5. RISK TOOLS AND TECHNIQUES

There are a variety of risk assessment tools and techniques that can be applied at different stages of the decision process. These range from high level methods to intermediate methods to detailed methods. Screening and prioritisation methods rely heavily on engineering judgement, whilst fully qualitative methods may involve full probabilistic analysis. Between these extremes there are a range of generic quantitative methods. This chapter describes some of the risk tools and techniques that are applicable to coastal and fluvial engineering across each stage of the decision making process. A brief description of who the likely users of the methods are, is also provided.

A number of publications have been reviewed when compiling this chapter. In particular information from RPA (2001), MAFF 2000, Environment Agency (2000a) and Van Gelder (1999) is extensively drawn upon.

- **High level methods**
  - Brainstorming
  - Consultation Exercises
  - Risk Register
  - Screening
- **Intermediate methods**
  - Analysis of interconnected Decision Areas (AIDA)
  - Decision trees
  - Expert judgement
  - Pairwise comparisons
  - Risk Ranking Matrix
  - S-P-R-C models
  - Uncertainty radial charts
- **Detailed methods**
  - Bayesian Analysis
  - Cost-benefit analysis
  - Cost effectiveness analysis
  - Cross impact analysis
  - Event tree analysis
  - Extreme value methods
  - Figure of merit
  - FMECA – Failure mode, element and criticality analysis
  - Fragility curves
  - GLUE
  - Joint probability methods
  - Monte Carlo analysis
  - Probabilistic reliability
  - Scenario modelling
  - Sensitivity analysis
  - Utility theory

5.1 High level methods

Brainstorming
Brainstorming is a useful tool for generating potential options. When having a brainstorming session, it is beneficial to have individuals from a variety of backgrounds and interests. Generally the objective is to

generate as many options as possible. Brainstorming sessions should not include criticism and evaluation of ideas.

Consultation Exercises
Consultation exercises are critical to the success of any flood and coastal defence decision. They are appropriate at a variety of stages within the decision-process. Historically, they have generally take the form of a questionnaire or telephone interview, put today considerably more emphasis is placed on more fully engaging stakeholders through face-to-face interview, roadshow as well as internet based discussion groups.

Risk Register
Risk Registers are used to help in hazard identification, to record information about risks and to document decisions taken and have been widely adopted throughout the Agency (for example the Risk 2.1 document used by the National Capital Programme Management business group). An example of a risk register for a project concerned with reducing the scour around bridge piers on a river bed is given below.

Example of a Risk Register (extracted from RISKCOM software):

Area	Risk summary	Likelihood	Consequence	Risk rating	Control strategy	Owner
Planning	Failure to get access approvals	M	H	H	Start approval process prior to completion of design	Project manager
Planning	Failure to get environmental approvals	H	H	H	Undertake consultation with SEPA	Project manager
Planning	Failure to get funding in place	L	H	M	Start approval process prior to completion of design	Project manager
Safety	Excavator adjacent to road	L	H	M	Establish an exclusion zone around the bridge at road level	Safety manager
Safety	Failure of winch cables - whiplash	L	M	L	Specify polypropolene cables	Safety manager
Safety	Excavator not secured to pontoon	L	M	L	Require fixing system to be designed	Safety manager
Technical	High river flow velocity	M	L	L	Connect to flood warning system	Project manager
Technical	Erosion of access ramp	L	L	L	Rock armour around ramp	Designer
Technical	Settlement of access ramp	L	L	L	Geotextile at foundation	Designer
Cost	Rock armour not available	L	H	M	Pre order supply	Project manager
Cost	Erosion of material	L	L	L	Reduce exposed length	

The Agency has a standard set of risk registers that are prescribed for use in all Agency engineering works. Their risk register is divided into 3 parts (see Appendix 1):

A Generic risks
B Specific risks
C Residual risks

Generic risks have been identified for engineering projects in 3 categories:

i) General engineering and project management Risks
ii) Land acquisition and compensation
iii) Environmental risks

Specific risks are to be identified and included on the risk register in Part B.

Residual risks occur when the method of controlling generic and specific risks is not fully effective. If the residual probability and consequence of a controlled risk is unacceptable , then it must be logged in part C.

Screening
Screening Techniques are used to identify hazards, processes and impacts, which are, and are not, significant in the overall decision-making process. These are 'broad brush' techniques, which generally require a reasonable understanding of the system. Screening tests are by their nature approximate and so should be designed to be conservative so that important issues are not rejected at an early stage. Risk registers and ranking techniques can be used as a method of prioritisation and screening.

5.2 Intermediate methods

Analysis of Interconnected Decision Areas (AIDA)

AIDA is a method of visualising different decision areas (where a decision area consists of two or more mutually exclusive alternatives (options)) and the relationships between options within each decision area. An AIDA option graph is shown in Figure 1 (reproduced from RPA (2001), together with discussion).

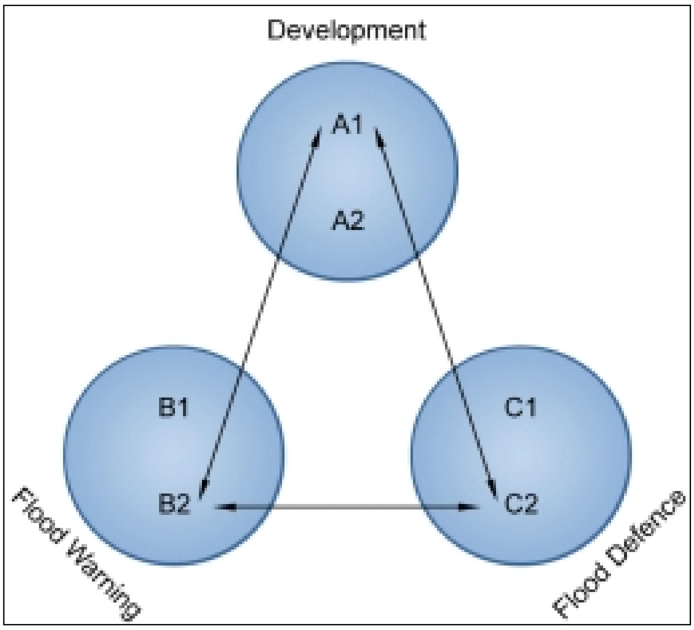


Figure 5.1 AIDA option chart

Within Decision Area A (development): A1 = more development; and A2 = no new development. For Decision Area B (Flood Warning): B1= better flood warning; and B2 = retain existing system. For Decision Area C (Flood Defence) C1= improved defences; and C2 = retain existing defences. Incompatible options (as represented by the option arrows) are: A1/B2; A1/C2; and B2; C2.

In other words, if the option for more development (A1) is taken, both the flood warning system (B1) and the flood defences (C1) must be improved. However, even if there is no new development, the flood warning or the flood defences, must still be improved, as the current situation B2/C2 is unacceptable. One of the objectives of subsequent stages of the analysis will be to determine whether the suggested improvements to flood defences and/or warning system will be robust to climate change.

Decision Trees
These trees provide a tool for structuring and undertaking the risk assessment component of an appraisal. This tool enables a clear structure for clarifying and combining problems in a logical manner. An example is shown in Figure 5.2 (reproduced from MAFF (2000)). Here a decision between options results in a range of possible consequences depending on the maximum high water level and the performance of the

structure during that high water event. The structure performance is represented by the probability of a breach developing. The expected value of each option can be calculated taking account of the probabilities and consequences of the outcomes.

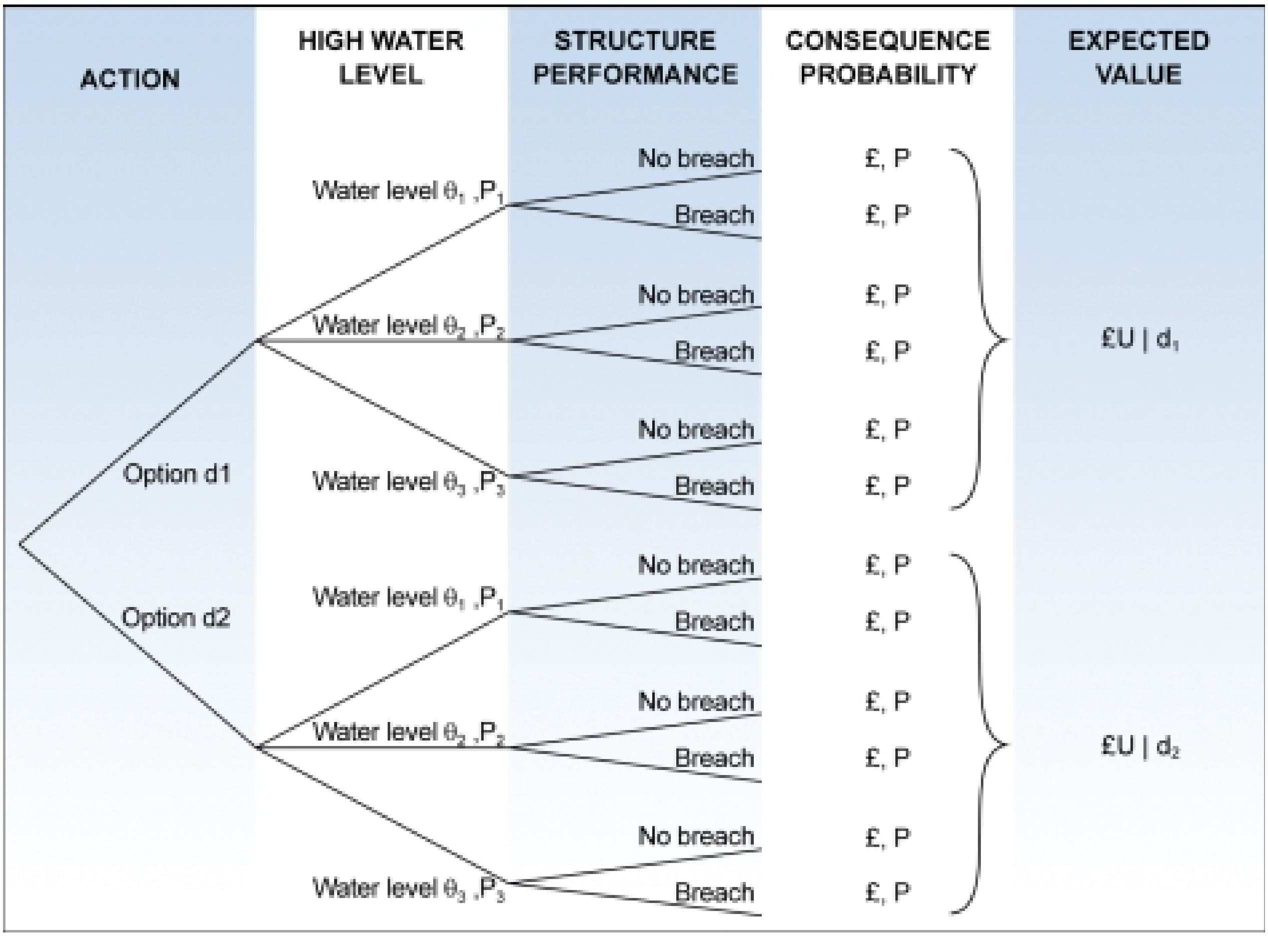


Figure 5.2 Decision Tree

Expert Judgement

Where knowledge is lacking, expert judgement is often used to aid the decision making process. Expert judgement can be used to assess the impacts of events and also the likelihood of occurrence. For example, when scenario modelling is used, often there is no probability or likelihood associated with each scenario. In such circumstances, expert judgement can be used to assign probabilities. Alternatively, where a physical process like breaching of a sea defence is poorly understood, expert judgement can be used to assign probability of breaching under different loading conditions.

Pairwise Comparisons

Pairwise analysis is a method for comparing and choosing the most appropriate solution or option. Options are compared against each other on a number of criteria (e.g. performance objectives). The comparisons can be qualitative or quantitative and different weightings can be applied for each individual objective.

For example, consider four options for a flood defence scheme: A (do nothing); B (managed retreat); C (hold the line); and D (advance the line). The analysis would consist of the following comparisons and may appear as follows:

Benefit/Cost Ratio: A>B, A<C, A>D, B<C, B<D, C>D (So C has the highest BCR)

Environmental considerations: A<B, A<C, A>D, B>C, B>D, C>D (So B is the best option in terms of the environment).

Amenity: A<B, A<C, A<D, B<C, B<D, C<D (So D has the highest amenity value).

These comparisons can be summarised in a table:

	BCR	**Environment**	**Amenity**
Option A	Mid	Mid	Worst
Option B	Worst	Best	Mid
Option C	Best	Mid	Mid
Option D	Mid	Worst	Best

Depending on the weighting of the different objectives, a decision regarding the most beneficial option can be made. This type of analysis is only suitable where the range of options and performance measures are relatively few.

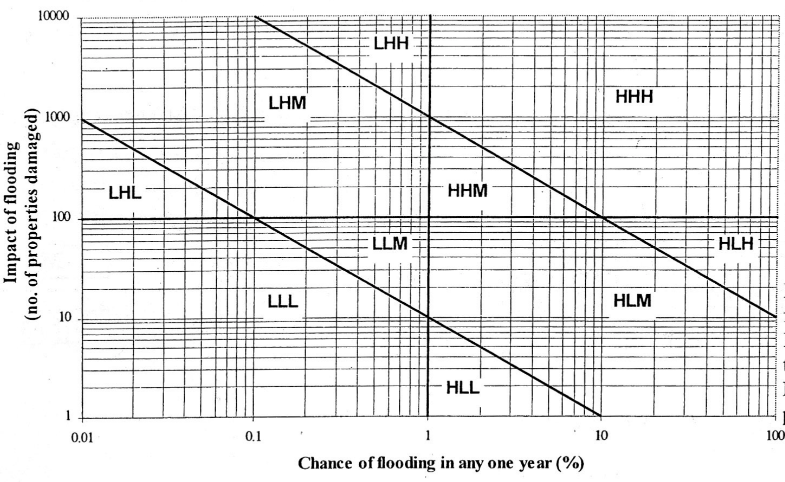
Risk Ranking Matrix
Once risks have been identified, their relative importance can be assessed using risk ranking techniques. A frequently applied technique is the risk ranking matrix. An assessment of the likelihood and consequence of each individual risk is made. These risks can then be prioritised and an appropriate risk management plan formulated.

The rankings can be either numerical or verbal. An example of a simple verbal risk ranking matrix is given below:

Risk ranking matrix		**Likelihood**		
		High	**Medium**	**Low**
Consequence	High	1	2	3
	Medium	2	3	4
	Low	3	4	5

This concept has been extended and applied in the Environment Agencies classification of flood risk areas for use in their flood warning and awareness programme (Environment Agency (2000b)). The extended approach includes a more complex risk rating made up of a three letter code.

Flood Warning Risk Decision Box



Category	Probability	Impact	Risk
HHH	High	High	High
HLH	High	Low	High
LHH	Low	High	High
HHM	High	High	Med
HLM	High	Low	Med
LHM	Low	High	Med
LLM	Low	Low	Med
HLL	High	Low	Low
LHL	Low	High	Low
LLL	Low	Low	Low

Probability: the chance of a given flood occurring in one year
Impact: the number of properties liable to be flooded by a given flood
Risk: the weighted combination of probability and impact

Structure of flood warning system / awareness programme:

Category / Risk	***Awareness Programme Intensity***	***Direct Warnings***	***Indirect Warnings***	***Major Incident Plans***
HHH / High	*High*	*Selected*	*Yes*	*Yes*
HLH / High	*High*	*Yes*	*Yes*	*No*
LHH / High	*High*	*Selected*	*Yes*	*Yes*
HHM / Medium	*High*	*Selected*	*Yes*	*Yes*
HLM / Medium	*High*	*Yes*	*Yes*	*No*
LHM / Medium	*Medium*	*Selected*	*Yes*	*Yes*
LLM / Medium	*Medium*	*Selected*	*Yes*	*No*
HLL / Low	*High*	*Yes*	*Yes*	*No*
LHL / Low	*Low*	*No*	*Yes*	*Yes*
LLL / Low	*Low*	*No*	*Yes*	*No*

Figure 5.3 Environment Agency's revised flood warning risk decision box

The benefits of this system, when compared to the original matrix are that a clear connection from the flood risk categories to the risk management strategy is made.

Source-Pathway-Receptor-Consequence (S-P-R-C) Models
S-P-R-C models offer a simple conceptual tool for representing systems and processes that lead to a particular consequence or harm. For a risk to arise there must be hazard that consists of a 'source' or initiator event (i.e. high rainfall); a 'receptor' (e.g. cliff top or flood plain properties); and a pathway between the source and the receptor (i.e. flood routes including defences, overland flow or landslide). The combined probability of these three elements existing represents the probability term in the *risk = probability x consequence* equation (note: a hazard does not automatically lead to a harmful outcome, but identification of a hazard does mean that there is a possibility of harm occurring). Within such an analysis it must be recognised that there are likely to be multiple sources, pathways and receptors.

The Source-Pathway-Receptor-Consequence approach is applicable at all levels of risk assessment to aid the understanding of the likelihood of a particular consequence being realised, including:

- a 'screening' tool to establish whether flooding or erosion is a credible risk at a particular site, on the basis of the existence of a source, receptors, and pathways between them;
- a tool to help to identify failure mechanisms i.e. the ways in which flooding / erosion could occur;
- a tool to support a quantitative analysis in calculating the likelihood and consequences of a range of outcomes, based on a range of initial events.

The Source-Pathway-Receptor-Consequence model is simply a more formal approach to structuring a problem and not a significant departure from current best practice in flood and erosion management. It encourages a more holistic review and analysis of the causes of flooding, and deals explicitly with the impacts or consequences with which the decision-maker is concerned.

An example of a S-P-R-C model is shown in Figure 5.4. This model provided the basis for a risk assessment. This involved modelling the effect of a number of storms, with probabilities derived from extreme value analysis of historical data. A combination of well-established response functions together with expert judgement was used to assess the likelihood of a range of outcomes (i.e. flood areas and probabilities). These were processed to assess the impacts in economic and social impacts of flooding. The assessment model was used to help develop options for protection (most of which involved modifying the pathways) and appraisal of options.

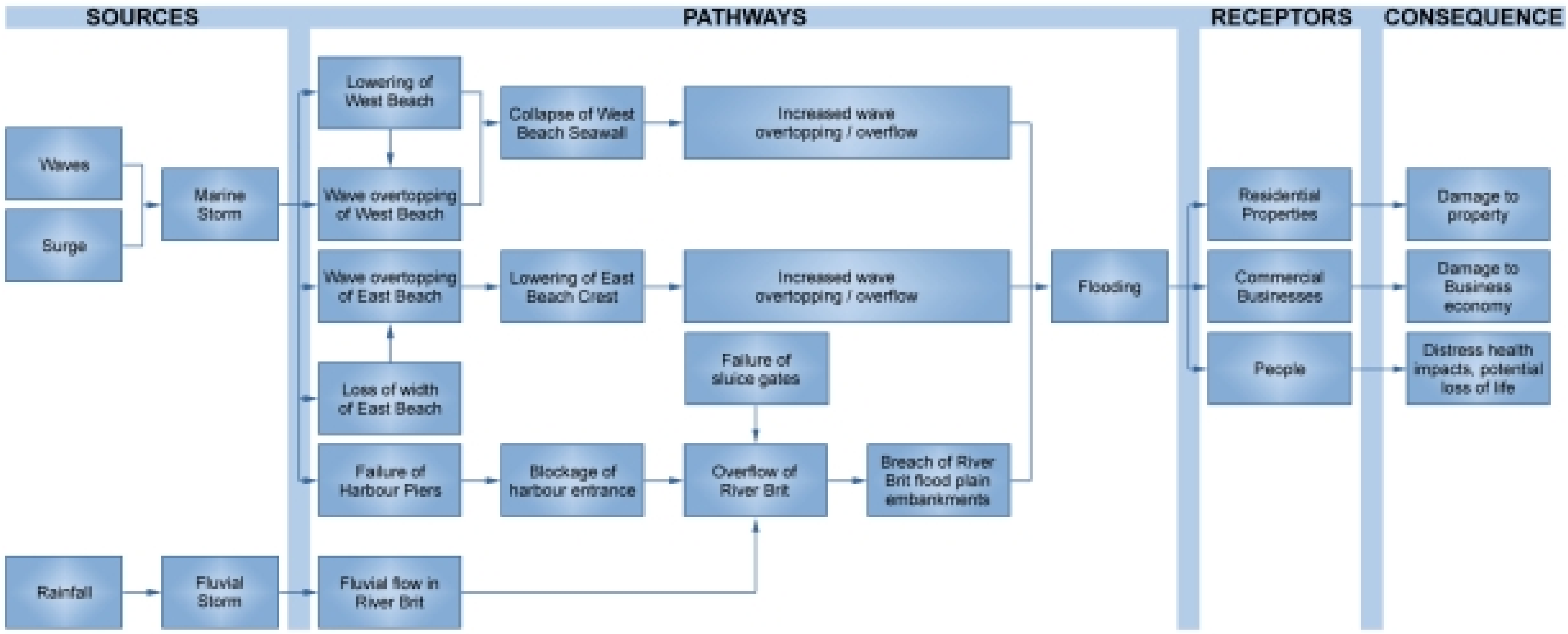


Figure 5.4 Example of a Cause-Consequence diagram developed using a Source-Pathway-Receptor Consequence model (Note this is a relatively complex case, mainly due to the complex, multiple pathways. Analysis effort would be focussed on the most important mechanisms in terms of their contribution to risk).

Uncertainty Radial Charts
Uncertainty radial charts provide a simple approach for assessing the relative importance of different uncertainties affecting a decision.

The type of uncertainty is indicated by the position on the chart, relative to different axes (Figure 5.4 (reproduced from RPA (2001)). The strength of uncertainty is indicated by the size of the symbol used (a large symbol representing large uncertainty. The relevance of the uncertainty is indicated by the distance of the symbol from the centre of the chart, the closer to the centre, the more relevant to the decision.

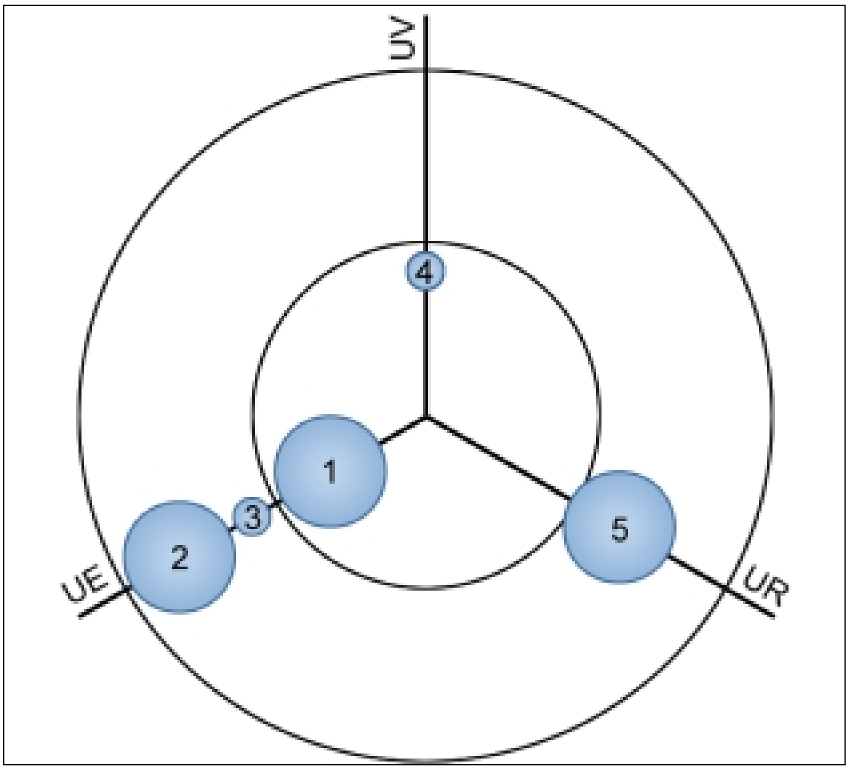


Figure 5.5 Uncertainty Radial Chart

Consider a beach renourishment programme, planned over a scheme life of the next 50 years :
The three axes represent 3 types of uncertainty: Uncertainty in the environment (climate change) (UE); uncertainty in values (UV) and uncertainty in related decisions (UR). The numbered circles represent the following:

1 Uncertainty in sea level rise predictions.
2 Uncertainty in the output of global circulation models.
3 Uncertainty in future CO_2 levels.
4 Uncertainty in the ‘costs’ of re-nourishment material.
5 Uncertainty in future legislation of offshore dredging.

The uncertainties are plotted by type (separate axis), magnitude (size of the circle) and relevance (proximity of the circles to the centre of the diagram. The uncertainty in sea level rise is therefore the most significant uncertainty.

5.3 Detailed methods

Bayesian analysis

Bayes theorem provides a means of using new information to revise probabilities based on old information. Where there is initial uncertainty regarding a variable, this type of analysis can be used to incorporate new information and provide new estimates, with reduced uncertainty.

The methodology developed in CEH (1999), for estimating the rarity of flood peaks, provides an example of empirical Bayes estimation. Information from rivers with similar characteristics to the river under study is obtained. This information is ‘pooled’ with the information that is available on the river under study and return period, flood peak estimates are calculated. The aim of this methodology is to reduce the Statisitcal Inference Uncertainty (see Chapter 6) by providing more base data. However, this reduction in Statistical Inference Uncertainty has to be considered together with the increase in the uncertainty of the base data set, which is not from the river under study. In statistical terms, a slightly biased estimator with a narrow confidence interval (more certain) may provide a better predictor than an unbiased estimate with a wider confidence interval (less certain).

Another example of Bayesian methods is the GLUE Methodology (see Page 69).

Benefit Cost Analysis (BCA)

BCA involves comparison of the costs and benefits associated with each option. It is designed to aid the selection of the option with the greatest excess benefits over the costs and allows the choice of options to be refined. The method requires a single unit, which is normally monetary and thus valuation methods are required (for example valuing the saving of life). A key feature of BCA is that it accounts for costs and benefits over different time scales, by the use of discounting techniques. BCA is the tool recommended by DEFRA for appraising flood and coast defence systems.

Cost effectiveness analysis (CEA)

CEA is a comparison of alternative ways of achieving an already specified target so as to achieve this target at the lowest possible cost. In contrast to BCA, the benefits are constant and the aim of the analysis is to minimise the costs associated with achieving a specific objective.

Cross Impact Analysis

Cross Impact Analysis is a formal tool for assessing the dependencies between events and future developments. CIA is used to gain an understanding of the change in probability of a future event(s), given another event has occurred (i.e. assessment of the conditional probability).

CIA can take a quantitative Monte-Carlo simulation form, or a simpler, qualitative form. An example of the simple approach is given below (from RPA (2001)).

	Climate change	**Coastal Dynamics**	**Biodiversity**	**Fisheries**	**Landscape**
Climate change		2	2	1	2
Coastal dynamics	0		2	?	1
Biodiversity	0	1		2	2
Fisheries	0	0	2		0
Landscape	0	0	2	0	
Key: 0 no relationship; 1 weak relationship; 2 strong relationship; ? possible/uncertain relationship					

The information in the table is straightforward to interpret, and provides a summary of the dependencies between each of the different processes.

Event trees (fault trees)

Event trees are used to analyse a range of likely causes of a particular outcome (i.e. flooding / no flooding) that may arise from a given initiating event (i.e. heavy rainfall). They track routes by which certain events can occur, starting with an outcome, which then leads to a possible range of initiating events depending on the route taken (see Figure 5.6 (reproduced from RPA (2001)).

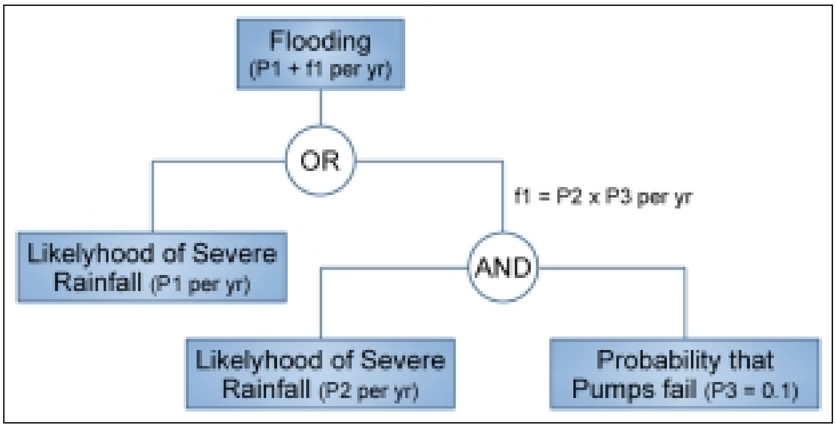


Figure 5.6 Event tree (from RPA 2001)

Fault trees are similar to event trees although they start with an initiating event (heavy rainfall) and analyse the impact of the event through consideration of a range of logical AND and OR gates (see Figure 5.7 (reproduced from RPA (2001)).

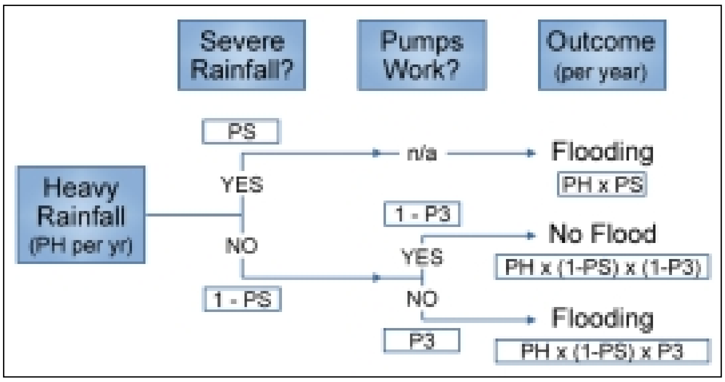


Figure 5.7 Fault tree (from RPA 2001)

Extreme value methods
Extreme value distributions are generally expressed as probability density functions. These functions are specifically derived for estimating low probability events (traditionally expressed as a return period). The functions are fitted to data using a number of fitting methods. Two commonly applied fitting methods are maximum likelihood (ML) and probability weighted moments (PMW). There are a range of different distributions that can be used, some of the more frequently applied are: Generalised Extreme Value (GEV), Weibull, Generalised Pareto (GP), and Gumbel. The choice of distribution depends upon the sampling frequency of the data (the GEV and Gumbel distribution are generally fitted to annual maximum data, whilst the Weibull and GP are generally fitted to peaks over threshold (POT) data) and, to a certain degree, the user's preference.

Figure of merit
Figure of merit is a tool that can be used to assess the performance of a scheme over a number of different processes. It can therefore be used aid the decision maker in selecting the most appropriate scheme. For example, consider Figure 3.1 where two schemes are compared over a number of criteria: Engineering, economics, operation, erosion, flooding, tourism. The individual respective performance criteria will generally be expressed in dimensional terms (e.g. monetary, erosion rates, flooding volumes). To compare the performance of the two schemes over the range of criteria, the dimensional performance measures are transferred onto a non-dimensional scale (0-1). Each criterion can have a weighting assigned, based on the preferences of the decision maker or guidance under which the decision maker is operating. The weightings and non-dimensional scores are combined and assessed for each criterion, for each scheme. An overall figure of merit score can then be calculated, giving a performance ranking for each scheme.

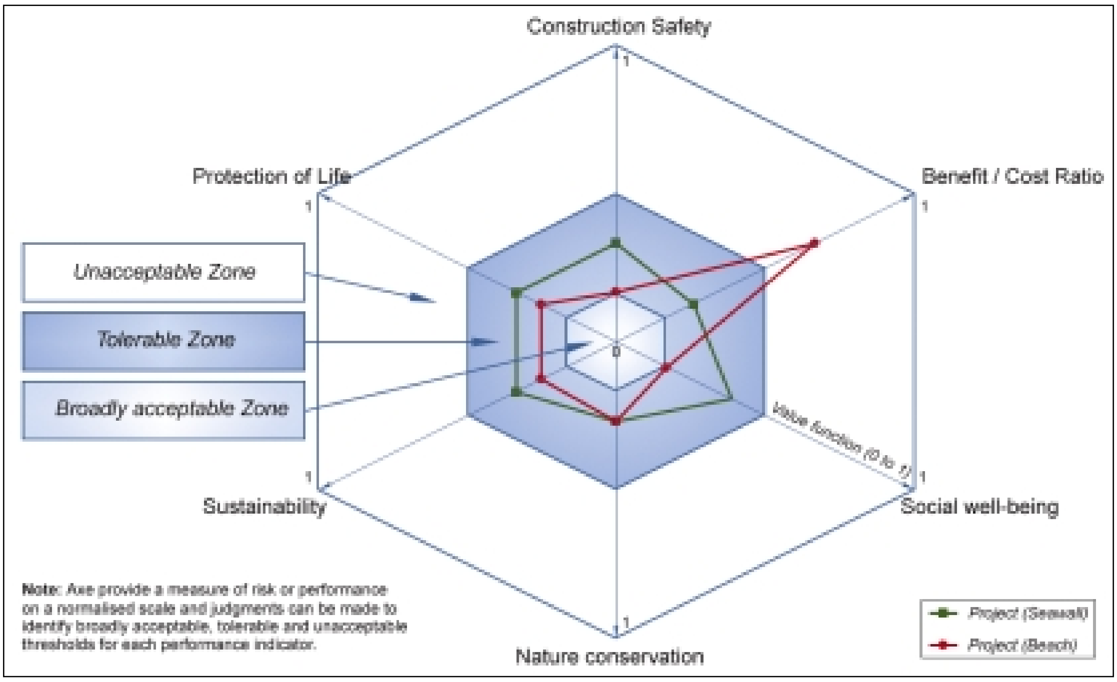


Figure 5.8 Figure of merit analysis (taken from Chapter 3)

FMECA – Failure Mode Element and Criticality Analysis
The FMECA approach is aimed at prioritising the risk posed by elements with a structure or defence in terms of causing structural failure (partial or complete). The FMECA philosophy combines event/fault tree with risk registers to produce Location/Cause/Indicator diagrams. Often the FMECA technique offers a mechanism for considering risk in a consistent and auditable manner whilst avoiding the pitfalls of undertaking excessive probabilistic analysis.

The FMECA technique has been successfully applied within the UK Dams Industry, (CIRIA (2000)). A FMECA also provides the basis of the quantified risk assessment approach adopted by BC Hydro in Canada, by identifying the failure events that need to be studied in detail. Typically, an FMECA approach:

- avoids the use of specific probabilities; adopting instead a descriptive system
- uses a common calculation system for all elements which allows the risk from all elements from all sites to be compared directly against each other and hence prioritised
- encourages the use of risk registers and the systematic identification and management of risk
- provides a mechanism for recording all risks at a site

Fragility curves
A fragility curve describes the probability of failure given a certain loading condition. An example of a fragility curve is shown in Figure 5.8.

Fragility curves can be used to assess the annual probability of failure of a defence, and thus provide a more risk-based measure of defence standard than Standard of Service or condition grade assessments.

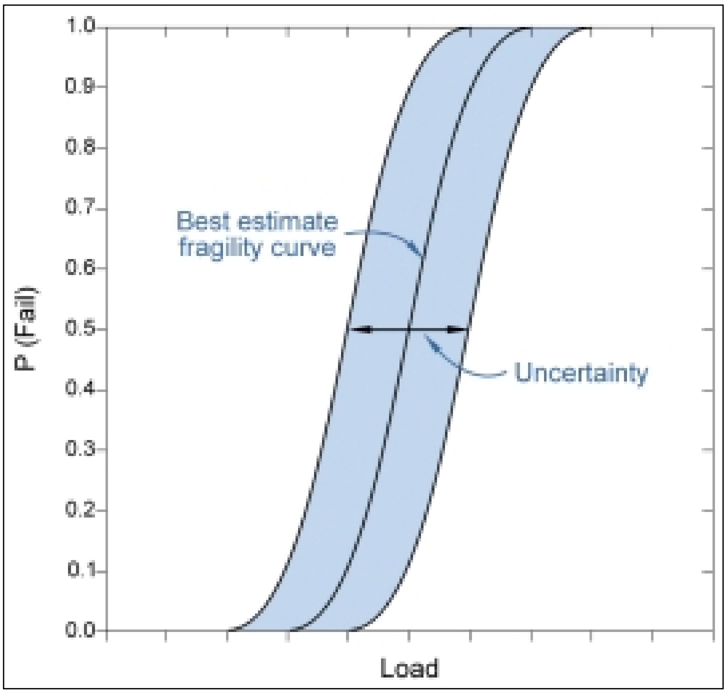


Figure 5.9 Example fragility curve

Generalised Likelihood Uncertainty Estimation (GLUE)
GLUE is a methodology for assessing the predictive uncertainty associated with process models (Beven and Binley (1992)). The underlying concept of this approach is the rejection of the idea that an optimum model parameter set exists, in favour of the concept of equifinality (i.e. there are many different sets of parameters that can provide acceptable answers). The methodology therefore focuses on assessing the performance of parameter sets (derived by Monte Carlo sampling techniques (see below)), against the calibration data, through calculation of a range of likelihood measures (i.e. functions that assess how well

the environmental model results, produced by a parameter set, match the calibration data). This procedure allows the rejection of model parameter sets that fall below acceptable thresholds of likelihood. Such parameter sets are termed non-behavioural; parameter sets that are above the thresholds are termed behavioural. The behavioural parameter sets are then weighted according to the likelihood measures to provide a range of response from the response model. Clearly the choice of threshold, the measures of likelihood and the method of combining the information from different likelihood measures are subjective. However, it is argued that these choices must be made explicit and can therefore be subjected to scrutiny and discussion.

The GLUE methodology has been applied to a variety of environmental prediction problems, including rainfall-runoff modelling (Beven and Binley (1992)); flood inundation prediction and CFD simulation of rivers.

Joint probability methods

Where the source consists of one or more variables (e.g. coastal flooding caused by extreme wave heights and water levels, or estuarine flooding caused by high river flows and high tidal levels), it is necessary to consider their joint probability. There are different levels of complexity for joint probability methods but all require some assessment of the dependence between the variables.

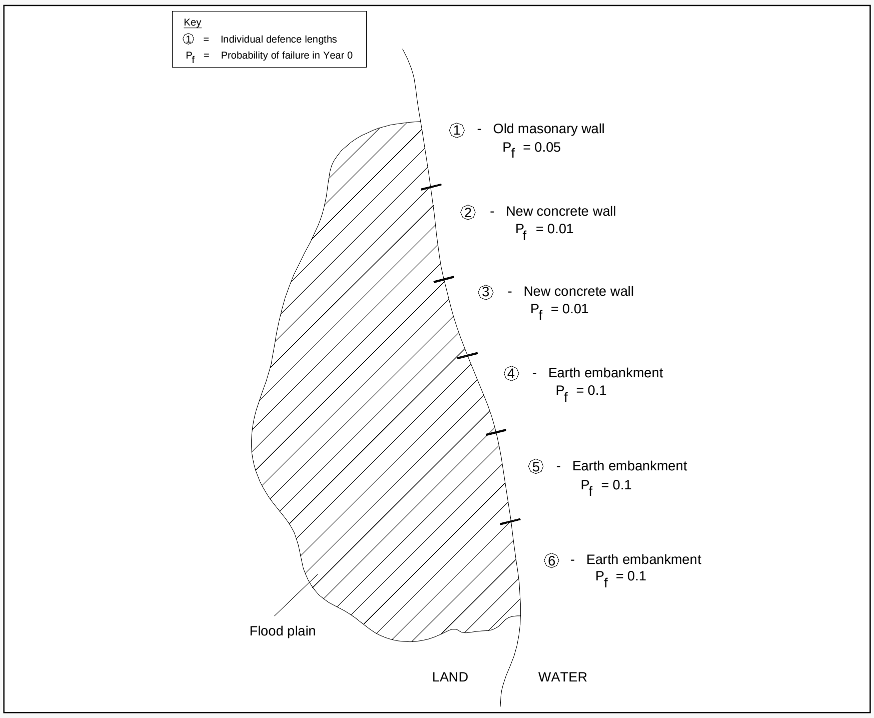
A relatively simple method (see CIRIA (1996)) makes use of the marginal (individual) distributions of wave heights and water levels and an assessment of their dependence. This information is used to express the joint return period of the loading conditions in terms of combinations (there are many combinations of the two variables that have an equal joint return period) of the marginal return periods. The benefits of this approach are that it is practical and relatively straightforward to apply. The main disadvantage of this approach is that the relationship between the return period of the load (i.e. the joint wave and water level return period) is not the same as the return period of the response variable (see Chapter 2).

A more sophisticated approach involves fitting a probability distribution to the joint distribution of the variables and extrapolating the joint probability density. The benefits of this approach are that the return period of the response variable can be determined directly, and can thus be used more directly in risk calculations. The main drawback of this method is that a significant amount of concurrent data of the two variables is required.

This approach is adopted in the JOIN-SEA joint probability software (HR Wallingford 1998) uses a Level III approach and was originally developed to assess the reliability of the following response functions: runup, overtopping, wave forces, armour stability (NB. The parameters of the response functions are treated as single values and not probability distributions in the present set-up). However, recent developments have included a contouring procedure that enables evaluation of complex response functions (i.e. where the relationship between the input variables and the response variable is complex and therefore not known). The response function is evaluated at a sample of points in the input variable space and a surface is fitted that represents the response function. The full distribution of the response function is then assessed through evaluating the input variables and output from the Monte Carlo simulation, with reference to the fitted surface. This approach has been applied to estimate extreme water levels in the Severn Estuary, where, a 1D hydraulic model was used to assess the relative influence of river flows and sea levels (HR Wallingford in press).

Box 5.1 Applying joint probability methods to flood defences – a discussion

Consider the situation of a series of flood defences protecting a single flood plain (the *pathways*) containing a number of properties (the *receptors*) exposed to marine storms (the *source*) (see figure below). For reasons of clarity, consider the issue of establishing the probability of flood defences failing. A key issue for the decision-maker is to understand the likelihood of a failure at any, or several, location(s) within the defence system (i.e. the *pathway*), and not simply the behaviour of the individual defences.



Schematic of defence lengths protecting a flood cell

In this situation, three alternatives exist for describing the relationship between the individual defences and hence calculating the probability of failure of the defence system (note: similar concepts are equally applicable to all aspects of the flood and erosion management system):

- **Fully independent**
  In this case it is assumed that a particular defence length will behave in accordance with its own intrinsic qualities such as construction material and residual structural strength. Under this assumption the probability of system failure within a specified timeframe is easily described as:

  $\mathbf{P}_{system}$ = 1-((1-pf$_1$). (1-pf$_2$) ... (1-pf$_{n-1}$), (1- pf$_n$)) (e.g. from Figure 2.2, where n=6, $\mathbf{P}_{system}$ = 0.32)

  Where;
  n = the number of discrete defence lengths
  pf = the probability of failure of an individual defence length within a specified timeframe

- **Fully dependent**
  In this case it is assumed that there is a tendency for defences exposed to similar loading to behave in a similar way. For example, for each defence length, failure is most likely to occur during a major storm. Under this assumption the probability of system failure within a specified timeframe is easily described as:

Box 5.1 Applying joint probability methods to flood defences – a discussion *continued*

$\mathbf{P}_{system}$ = Maximum (pf_i) i=1 to n (e.g. from Figure 5.10 $\mathbf{P}_{system}$ = 0.10)

- **Partial dependence**

  In reality it is likely that $\mathbf{P}_{system}$ will lie somewhere between 0.32 and 0.10 and the degree of correlation between defences will depend on their proximity, structural form and failure mechanisms, as well as their exposure to extreme loads that may lead to failure. The most complex part of this process is to determine the correlation between these components and hence the 'system' failure probability. To determine the value of P_{system} a number of possible methodologies are available to achieve a more realistic representation of partial dependence between defences. These are discussed below.

  - *Approximate methods to introduce a degree of dependence*

    There are range of methods of varying complexity that can be applied in this situation of partial dependence. For example a relatively simple approach has been applied on the Thames Tidal Embayments Studies (Environment Agency 2000c) based on separating the defences into two classes and considering the performance of each class of defence independently before combining the results assuming dependence. Equally, high level methodologies for appraising risk on a national scale are being developed at HR Wallingford and Bristol based on the assumption that loading on a defence system maybe considered dependent whereas the individual strengths of the defences are independent.

  - *Develop correlation matrices that describe relationships between defences*

    The approximate methods can be improved to enable the condition of the immediate neighbours to a defence to influence the likelihood of its failure by using a Conditional Probability Relationship as discussed in MAFF (2000). This involves the establishment of a correlation matrix to describe conditional failure probability relationships (i.e information on the change in the likelihood of failure of a particular defence assuming its neighbouring defence fails or a severe storm is encountered). However, although this is relatively simple in theory, application of this approach in practice is constrained due to the limited understanding of the interaction of defences and their structural performance under extreme loads. Therefore, although a promising approach, it will require further thinking and research to develop evidence based correlation matrices. However, this type of approach is currently being developed by the Dutch, for managing dyke rings (PC Ring Project) that includes correlation between loading and condition assessments (Vrijling and van Gelder, 2000).

  - *Develop full simulation based approaches of defence performance*

    The most powerful approach is one of full simulation that seeks to combine evidence on defence performance, loading and response. These techniques are starting to be explored through the use of simulation tools that consider the reliability of defence system as a whole with 'built-in' correlation between defence elements and loading. These type of approaches are presently being considered for application in the UK where the defence system and flood plain is complex, although it will require considerable research effort to develop useable and scaleable methodologies.

Probabilistic reliability methods
These methods improve upon traditional deterministic design methods by considering the full distribution of loading and strength variables, as opposed to considering a characteristic design value (e.g. design wave height). The methods assess the safety or reliability of a structure through assessment of the probabilities of different failure mechanisms. Failure can be defined in a number of different ways. For example, a seawall can be considered to have failed if the overtopping rate exceeds a specified value, or alternatively, failure may be defined as structural collapse of the seawall. Having identified the failure modes, functions that describe the failure process (response functions) are applied to define a reliability function (usually denoted as Z). This function is described in terms of the loading and strength variables such that:

$Z>0$ safe region
$Z<0$ failure region
$Z=0$ represents the boundary between failure and safety. This is termed the limit state (see Figure 5.10)

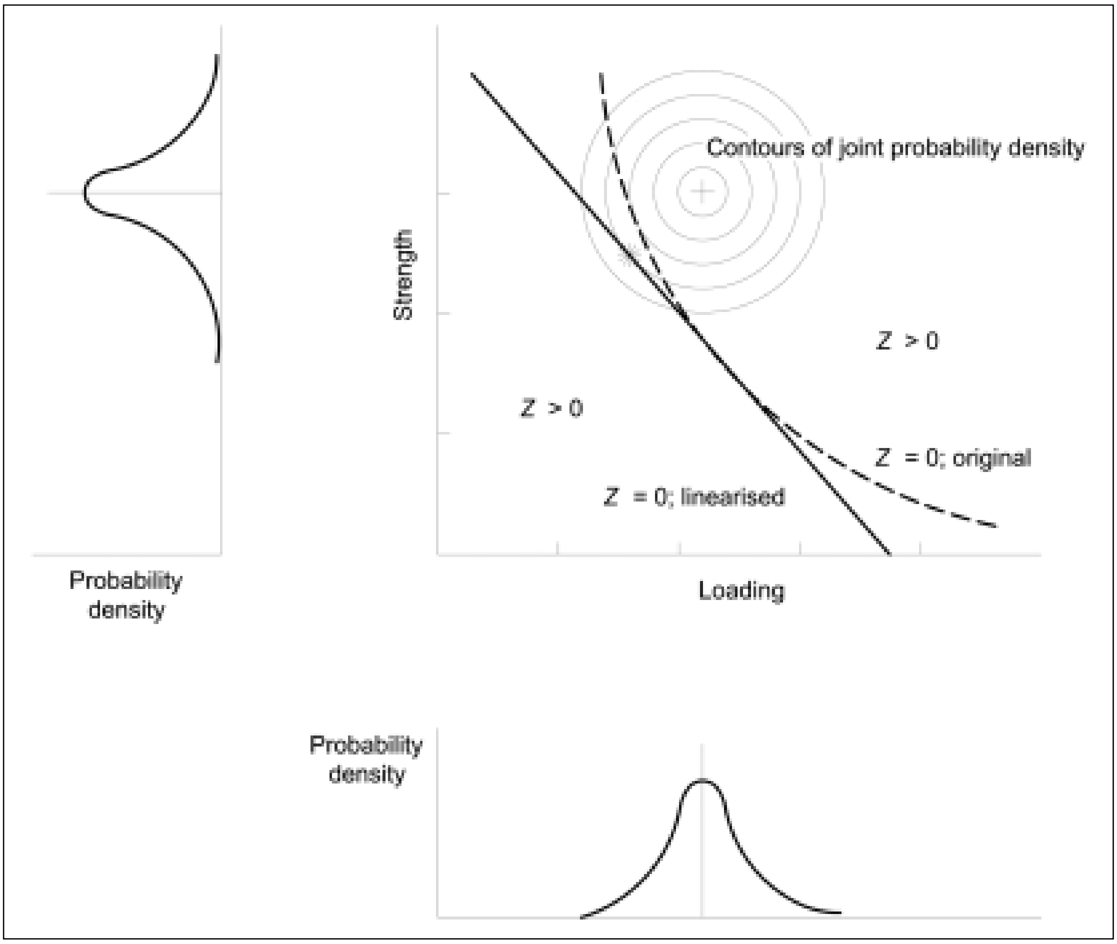


Figure 5.10 Illustration of the relationship between loading, strength and the limit state

These methods have been categorised into levels based upon the complexity of the approach.

Level III methods are the most extensive and use full probability distributions for all of the input variables (sometimes termed basic variables). These methods also represent any dependency between the input variables. The failure region is exactly represented through numerical integration of the probability density of the input variables. Often, analytical integration is too complex and Monte Carlo simulation techniques are used (see above).

Monte Carlo analysis
Monte Carlo analysis is a tool for combining input probability density functions (mathematical functions that describes a continuous probability distribution of a variable) through a response function or model, to

obtain the output in terms of a probability distribution (see Figure 5.11). This tool is particularly useful for analysing uncertainties, if the uncertainty on input variables can be described by a probability density function.

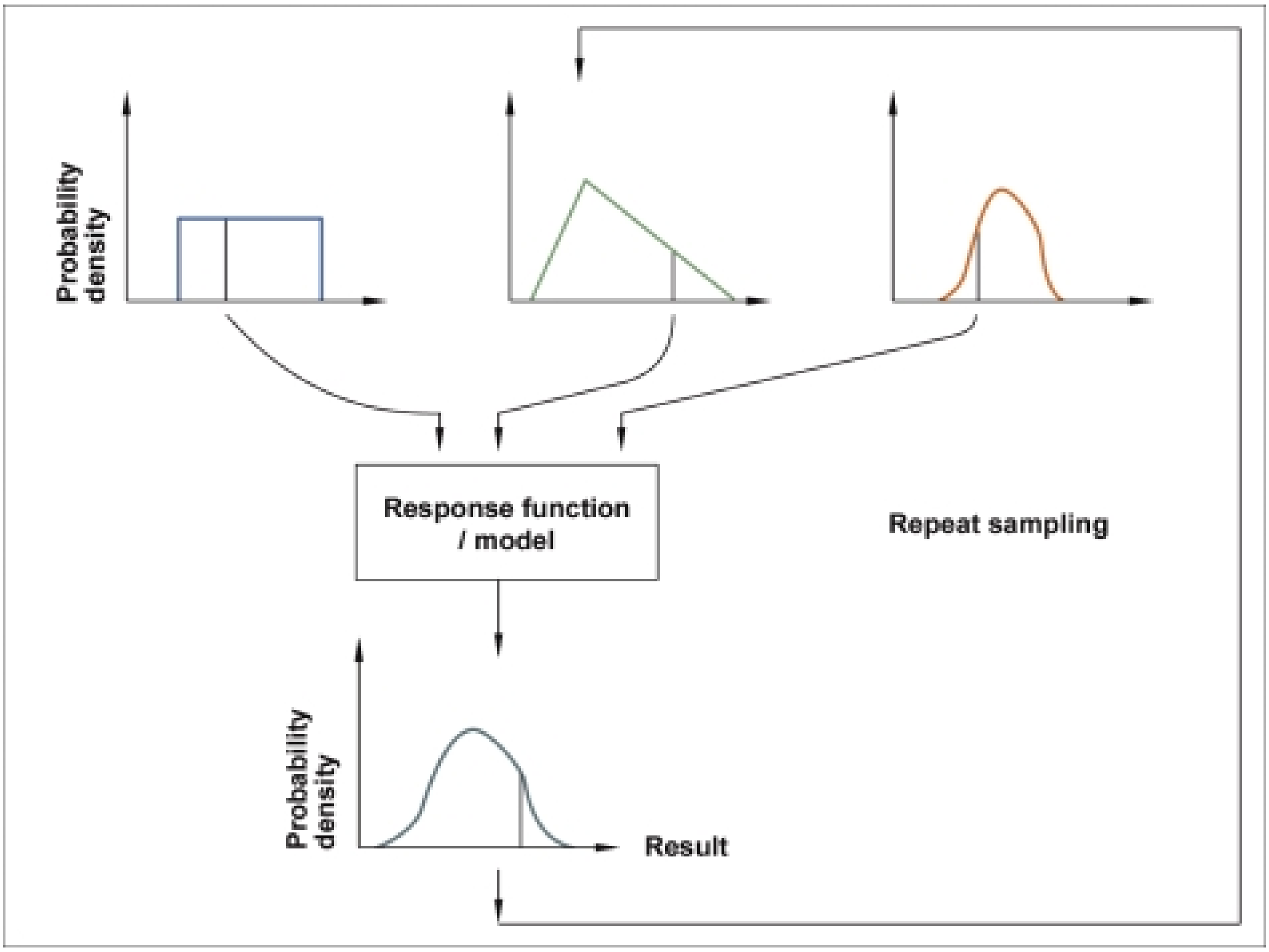


Figure 5.11 Schematic showing the steps involved in a Monte Carlo Modelling approach

The technique involves randomly selecting a value from each of the input probability distributions and passing this combination of inputs through the response function, to obtain one realisation of the response variable. This sequence of events is repeated many (sometimes in the region of 10 000) times over, and a probability distribution of the response variable is produced.

When using this technique, it is important to assess any dependencies between the input variables, and include these in the modelling process. Making the assumption of independence between variables that are partially correlated, can result in significant bias in the output.

Level II methods differ from Level III methods as they approximate the failure region (see Figure 5.12) and are therefore simpler to use. This is generally a linear approximation (First Order Reliability Method (FORM)) but can also be a more advanced second order approximation (Second Order Reliability Method (SORM)). Although less accurate than Level III methods, Level II methods have their advantages. For example, Level II methods automatically produce information regarding the sensitivity of the response function to the input variables and parameters. This information can be used to focus attention on reducing uncertainty on the variables or parameters that are of greatest significance.

PARASODE (Probabilistic Assessment of Risks Associated with Seawall Overtopping and Dune Erosion) (Hedges and Reis (1999)) is software that uses a FORM to assess overtopping and dune erosion response functions.

Level I methods are quasi-probabilistic and involve the assessment of reliability by specification of a number of partial safety factors related to some pre-defined characteristic values of the basic variables. For example, the ratio of load at failure to permissible working load.

Scenario modelling
Scenario modelling is used to examine the implications of uncertainty on a particular decision. There are significant uncertainties regarding climate change and thus scenario modelling is particularly prevalent in this field. Scenarios maybe specified in quantitative (e.g. CO_2 will double from present day emissions, by the year 2075) or qualitative terms (e.g. business as usual, best estimate, worst case). The implications of each scenario on the decision can then be assessed. If the 'best option' varies under different scenarios, then further assessment can be undertaken, however, this can be complicated where there is no guidance on the relative likelihood of individual scenarios. In such circumstances expert judgement is often used.

Sensitivity analysis
Sensitivity analysis involves identifying and investigating the sensitivity of the outcome or response variable to changes in input variables and parameters. The input variables/parameters are adjusted within what are thought to be plausible limits, and the impact on the response measured. Where a response is particularly sensitive to a variable/parameter, efforts can be directed to reducing the uncertainty on the 'key' variable/parameter.

Uncertainty analysis that uses probability distributions to represent uncertainty and involves Monte-Carlo simulation techniques, is a formal method of sensitivity analysis.

Utility Theory
Utility (in context) is a measure of the desirability of consequences of courses of action that applies to decision-making under risk. The fundamental assumption in utility theory is that the decision maker always chooses the alternative for which the expected value of the utility is a maximum. If that assumption is accepted, utility theory can be used to prescribe the choice that the decision maker should make. For that purpose, a utility has to be prescribed to each of the possible consequences of every alternative. A utility function is the rule by which this assignment is done and depends on the preferences of the decision maker. As a consequence of this subjectivity it is possible to distinguish whether the decision maker is risk prone, risk averse or risk neutral risk averse.