→	Gabion	→					

Groyne	→	Piles	→
High Ground	→	Piles – sheet	→
Natural	→	Piles- timber	→
Parapet	→	Plastic	→
Pile	→	Reno Mattress	→
Ramp	→	Rock armour 1-4 tonnes	→
Revetment	→	Rock armour 3-6 tonnes	→
Rock Armour	→	Rock armour 5-8 tonnes	→
Seawall	→	Shingle	→
Shingle bank	→	Stone	→
Slipway	→	Trees	→
Splash Wall	→	Turf	→
Tetrapod	→	Wood	→
Toe	→	Other	→
Wall	→		
Wave reflection wall	→		

Table B.3 Component Failure

Asphalt

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Bituminsed Aggregate

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Cobbles

Condition Grade	Exposure High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Concrete in-situ

Condition Grade	Exposure High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Concrete precast dolos

Condition Grade	Exposure High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Concrete precast tetrapod

Condition Grade	Exposure High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Concrete precast armourflex

Condition Grade	Exposure High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Concrete precast piles

Condition Grade	Exposure High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Concrete precast other

Condition Grade	Exposure High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Concrete cladding

Condition Grade	Exposure High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Fabric

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Gabion

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Piles

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Piles - sheet

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Piles - timber

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Plastic

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Reno Mattress

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Rock armour 1-4 tonnes

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Rock armour 3-6 tonnes

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Rock armour 5-8 tonnes

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Shingle

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Stone

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

Trees

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
Bad	X	X	X

Turf

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
Bad	X	X	X

Wood

Condition Grade	Exposure		
	High	Medium	Low
V good	X	√	√
Good	X	√	√
Fair	X	X	√
Poor	X	X	X
V poor	X	X	X

Other

Condition Grade	Exposure		
	High	Medium	Low
V good	√	√	√
Good	√	√	√
Fair	X	√	√
Poor	X	X	√
V poor	X	X	X

None

Condition Grade	Exposure		
	High	Medium	Low
V good	X	X	√
Good	X	X	√
Fair	X	X	X
Poor	X	X	X
V poor	X	X	X

(iv) Test 4 – Loss of Core

The results of the toe erosion and component failure tests indicate whether a defence will suffer core erosion, as Table B.4 below.

Condition	**Toe Erosion**	**Component Failure**	**Core Erosion**
V good	X	X	X
	√	X	X
	X	√	X
	√	√	√
Good	X	X	X
	√	X	X
	X	√	X
	√	√	√
Fair	X	X	X
	√	X	X
	X	√	X
	√	√	√
Poor	X	X	√
	√	X	√
	X	√	√
	√	√	√
V poor	X	X	√
	√	X	√
	X	√	√
	√	√	√

Table B.4 Erosion of Core

(v) Joint Failure

Included as part of general deterioration (Test 1) and core erosion (Test 4).

(vi) Test 5 - Overflow

This is a two stage test:

1 Calculate freeboard = Crest level – HAT
2 Use look-up Table B.5 to determine overflow risk

Freeboard	**Condition grade**				
	V good	**Good**	**Fair**	**Poor**	**V poor**
<= 1.0m	X	X	X	X	X
1.0 – 2.0 m	√	√	√	X	X
> 2.0 m	√	√	√	√	√

Table B.5 Overflow

(v) Test 6 - Overtopping

This is a two stage test:

1 Calculate freeboard = Crest level – HAT
2 Use look-up Table B.6 to determine overtopping risk

Freeboard	**Exposure**	**Condition grade**				
		V good	**Good**	**Fair**	**Poor**	**V poor**
<= 2.0m	High	X	X	X	X	X
	Med	√	√	X	X	X
	Low	√	√	√	X	X
2.0 – 3.0m	High	√	√	√	X	X
	Med	√	√	√	√	X
	Low	√	√	√	√	√
> 3.0m		√	√	√	√	√

Table B.6 Overtopping

b) Geotechnical Failure

(i) Test 7 – Seaward Slip

Use Table B.7 to assess potential for seaward slip.

Beach Stability	**Foreshore Level**		
	High	**Medium**	**Low**
Post event erosion	√	X	X
Post event accretion	√	√	√
Eroding	√	X	X
Stable	√	√	X
Accreting	√	√	√
Volatile	X	X	X
Variable	√	X	X
Within Seasonal Limits	√	√	X

Table B.7 - Geotechnical Failure, Seaward Slip

(ii) Test 8 – Landward Slip

This is a three stage test:

1. Embankment? If yes, then proceed to Test 2; else = Pass
2. Lack of freeboard – see Table B.8. If yes, then go on to Test 3; else = Pass
3. If crest, inward face or revetment type is mud/ turf = fail; else = Pass

Freeboard (crest level-HAT)	**Condition Grade**				
	V good	**Good**	**Fair**	**Poor**	**V poor**
<=1.0m	X	X	X	X	X
1.0- 2.0m	√	√	X	X	X
>2.0m	√	√	√	√	X

Table B.8 Geotechical Failure, Landward Slip

B.2 Constructing the Defence Timeline

B.2.1 General Form of Timeline

The general form of the defence failure timeline is shown in Figure B.2.

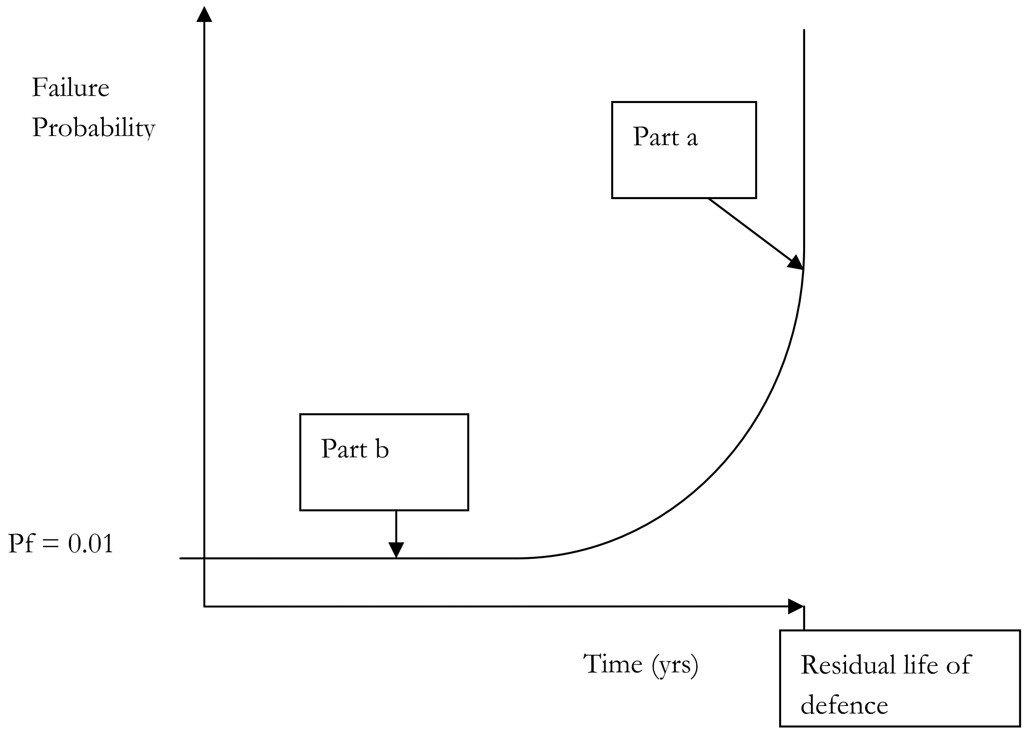


Figure B.2 General Form of Defence Timeline

Part b of the curve is related to the probability of defence failure prior to the residual life of the defence being reached, whilst part a of the curve is set at the residual life of the defence.

There are confidence bands either side of the main timeline. These are influenced by the results of the screening tests and will diverge with time as the confidence of the user declines.

B.2.2 Setting Part b of theTimeline

For this level of assessment, the probability of defence failure is represented by part b of the curve. This is set by use of NFCDD design standard and residual life data to determine annual likelihood of exceedence, ie probability of failure, as in Appendix A.

B.2.3 *Confidence Limits*

The confidence bands relating to part a of the curve are influenced by tests 1, 3 and 4, whilst those for part b are influenced by tests 2, 5, 6, 7, and 8. It is necessary to summarise the number of screening test that the defence passes or fails in order to determine the appropriate confidence bands. Tables B.9 and B.10 show how the confidence limits to be adopted for the different parts of the curve are related to these summaries.

No of tests		**Confidence Limits**
Pass	**Fail**	
2	0	25%
1	1	50%
0	2	75%

Table B.9 Confidence Limits for Part a of Timeline

No of tests		**Confidence Limits**
Pass	**Fail**	
5	0	15%
4	1	30%
3	2	45%
2	3	60%
1	4	75%
0	5	90%

Table B.10 Confidence Limits for Part b of Timeline

B.2.4 *Construction of Defence Timeline*

In order to construct the timeline for the defence and associated confidence bands it is necessary to consider the whole life of the defence. To do this, the screening tests need to be undertaken at regular intervals during the predicted remaining life of the defence. Depending on the residual life of the defence, it may be necessary to repeat the tests at 5 yearly (or even more frequently) intervals in order to provide enough points from which the timeline and confidence bands can be constructed. The main areas of change over time will be the deterioration of defence condition. Other possible changes include variation in beach level, although this may be difficult to predict. The confidence bands will naturally diverge with time as one becomes increasingly less certain about future defence performance.

Annex C

Broad Numerical Analysis

C Technique 3, Broad Numerical Analysis

C.1 *Aim*

This technique will produce the first quantitative assessment of the likelihood of defence failure. It uses numerical analysis to produce a preliminary estimate of the probability of failure of a defence structure. This is done via a series of tests that investigate failure mechanisms for different defence forms. In order to account for changes during the life of a defence, the tests will be repeated at intervals over the residual life.

C.2 *Data Required*

For this level of analysis, a wide variety of data must be available. This includes NFCDD data and site visit observations from earlier techniques, as well as site specific data such as ABMS and published general studies of the defence and local coastline, e.g. SMPs. It will, for instance be necessary to know general water, wave and beach levels at the defence, as well as basic details of the defence, e.g. crest level, structural form. The particular information required for each test is set out in the analysis methods below. For some sites, very detailed information may exist from previous studies. It is likely that there will be only a few such sites and that these records exist because complex erosion events have/ are occurring. In such cases, it is likely that broad scale analysis is inappropriate and detailed, site specific methods should be used, as in later techniques.

C.3 *Testing Methodology*

The flow chart shown in Figure C.1 illustrates the analysis procedure to be followed. At this broad scale, sufficient data will exist to undertake a first numerical assessment of the potential for landward/ seaward slips of the defence – tests to consider more complex geotechnical failure modes will have to be conducted as part of more detailed analyses. Similarly a basic assessment of the overflow and overtopping potential will be all that is possible - overtopping is best calculated on a site specific basis as information as well as data on the defence profile and prevailing loading climate must be accurate detailed if calculations are to be meaningful.

It should be noted that a spreadsheet has been developed to automate the testing process. The user has to enter the defence data and then the tests are undertaken automatically and a resultant defence failure timeline produced. As well as speeding up the assessment process, the spreadsheet demonstrates that this process can be automated and is suitable for turning into a computer programme, as will be required for full development of the technique for national use in the future.

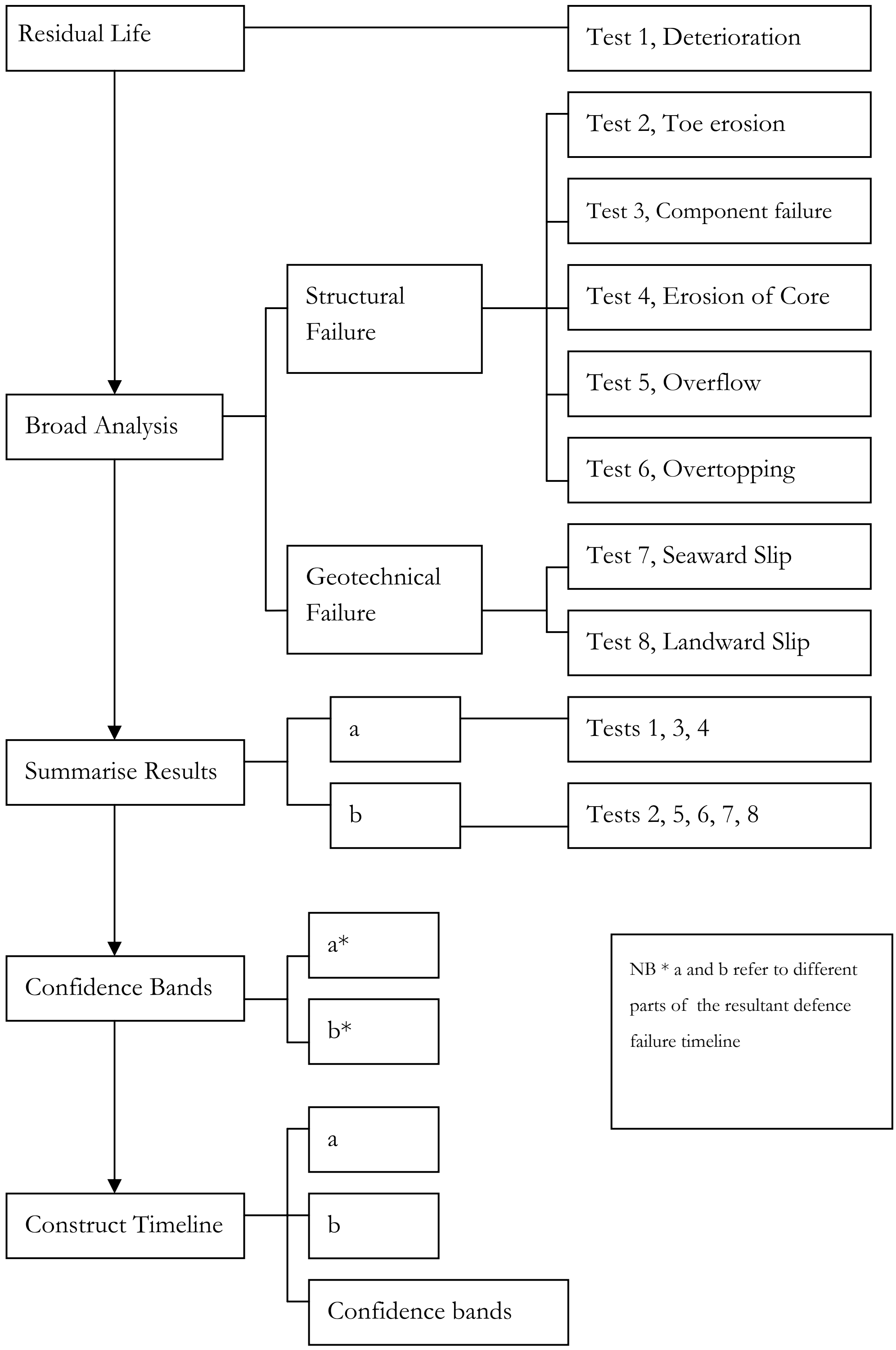


Figure C.1 Flowchart for Broad Numeric Analysis

C.4 ***Identification of Coastal Defences***

For the purposes of the testing, the primary structural form of a defence must be classified into one of the forms shown in Figure C.2 below.

C.7 ***Broad Scale Analysis***

C.6.1 *Background*

As can be seen in the flowchart in Figure C.1, the analysis concerns the same factors that influence defence breach as previous techniques. These are the failure mechanisms illustrated in Appendix E (Figure 2.1), which fall into the two categories of structural and geotechnical failure. The following sections set out the analyses to be undertaken for each failure mechanism. As part of this analyses, the defences will be classified with respect to their structural form in accordance with Figure C.2.

C.6.2 *Residual Life*

This test considers the residual life of the defence, i.e how long it will continue to provide protection.

As part of the Shoreline management Plan Guidance (Volume 2 – Procedures, Table D1) currently being development for DEFRA and due for release in March 2006, the residual life estimates given by the 'AssetCondition' parameter in NFCDD have been extended up to 35 years, as shown in Table C.1.

The condition of beaches can vary considerably over time. These are thus best assessed with a site visit.

Defence Description	**Existing Defence Condition Grade**				
	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**
Seawall (concrete/ masonry)	25 to 35	15 to 25	10 to 15	5 to 7	0
Revetment (concrete/ rock)	25 to 35	15 to 25	10 to 15	5 to 7	0
Timber structures	15 to 25	10 to 20	8 to 12	2 to 7	0
Gabions	10 to 25	6 to 10	4 to 7	1 to 3	0
NOTE Grade 5 is not used in the CPSE, but is included here as a measure of failure					

Table C.1 Estimates of Residual Life from SMP Guidance

Test 1: Residual life use Table C.1 to determine residual life

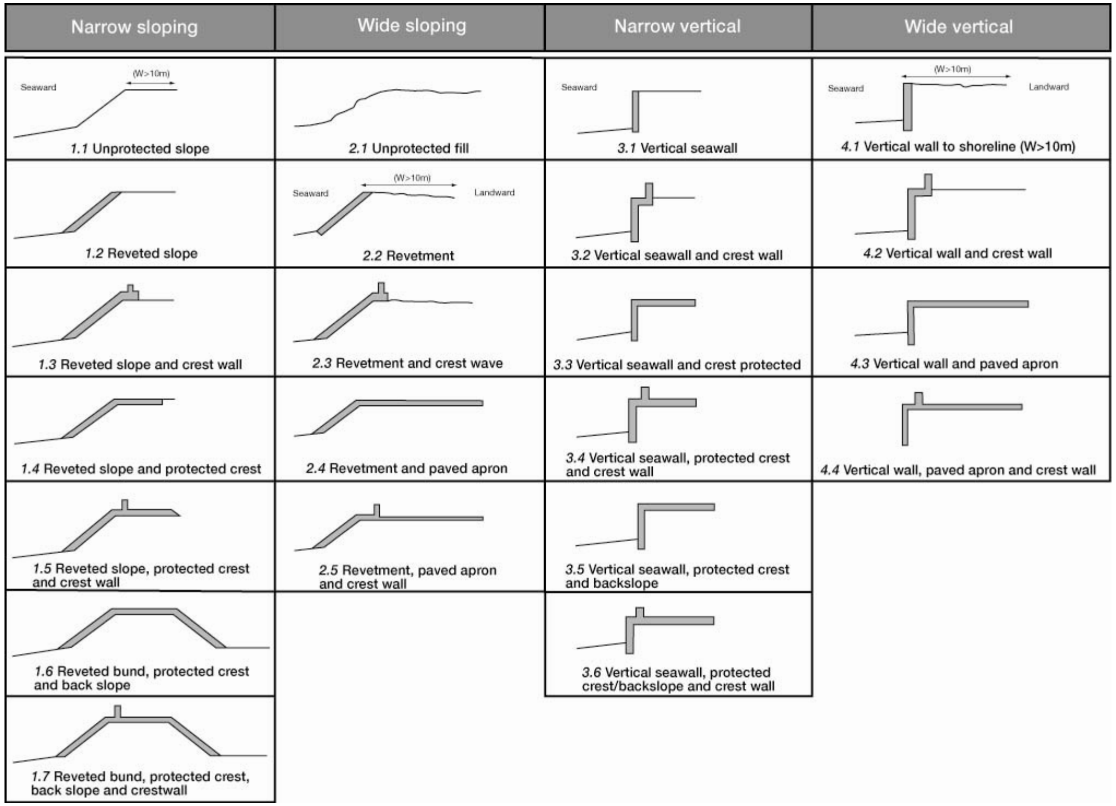


Figure C.2 Summary of Structure Classifications

C.6.3 *Structural Failure*

As previously, the risk of structural failure of the coast protection defences can be determined by assessing the following failure mechanisms:

- Toe erosion
- Component failure
- Loss of core
- Overflow damage;
- Overtopping damage

a) Toe Erosion

<u>Information required</u>

- Form of structure
- Current beach level
- Current beach trend
- Historical beach levels

<u>Analysis Method</u>

Test 2: Toe Erosion

(i) Calculate current beach level, BL_{act} – historical minimum beach level, $BL_{min:}$

(ii) Use look-up Table C.2 to determine probability of failure.

$BBL_{act}–BL_{min}$	Beach Stability	Toe Dependency of Structure		
		High	Medium	Low
> 0	Eroding	H	H	M
	Stable	L	L	L
	Accreting	L	L	L
	Volatile	M	M	L
	Seasonal	L	L	L
< 0	Eroding	H	H	H
	Stable	H	H	H
	Accreting	H	H	H
	Volatile	H	H	H
	Seasonal	H	H	H

Table C.2 Toe Erosion

b) Component Failure

Information required

- Defence condition
- Design water level, WL_{des}
- Beach trend
- Historical maximum water level. WL_{max}

Analysis Method

Test 3: Component Failure

(i) Calculate $WL_{des} - WL_{max}$:

(ii) Use look-up Table C.3 to determine probability of failure.

$WL_{des} - WL_{max}$	**Condition Grade**	**Beach Trend**				
		Accreting	**Stable**	**Volatile**	**Eroding**	**Seasonal**
> 0	V good	L	L	H	H	L
	Good	L	L	H	H	L
	Fair	L	L	H	H	L
	Poor	M	M	H	H	M
	V poor	H	H	H	H	H
< 0	V good	H	H	H	H	H
	Good	H	H	H	H	H
	Fair	H	H	H	H	H
	Poor	H	H	H	H	H
	V poor	H	H	H	H	H

Table C.3 Component Failure

c) Loss of Core

Information required

- Defence condition
- Probability of toe erosion (from Test 2)
- Probability of component failure (from Test 3)

Analysis Method

Test 4: Loss of Core

Use look up Tables C.4 (i) to (v) to determine probability of failure

Toe Erosion	**Component Failure**	**Loss of Core**
L	L	L
L	M	L
M	L	L
H	H	H
L	H	M
H	L	M
M	H	H
H	M	H
H	H	H

Table C.4(i) Loss of Core - Condition Grade V good

Toe Erosion	**Component Failure**	**Loss of Core**
L	L	L
L	M	L
M	L	L
M	M	M
L	H	M
H	L	M
M	H	H
H	M	H
H	H	H

Table C.4(ii) Loss of Core - Condition Grade Good

Toe Erosion	**Component Failure**	**Loss of Core**
L	L	L
L	M	M
M	L	M
L	H	H

M	M	M
H	L	H
M	H	H
H	M	H
H	H	H

Table C.4(iii) Loss of Core - Condition Grade Fair

Toe Erosion	**Component Failure**	**Loss of Core**
L	L	M
L	M	H
M	L	H
L	H	H
M	M	M
H	L	H
M	H	H
H	M	H
H	H	H

Table C.4(iv) Loss of Core - Condition Grade Poor

Toe Erosion	**Component Failure**	**Loss of Core**
L	L	H
L	M	H
M	L	H
L	H	H
M	M	M
H	L	H
H	H	H
H	H	H
H	H	H

Table C.4(v) Loss of Core - Condition Grade V Poor

d) Overflow

<u>Information required</u>

- Structural form of defence
- Crest level
- Degree of exposure
- Defence condition
- Extreme water levels

Analysis Method

Test 5: Overflow

Level 3 – (i) Compute effective crest level

Structure type = {type 1.1, 1. 2, 2.2} r= 0.6m
= {type 1.3, 2.3 } r= 0.5m
= {type 1.4, 1.5, 1. 6, 1.7, 2.4, 2.5} r= 0.3m
= {type 2.1} r= 1.0m

And r= potential reduction in crest level due to structure type

Condition = {v good} k_c= 0.1m
= {good) k_c= 0.2m
= {fair} k_c= 0.3m
= {poor} k_c = 0.7m
= {v poor} k_c = 1.0m

And k_c = potential reduction in crest level due to condition

With effective crest level = crest level – r. k_c

(ii) compute degree of exposure to assign freeboard at site, F

- F (high exposure) = 0.75m
- F (medium exposure) = 0.5m
- F (low exposure) = 0.3m

(iii) Compute maximum safe water level, WL_{safe}, where

WL_{safe} = effective crest level – F, freeboard

(iv) test WL_{safe} against extreme water levels WL_{100} and WL_{50}

- $WL_{safe} > WL_{100}$ low risk
- $WL_{safe} < WL_{100}$ and $WL_{max} > WL_{50}$ medium risk
- $WL_{safe} < WL_{50}$ high risk

WL_{50} and WL_{100} are the 50 and 100 year extreme water levels

e) Overtopping

Information required

- Defence crest level
- Defence condition
- Design hydraulic conditions
- Historical minimum beach levels
- Actual hydraulic conditions (extremes)
- Effective crest level (from Test 5)

Analysis Method

Test 6: Overtopping

i) Check for depth limiting conditions
- WD_{max}, Maximum water depth = WL_{max} – BL_{min}
- H_{sd}, Depth limited wave height = 0.78. W_{Dmax}
- If H_{s100} > H_{sd}, then use H_{sd} else use H_{s100}
- and run-up_{100} = 1.5. H_{s100} (or H_{sd} if H_{sd} is smaller)

ii) effective crest level > (WL_{100} + run-up_{100}) low risk
iii) effective crest level < (WL_{100} + run-up_{100}) and
effective crest level > (WL_{50} + run-up_{50}) medium risk
iv) effective crest level < (WL_{50} + run-up_{50}) high risk
And WL_{50} and WL_{100} are the 50 and 100 year extreme water levels

C.6.4 *Geotechnical Failure*

For geotechnical failure, further assessment of the probability of failure can be made by undertaking additional stability analysis. This can assess the potential risk of landward or seaward slips.

a) Seaward Slips

Information required

- Design Beach Level
- Historical beach levels

Analysis Method

Test 7: Seaward Slip

Level 3 – (i) determine actual BL_{min}
(ii) if actual BL_{min} > design BL_{min100} then low risk
(iii) if actual BL_{min} < design BL_{min100} and
if actual BL_{min} > design BL_{min50} then medium risk

(iv) if actual BL_{min} < design BL_{min50} then high risk

b) Landward Slips

Aim of test

To determine risk of landward slips of defence structures. Applies to embankments only

Information required

- Crest Level
- Actual hydraulic conditions (extremes)

Analysis Method

Test 8: Landward Slip

(i) determine actual WL_{100}
(ii) if crest level > WL_{100} then low risk
(iii) if crest level < WL_{100} and
if crest level > WL_{50} then medium risk
(iv) if crest level < WL_{50} then high risk

C.8 Constructing the Defence Timeline

C.8.1 General Form of Timeline

The general form of the defence failure timeline is shown in Figure C.3.

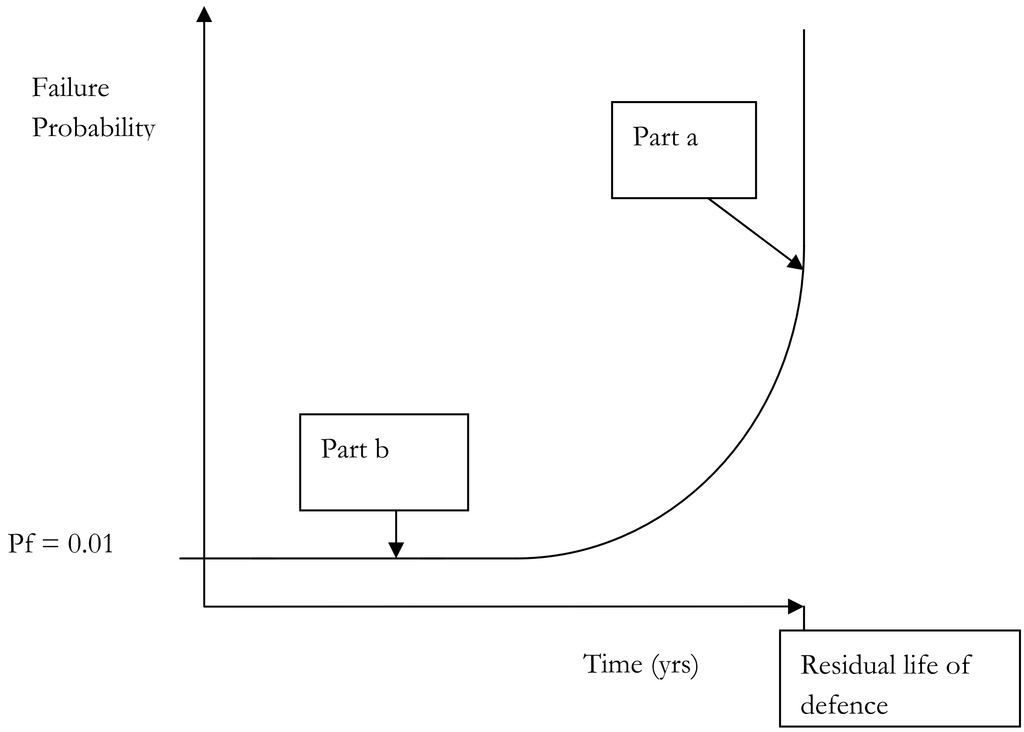


Figure C.3 General Form of Defence Timeline

Part b of the curve is related to the probability of defence failure prior to the residual life of the defence being reached, whilst part a of the curve is set at the residual life of the defence.

C.8.2 *Setting Part b of theTimeline*

For this level of assessment, the probability of defence failure is represented by part b of the curve. This is set by use of NFCDD design standard and residual life data to determine annual likelihood of exceedence, ie probability of failure, as in Appendix A.

There are confidence bands either side of the main timeline. These are influenced by the results of the screening tests and will diverge with time as the confidence of the user declines.

C.8.3 *Confidence Limits*

The confidence bands relating to part a of the curve are influenced by tests 3 and 4, whilst those for part b are influenced by tests 2, 5, 6, 7, and 8. It is necessary to summarise the number of screening test which the defence passes or fails. Tables C.5 and C. 6 show how the confidence limits to be adopted for the different parts of the curve are related to these summaries.

No of tests			Confidence Limits %
High	Medium	Low	
2	0	0	90
0	2	0	45
0	0	2	15
1	1	0	75
1	0	1	60
0	1	1	30

Table C.5 Confidence Limits for Part a of Timeline

No of tests			Confidence Limits %
High	Medium	Low	
5	0	0	5
0	5	0	30
0	0	5	90
4	1	0	10
4	0	1	35
3	2	0	15
3	1	1	40
3	0	2	45
2	3	0	20
2	2	1	50
2	1	2	55
2	0	3	60
1	4	0	25
1	3	1	35
1	2	2	65
1	1	3	70
1	0	4	75
0	1	4	85
0	2	3	80

Table C.6 Confidence Limits for Part b of Timeline

C.8.4 *Construction of Defence Timeline*

In order to construct the timeline for the defence and associated confidence bands it is necessary to consider the whole life of the defence. To do this, the screening tests need to be undertaken at regular intervals during the remaining life of the defence. Depending on the residual life of the defence, it may be necessary to repeat the tests at 5 yearly (or even more frequently) intervals in order to provide enough points from which to the timeline and confidence bands can be constructed. The main area of change over time will be the deterioration of defence condition. Other possible changes include variation in beach level, although this may be difficult to predict. The confidence band will naturally diverge with time as is increasing less certain about future defence performance.

Appendix D

Spreadsheets: available from website

Ergon House
Horseferry Road
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