CHAPTER 227

Risk assessment for coastal and tidal defence schemes

Meadowcroft IC[1], von Lany PH[2], Allsop, NWH[3] and Reeve DE[2]

ABSTRACT

This paper describes risk assessment techniques developed in a research project carried out for the UK National Rivers Authority (NRA) (Meadowcroft and Reeve, 1993). The main aim is to develop probabilistic design and analysis methods to assess the risks of failure for new and existing sea and tidal defence schemes. The flood risk takes account of the failure probability and the consequences of failure. There is a contrast between conservative design criteria that attempt to minimise failure rates, and risk-based design criteria that offer a more cost-effective solution despite a possible increase in failure frequency. The procedures are intended to be used in the design of new schemes, for assessment of existing defences and prioritisation of maintenance and refurbishment.

1. INTRODUCTION

The paper outlines new procedures under development for the National Rivers Authority to assess risks of failure for new and existing sea and tidal defence schemes. The project includes assessment of areas at risk of flooding, but this paper concentrates mainly on risk assessment and probabilistic analysis of structures. The research is being used to formulate procedure for assessment of flood risk. The key elements of the procedures are:

- A tiered classification system;
- Modular procedures allowing more or less complex methods to be applied as appropriate;
- Risk defined as a combination of the probability and consequence of flooding;
- Screening tests using existing data such as that held in the National Sea Defence Survey (NSDS) to identify defences at greatest risk;
- Identification of principal failure modes and more detailed analysis of these using probabilistic methods;
- Advice on methods for flood area mapping and data collection as a means of

[1]HR Wallingford, Howbery Park, Wallingford, Oxon, OX10 8BA, UK

[2]Sir William Halcrow and Partners Ltd, Burderop Park, Swindon, Wiltshire, SN4 OQD, UK

[3]HR Wallingford, Howbery Park, Wallingford, Oxon; Professor (Associate) University of Sheffield

assessing the consequences of failure.

The paper firstly describes the overall structure of the procedures, and then examines in more detail the role of probabilistic methods in assessing flood risk.

2. STRUCTURE CLASSIFICATION AND FAILURE MODES

One of the first tasks of the research was to develop an appropriate classification system for structures. The classification system is hierarchical, based on three levels:

Level 1:	generic type eg narrow embankment with sloping face
Level 2:	general form of construction eg vertical wall with crest and back slope unprotected
Level 3:	detail of individual components eg revetment type

The advantage of this approach is that failure mechanisms at different levels of detail can be assigned to each level of the classification. The structure classification is used to guide preliminary assessment at the screening stage. The structure type affects its vulnerability to different failure mechanisms. Part of the structure classification system is

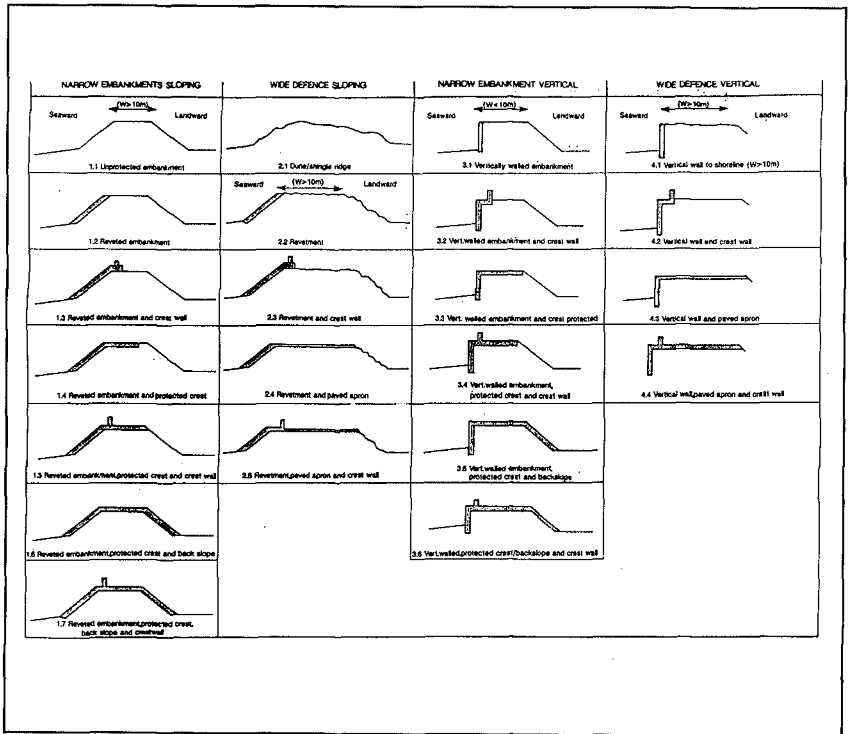

Figure 1 Structure classification scheme. The structure type can be used as a guide to the most likely failure mechanisms, and to identify appropriate response functions.

shown in Figure 1.

An example of the linkage between structure classification and response function is the selection of an appropriate method for calculating wave overtopping. Potential consequences of overtopping include flooding, danger to the public and damage to defence structures. Numerous methods are available depending on the geometry of the structure.

Four categories of structure each requiring different methods are detailed:

i) For sloping seawalls, the actual overtopping, Q_{act}, may be calculated using an equation developed from the method by Owen (1980)

$$Q_{act} = Ae^{\left(\frac{-B R_c/r}{T_m\sqrt{(gH_s)}}\right)} T_m g H_s \quad (m^3/s/mrun)$$

A and B can be obtained from standard tables
r is the effective roughness of the seawall slope, established from site visit or from table 3, Owen (1980)
R_c is the freeboard (crest level minus water level)

ii) For sloping seawalls with wave return walls, the method derived by Owen & Steele (1991) is appropriate. This extends from the method for sloping sea walls, with the freeboard being considered as the distance from SWL to the top of the wave wall, as opposed to the top of the seawall. It should be noted that this method was derived for recurved wave return walls and will therefore give a value which is less than the actual overtopping discharge for vertical wave return walls which experience a greater degree of overtopping.

iii) Overtopping for vertical walls is calculated using standard graphs and the expression (Goda, 1971)

$$Q_{act} = Q^*(2gH_s^3)^{0.5}$$

iv) For vertical seawalls with wave return walls, no defined method was found. It was concluded that the seawall and the wave wall should be considered as a single defence, taking the structure height as the height of the two defences combined. The method for standard vertical walls can then be applied.

Table 1 illustrates a simple look-up procedure to link seawall type, profile classification and calculation method. Profile references refer to the structure types identified in Figure 1.

A wide range of other failure mechanisms have been identified and appropriate response functions recommended (eg Allsop 1993).

Structure type	Profiles	Method
Sloping seawall	1.1, 1.2, 2.1, 2.2	(i)
Sloping seawall with wave return wall on crest	1.3, 1.5, 1.7, 2.3, 2.5	(ii)
Vertical seawall	3.1, 3.3, 3.5, 4.1, 4.3	(iii)
Vertical seawall with wave return wall	3.2, 3.4, 3.6, 4.2, 4.4 (assuming height of structure to be sum of seawall and wave return wall heights)	(iv)

Table 1 Overtopping calculation method depending on structure classification

A survey of flood defence failures has been undertaken as part of the project. This has shown that, while there have been a numerous reported flood events due to defence failures, information about failures of defences is normally very limited in scope, and is rarely sufficient for identifying the precise sequence of mechanisms leading to a failure. One may gain more useful information from studying rates of damage and deterioration, where the condition of the defence may indicate potential failure mechanisms.

Damage cause by burrowing animals

According to anecdotal and documented information from NRA staff, a particular area of concern is the damage caused by burrowing animals such as rabbits and badgers. The main problems are the serious structural damage caused, including voids and passages through embankments, the difficulty in carrying out effective repair, short of re-building the affected part of the embankment, and the likelihood of re-infestation. The number of rabbits, in particular, can be particularly difficult to control. In one severe case, over 1000 rabbits are reported to have been killed over a few months, but the embankment continues to be colonised. Conservation interests can have a great influence on the measures taken. There are, for example, controls on the disturbance of badger setts.

The project has found very little information on the effect of animal burrows on embankment safety and flood risk, either in terms of animal behaviour or from the point of view of hydraulic and geotechnical impacts. Research is at present underway to fill some of these gaps, but in the meantime, approximate methods such as assuming a reduced effective crest level can be used. Site investigation is also important, from recording the number of burrows, and their positions, to mapping the internal structure of voids caused by animals. Non-destructive investigation techniques may have potential to investigate the size, extent and location of burrows and other voids.

3. RISK ASSESSMENT METHODS

There are several different definitions of 'risk', but for our purposes, risk is defined as the combination of the probability or frequency of occurrence of a defined hazard, and the magnitude of the consequences.The method of combination is generally to multiply the probability and consequences. This gives a measure of the expected value of the consequence incurred in the time period being considered. Risk as defined is thus closely related to the assessment of benefits which is commonly carried out as part of the project appraisal process.

Even within the relatively narrow topic of flood risk, there are a number of aspects of risk likely to be of interest to user of the procedures:

- The danger to the public from flooding, expressed in terms of number of injuries or deaths, and associated frequency
- The probability of death or injury to individuals
- The frequency of flooding at different locations in the potential flood area taking account of all the possible causes of flooding and all possible failure mechanisms. This information can be shown as frequency contours.
- The depth and duration of flooding.
- The degree of risk inherent in each defence structure ie the expected annual consequences of failure of the structure
- 'What if' scenarios, ie flood outlines conditional upon some prescribed defence failure

A general procedure for risk assessment is illustrated in Figure 2, which illustrates the process of hazard identification, and assessing the probabilities and consequences of failure.

Although the concept of risk is straightforward, the implementation is complicated because a full risk assessment must consider *all* hazards which could result in damage or loss. Clearly some hazards will make an insignificant contribution compared to others, but in principal all hazards must be identified and studied as far as necessary to establish what degree of risk they pose. Similarly, even a relatively simple structure will have a number of potential failure mechanisms, and it will not usually be known with certainty which are the most likely to contribute most to the risk.

The procedure illustrated in Figure 2 should therefore be repeated for different hazards, and for different failure mechanisms. This would result in a large amount of work which would prevent the wide application of detailed risk assessment. This explains the need for simplified procedures to screen out 'low risk' structure and to identify those in need of the most detailed analysis.

The project has identified failure modes, defined as a number of individual mechanisms. Failure mechanisms are described using a nested system to reflect the level of detail of the classification system . At Level 1, the failure mechanisms are simply breaching and overtopping/overflow. At Level 2, we identify mechanisms affecting the main parts of the structure such as the seaward face, crest, and landward face. Level 3 considers failure of individual structure elements such as breakage of revetment units.

One of the early findings of this work was that, whilst conventional fault trees and event trees as used in the electronics and chemical industries may be suitable for systems of binary components that either fail or do not fail, they are not sufficient on their own for failure of sea walls and related structures. These exhibit complex failure modes with interactions between different damage mechanisms. For example, overtopping and geotechnical slope failure of the landward face of an embankment may not, individually, pose a high risk, but the damage due to the geotechnical failure will make erosion due to overtopping much more likely: the mechanisms interact. Furthermore, the quantity of water overtopping may be very important in determining the area flooded and hence the consequence: one cannot talk only of 'failure' and 'no failure' for this type of risk assessment, since a spectrum of outcomes can result.

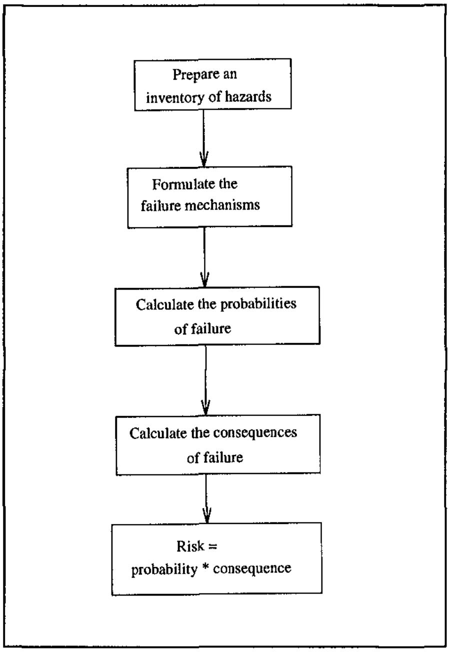

Figure 2 Overall procedure for risk assessment (from CUR/TAW, 1990)

The project considers a number of practical techniques for dealing with a broader range of mechanisms needed for an assessment of a sea defence system. One particular method makes use of 'event chains' leading from a particular trigger event (ie storm), through failure mechanisms to set a of consequences. For each consequence, a probability of occurrence is calculated, conditional upon the initial event. It is necessary to incorporate connections between some event chains, to account for the physical dependence noted above.

An advantage of the method is that it provides a framework which can be applied at several levels of complexity, providing a modular approach at each level of detail appropriate to the degree of risk and data availability. This tiered approach is illustrated in Figure 3. The first steps make use of data already held by the NRA as part of the National Sea Defence Survey (NSDS). This has created a set of data about sea defences in England and Wales, including information such as the length and position of defences, and an assessment of their condition and effectiveness. The survey includes classification of the area of the potential flood area and the land use within that area. Thus the NSDS provides an important starting point for assessing risk. Automated screening tests have been developed using this data, and the indicative or relative risk is also based partly on NSDS data. More detailed assessment of risk requires additional site-specific data.

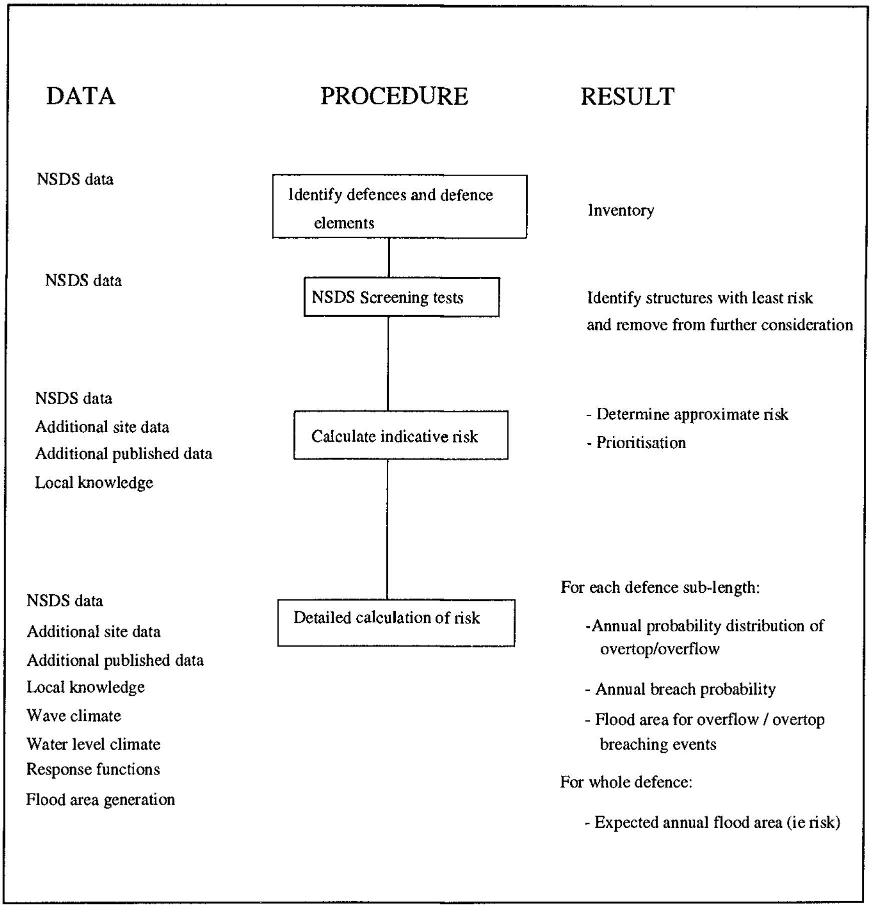

Figure 3 Tiered assessment procedure showing level of data, analysis and results at each stage

4. PROBABILISTIC METHODS

Probabilistic methods are used to account for uncertainty in data values or in response functions. The main sources of uncertainty are:

- Identification of hazards
- Identification of failure processes / failure modes
- Development of damage leading to failure, time effects
- Data on load parameters, lack of data or errors in data
- Long term changes including climate changes
- Stochastic nature of loading, even if statistics are well known
- Structure geometry and material properties
- Responses: form of functions and empirical coefficients

- Thresholds for failure

Probabilistic methods can be applied to account for many of these uncertainties to give an estimate of the response which is consistent with our level of knowledge or ignorance. This estimate will generally be in the form of a probability distribution, although if a threshold for failure is defined, the result may be in the form of a failure probability. Of course, the exact *actual* or realised failure probability of a particular structure will only be known in the future, and it will have a value of either 0.0 or 1.0, but random variations in loads, and uncertainties in strengths and response functions prohibit us from predicting failure or otherwise exactly. We can only hope to estimate a probability of failure based on current knowledge.

Probabilistic methods enable uncertainties in strength and loading variables to be propagated through the risk assessment procedure. The final risk assessment therefore takes account of lack of precise knowledge of the structure properties, the environmental loading, and the response function. Probabilistic methods provide a basis for accounting for the effects of uncertainty in a structured and systematic manner. These can have significant cost and benefit implications. Probabilistic methods may be subjective, based on engineering opinion, or objective, based on Monte-Carlo sampling or analytical methods.

Development and application of probabilistic methods for structural design and analysis is described in more detail elsewhere (CIRI, 1977, Thoft-Christensen & Baker 1982). Application of a range of methods to coastal structures is described by Meadowcroft & Allsop (1994).

The simplest analytical methods (known as Level II, first order mean value methods) are in fact closely related to sensitivity tests: the key advantage is that they account for the variability in input parameters as well as the sensitivity of the response to the inputs, and probabilistic methods take account of the combined effects of variability of all relevant parameters.

Several examples are now given which illustrate the data required and results obtained from probabilistic methods.

<u>Example 1: Level III (Monte Carlo sampling) prediction of damage to a rock armour structure</u>

This simplified example demonstrates clearly the influence of variability in input parameters on the resulting prediction. The response function is the Van der Meer (1988) equation to predict the degree of damage, S, to rock armour under plunging waves as a function of structure and load parameters. In this case, the occurrence of the design storm is presumed, so the variability results from uncertainty in structure parameters such as rock armour size, and from errors in estimating the design wave height. There is also some uncertainty in the values of the empirical parameters a and b in the response equation: these can be treated like any other probabilistic input parameter.

Input parameter	Distribution	Standard deviation (coefficient)	Mean
Significant wave height H_s (m)	Normal	10%	3.0 (depth limited to 0.55h)
Slope angle (o)	None	-	0.5
Rock density (kgm^{-3})	Normal	5%	2650
Nominal rock diameter D_{n50} (m)	Normal	5%	1.3
Permeability parameter P	None	-	0.1
Wave steepness s_m	Normal	10%	0.05 (truncated at 0.07)
van der Meer parameter a	Normal	10%	6.2
van der Meer parameter b	Normal	10%	0.18

Table 2 Input distributions for calculating probability distribution of damage

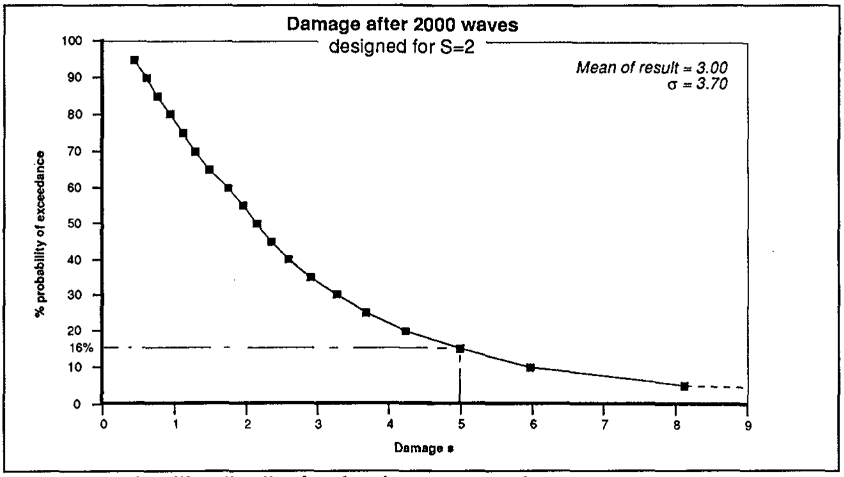

Figure 4 Probability distribution for damage to rock armour structure

The resulting probability distribution (Figure 4) shows predicted damage for a structure designed for minor damage (S=2). Reliability of the structure against other damage levels can be assessed. The probability of the damage exceeding 5, for example, is about 16%, and for S=8, corresponding to severe damage, about 3%.

Example 2 Level II assessment of damage due to overtopping

The amount of wave overtopping is a principal indicator of damage and failure of coastal structures. It is therefore important to be able to calculate the probability that a structure will fail to meet acceptable criteria for overtopping. These include the ultimate limit state (ULS) corresponding to damage which may lead to complete collapse and breach, and serviceability limit state (SLS) corresponding to failure to meet a service criteria such as danger to the public.

Level II methods are used to produce analytical approximations to the probability of failure. They are based on partial differentiation of the response function with respect to each of the probabilistic input variables.

The simulations shown below were carried out using a Level II probabilistic method, the Approximate Full Distribution Approach (AFDA). This is a relatively sophisticated technique that enables the use of input probability distributions which are non-normal, and uses iteration to converge on a more accurate solution than the mean value approach. Results in Table 3 show the impact of raising the crest of a structure on the annual probability of failure due to excessive wave overtopping. These results are illustrated in Figure 5, together with the annual probability of exceedance of a serviceability criteria.

Crest Level (mAD)	Annual probability of severe damage due to overtopping (ULS)
14.0	0.72
16.0	0.28
18.0	0.08
20.0	0.03

Table 2 Example of results of probabilistic analysis of a seawall to establish annual probability of severe damage at an ultimate limit state, ULS.

A key advantage of the full distribution method is its ability to cope with non-normal distributions. In this example, the significant wave height and still water level were both specified using Weibull distributions. Use of distributions fitted to all data rather than to annual maxima or other selected data enables two or more time-varying load variables to be combined simply. It is not necessary to consider the reduced probability of an extreme value of one variable occurring at the same time as the extreme value of another. In this case waves and water levels are independent although techniques are available to incorporate correlation into Level II methods.

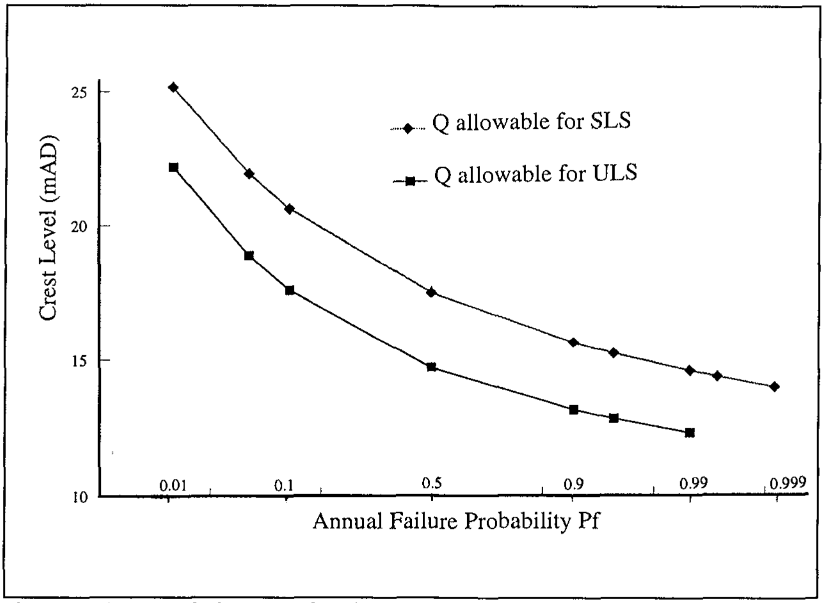

Figure 5 Probabilistic analysis of overtopping: annual failure probability for serviceability and ultimate limit states

Example 3 Probabilistic assessment of slope stability

This example illustrates the use of the Level II method in conjunction with a numerical model of slope stability. The advantage of this approach over the Level III method is that it is not necessary to carry out many repeat simulations to build up the resulting probability distribution. This can be particularly onerous when predictions are made using a computationally-intensive numerical model.

The method relies on carrying out a small number of model runs to enable numerical, rather than analytical differentiation of the response with respect to each probabilistic input variable. In this way a fundamentally deterministic model is used to produce probabilistic results by appropriate selection of input data and suitable analysis of the results.

The model in this case was SLOPE, part of the Oasys suite of geotechnical programs. This was used to analyse a circular slip surface on the landward face of an earth embankment (Figure 6). The model gives the factor of safety F, which is essentially the restoring moment divided by the disturbing moment. Thus a value of F less than 1 indicates failure of the slope.

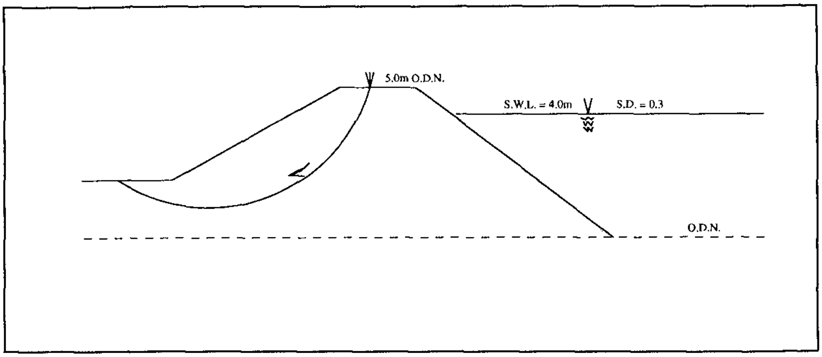

Figure 6 Circular slip failure mechanism for an earth embankment.

Input parameter	Distribution	Standard deviation (coefficient)	Mean
Cohesion c' (kNm^{-2})	Normal	29%	9.0
Angle of friction ϕ' (°)	Normal	16%	31
Dry density γ (kNm^{-3})	Normal	2.5%	16
Phreatic surface Ru	Normal	8%	0.50

Table 4 Data used for Level II slope stability prediction

Probabilistic data is given in Table 4. All data was assumed to be normally distributed. The factor of safety calculated from the mean values was 1.6, but given the prescribed variability in soil properties, the probability that the factor of safety is less than 1.0 is 0.03, or 3%.

5. CONCLUSIONS

The risk assessment procedures outlined here encompass a broad range of activities, including identification of hazards and key failure modes, classification of structures, assessment of hydraulic loading conditions, probability of failure due to the principal failure modes and modelling consequences in terms of flooded areas.

In view of the number of defences to be assessed, we have adopted a tiered approach for classification and analysis: the early stages are characterised by approximate screening procedures, with more detailed assessment on selected defences thought to be at highest risk.

The results of this project will substantially improve the methods available to analyse the risks of failure for existing flood defence schemes, and to design new schemes to agreed risk levels. The procedures will provide a consistent, rigorous framework for comparative assessment of a wide range of flood defences in tidal and coastal regions.

6. ACKNOWLEDGEMENTS

The research on which this paper is based has been supported by the UK National Rivers Authority (NRA) R&D Commission C - Flood Defence. Additional information has also been used from research at HR Wallingford supported by the Department of the Environment (DoE) under research contract PECD 7/6/248. The views expressed here are those of the authors and not necessarily those of the NRA or DoE.

REFERENCES

Allsop N.W.H. "Formulae for rubble mound breakwater failure modes" Final report of PIANC, PTC II, Working group 12, Sub-group A, PIANC, April 1993.

CIRIA (1977) "Rationalisation of safety and serviceability factors in structural design" Report 63.

CUR/TAW (1990) "Probabilistic design of flood defences" Centre for civil engineering research and codes / Technical advisory committee on water defences. Report 141.

Goda Y (1971) "Expected rate of irregular wave overtopping of seawalls" Coastal engineering in Japan, Vol 14.

Meadowcroft IC and Allsop NWH (1994) "Probabilistic assessment of coastal structures and breakwaters". HR Wallingford Report IT392.

Owen M.W. (1980) "Design of seawalls allowing for wave overtopping" Report EX 924, HR Wallingford, June 1980.

Owen MW and Steele AAJ (1991) "Effectivenss of recurved wave return walls" HR Report SR261

Thoft-Christensen P and Baker MJ (1982) "Structural reliability theory and its applications". Springer-Verlag.

Van der Meer JW (1988) "Rock slopes and gravel beaches under wave attack", PhD thesis Delft University of Technology, April 1988. (Available as Delft Hydraulics Communication 396)