Development of a probabilistic methodology for slope stability and seismic assessments of UK embankment dams

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SYNOPSIS. The introduction of the “An engineering guide to seismic risk to dams in the UK” in 1991 has led Inspecting Engineers to pay greater attention to the seismic risk of the dams they inspect. For owners of large stocks of dams, such as United Utilities (UU), this has resulted in the need to investigate a large proportion of their dams. In order to proceed in a structured way, UU commissioned a Panel of Experts to advise on a methodology to investigate and analyse their embankment dams and to establish the need for detailed investigation and/or remedial works.

Since the publication of the methodology, which was based on a pilot study of five dams, over 30 further embankment dams have been investigated using the approach. This has not only verified the appropriateness of the initial methodology but has also provided a database of geotechnical information. This information has allowed the methodology to be refined to incorporate probabilistic, in parallel with deterministic analyses. Deterministic analysis suffer from limitations such as the inability to consider variability in the input parameters. Also, there is no direct relationship between factor of safety and probability of failure. Probabilistic slope stability analysis allows for the consideration of variability in the input parameters and it quantifies the probability of failure of a slope. It can be performed using the Monte Carlo method, where a re-running of the analysis is performed using new input parameters estimated from the mean and standard deviation values of the chosen parameters. A distribution of factors of safety is then obtained which can be related to risk of failure. A methodology has been developed to incorporate the results of deterministic and probabilistic analyses, which aligns with current thinking regarding risk assessments.

Long-term benefits and performance of dams. Thomas Telford 2004.

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

INTRODUCTION

In order to ensure that a consistent and systematic approach was adopted to investigate the seismic stability of its large stock of embankment dams UU commissioned Bechtel to develop a methodology for seismic investigations in conjunction with a Steering Group of eminent dam engineers (Rigby et al, 2002). The methodology was required to comply with recommendations by Inspecting Engineers under the Reservoirs Act 1975 following the publication of "An engineering guide to the seismic risk to dams in the UK" (Charles et al, 1991) and its associated Application Note published by the ICE and DETR(1998). The methodology utilised conventional effective stress testing and classical soil mechanics theory for the development of slip surfaces. It was recognised that there are alternative approaches but it was considered that this approach would provide information suitable for long term use and for comparison with other studies. The original methodology was introduced in 2000 and has since been used as a basis for the analysis of over 30 of UU's embankment dams.

Since the introduction of the methodology the emphasis placed on risk management has increased (Hughes et al, 2000a and 2000b, Kreuzer 2000). This is leading the dam community to consider the methods used to evaluate embankment slope stability risk. For example Johnston in his Binnie Lecture (2002) commented:

"For the past half century the factor of safety calculated by a limit equilibrium analysis has been the accepted method of assessing stability. Now limit equilibrium's role as the sole or even the best method of analysis is being questioned. The factor of safety faces two challenges. Firstly, from finite element analysis which provides the ability to calculate how a dam will settle (or rise) and move upstream/downstream and how the stresses will change as a response to changing loads. The other challenge comes from advocates of probabilistic risk assessment who suggest that the factor of safety approach disguises the fact that even well built dams are a hazard. The probabilistic approach argues that, since failure cannot be completely ruled out, engineers should define and aim for a target probability of failure."

Bridle (2002a) further suggested that:

"Probability is part of the language of risk, much used and understood by managers and non-engineers. Giving them advice using risk language would therefore help them reach the right decisions about dams and dam safety. Use of this language would help us to consider how safe our dams are, which is important when it comes to the fundamental question of 'are they safe enough? It would also overcome the esotericism of our 'factor of safety' language, which means different things in different contexts."

This paper builds on the experiences of applying the UU methodology and explores the possibility of extending it into probabilistic analyses that align more closely to current thinking on risk management of dams.

DETERMINISTIC APPROACH

Deterministic slope stability analyses compute the factor of safety of a slope based on a fixed set of conditions and material parameters. If the factor of safety is greater than unity, the slope is considered to be stable, if the factor of safety is less than unity, the slope is considered to be unstable or susceptible to failure. Guidance on factors of safety for slope design of new embankment dams is given in "An engineering guide to the safety of embankment dams in the UK" (Johnston et. al, 1999). This approach is adopted in the current methodology with the factors of safety varying with the level of confidence in the data available as detailed in Table 1.

Table 1. Factors of safety used in the deterministic approach

Level of information available/Need for remedial action	Factor of Safety
Based on desk study information and decision charts for deep and shallow slips	at least 1.7
Based on assumed conservative parameters	at least 1.6
Based on the analysis of sufficient field and laboratory testing data	at least 1.5
Remedial works for deep slips	less than 1.3
Urgent attention required for deep slips	less than 1.2

Deterministic analyses suffer from limitations such as the failure to consider variability of the input parameters and inability to answer questions like "how stable is the slope?". Also, there is no direct relationship between the factor of safety and the probability of failure. In other words, a slope with a higher factor of safety may be no more stable than a slope with a lower factor of safety, depending on the nature and variability of the slope materials. For example, a slope with a factor of safety of 1.5, with a standard deviation of 0.5^{o} on the angle of shearing resistance used in the analysis, could have a much higher probability of failure than a slope with a factor of safety of 1.2 with a standard deviation of 0.1^{o} on angle of shearing resistance. The effect of variations in soil properties is illustrated in Figure 1.

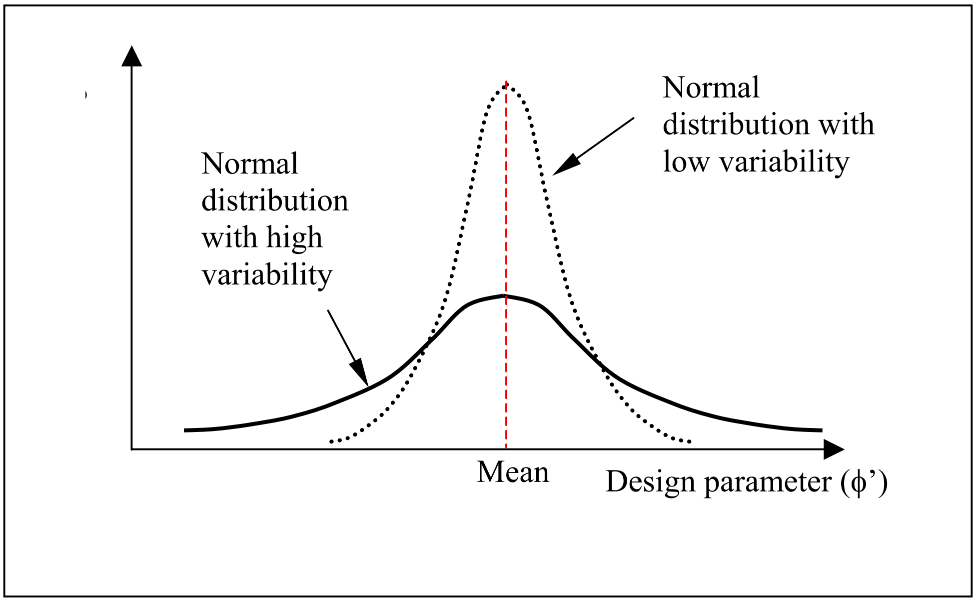
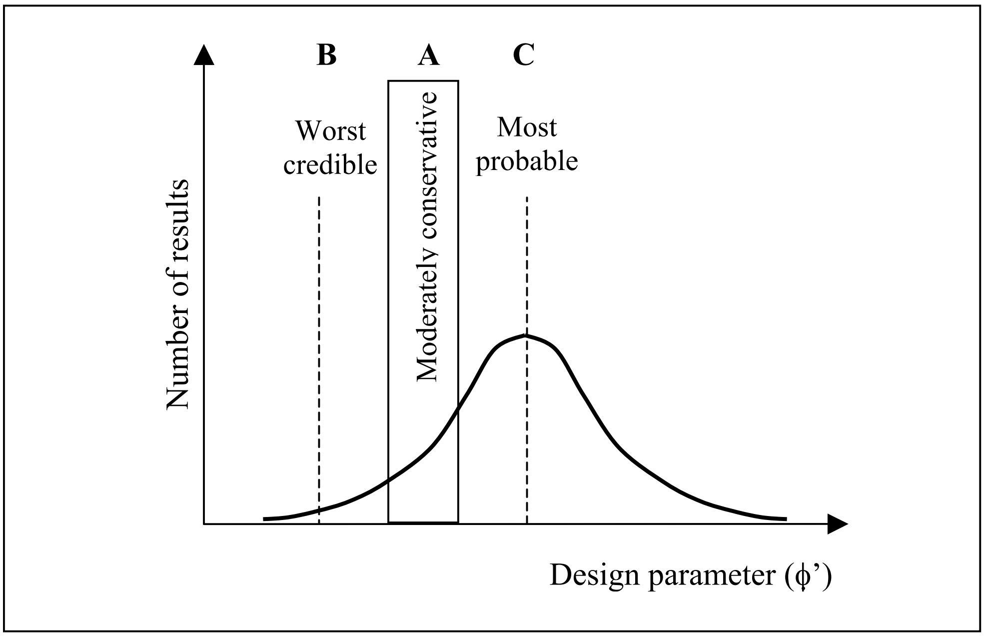


Figure 1. Variability in soil parameters

In the original methodology "worst" credible soil parameters are used in the analyses. The choice of parameters used needs to be considered in relation to the design methodology adopted. CIRIA Reports C580 and 104 (Gaba et al, 2003 and Padfield and Mair, 1984) dealing with retaining wall design define three levels of design parameters for different situations as indicated in Figure 2. As will be discussed later the probabilistic approach generally uses most probable parameters.

Recent investigations, undertaken on UU embankment dams, have allowed an assessment to be made of the effective stress shear strength parameters of a variety of embankment materials. A summary of the results for 10 dams is presented in Table 2. It should, however, be noted that whilst this is useful data, in statistical terms it still only represents a relatively small population. The selection of appropriate parameters is key to the use of both deterministic and probabilistic design methods.



A - The term Moderately Conservative is a conservative best estimate. Experienced engineers most often use this approach in practice.
B - The Worst Credible value is the worst that a designer could realistically believe might occur.
C - The Most Probable value is essentially the mean value excluding obviously anomalous values.

Figure 2. Definition of design parameters as defined CIRIA Reports C580 and 104

Table 2. Soil parameters from selected embankment dams

DAM	Material	Mean	Standard Deviation	No. of samples	Worst Credible Value
1	Core	30.8	5.2	10	22
	Shoulder (clay)	33.5	2.9	17	29
	Foundation	32.4	3.1	11	27
2	Core (clay)	30.0	0.8	6	29
	Shoulder (granular)	32.8	N/A	1	N/A
	Foundation	26.9	1.8	14	24
Cascade 1 (3 dams)	Core	32.3	4.5	9	25
	Shoulder (clay)	30.0	3.8	23	24
	Shoulder (gravelly clay)	40.2	2.8	4	36
	Foundation	27.9	2.4	17	24
6	Core	28.0	2.4	9	25
	Shoulder (clay)	28.4	2.4	79	25
	Foundation	27.8	1.8	59	25

DAM	Material	Mean	Standard Deviation	No. of samples	Worst Credible Value
7	Core	32.7	3.7	6	27
	Shoulder (clay)	35.0	3.9	9	29
	Shoulder (gravelly clay)	37.2	3.0	5	32
	Foundation	27.6	3.4	9	22
8	Core	31.5	3.3	6	26
	Shoulder (clay)	31.5	4.1	2	25
	Shoulder (gravelly clay)	42.0	4.3	11	35
	Foundation	34.2	4.4	3	27
9	Core	27.6	1.7	4	25
	Shoulder (gravelly clay)	37.5	2.6	10	33
	Foundation	31.2	4.5	7	24
10	Core	31.8	1.8	4	29
	Shoulder (gravelly clay)	40.8	1.8	3	38
	Foundation	37.2	2.0	2	34

PROBABILISTIC APPROACH

Probabilistic slope stability analysis allows for the consideration of variability in the input parameters and it quantifies the probability of failure of a slope. Probabilistic slope stability analysis can be performed using the Monte Carlo method. Basically, the method consists of re-running the analysis many times by inputting new parameters estimated from the mean and standard deviation values of the chosen parameters. A distribution of factors of safety is then obtained as indicated in Figure 3.

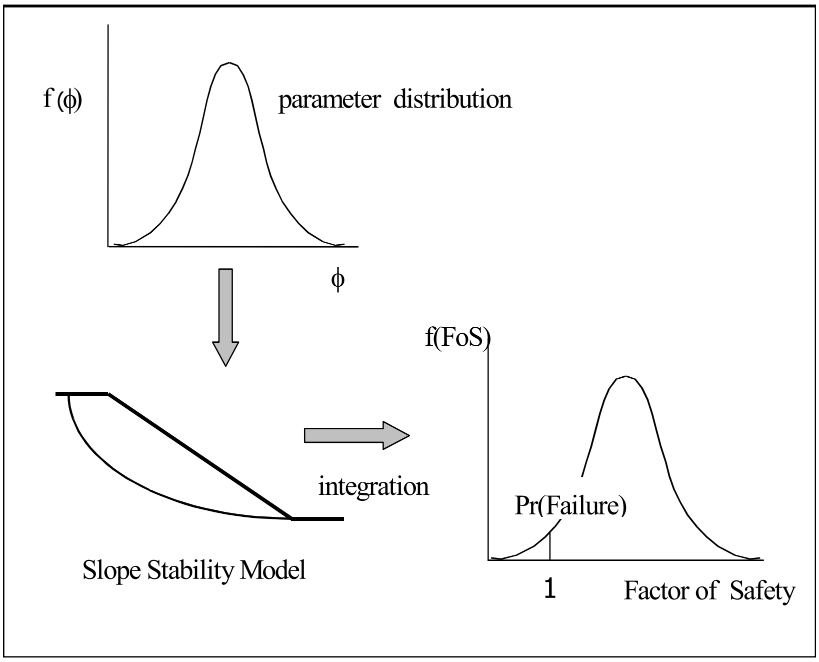


Figure 3. Summary of probabilistic approach

Probabilistic analysis can be performed on proprietary slope stability software such as GEOSLOPE, SLOPE/W. When employing such software the following considerations apply:

i. The use of a probabilistic analysis will not affect the deterministic solution. The software computes the factor of safety of all slip surfaces first and determines the critical slip surface with mean parameters as if no probabilistic analysis is chosen.

ii. A probabilistic analysis is performed on the critical slip surface only.

iii. When the analysis is completed, the factors of safety presented are the minimum, mean and maximum factor of safety of all Monte Carlo trials.

iv. In a probabilistic analysis, the input value of a parameter represents the mean value and the variability of the parameter is assumed to be normally distributed with a known standard deviation.

v. During each Monte Carlo trial, the input parameters are updated based on a normalised random number. The factors of safety are then computed based on these updated parameters. By assuming that the factors of safety are also normally distributed, the software determines the mean and the standard deviations of the factors of safety. A probability distribution function for the factor of safety can then be generated.

vi. The number of Monte Carlo trials required is dependent on the level of confidence and amount of variability in the input parameters. Theoretically, the greater the number of trials, the more accurate the solution. It is important that a sufficient number of trials be carried out. One way to check this is to re-run the analysis with the same number of trials; if the two solutions are different, the number of trials should be increased until the difference becomes insignificant (minimum number of trials is likely to be of the order of 5000).

vii. The probability of failure is the probability of obtaining a factor of safety less than 1.0 and is obtained from the probability distribution function (PDF).

Typical outputs are shown in Figure 4. Figure 4a) shows a situation of a low factor of safety and high probability of failure typical of a pseudostatic analysis of a downstream embankment slope where the analysis is used to estimate deformations using Ambraseys (1972), Ambrayseys and Menu (1988) and Swannell (1994). Figure 4c) shows the situation of a slope with an acceptable factor of safety and a very low probability of failure. Figure 4b) however gives a borderline factor of safety. The question that needs to be addressed is whether a probability of failure of 1 in 2000 is acceptable in relation to the consequence of failure.

ACCEPTABILITY CRITERIA

A number of acceptability criteria based on probability of failure have been found in the literature (based on mean parameters) as detailed in tables 3 to 7.

Table 3. Acceptability Criteria - Smith (1986)

Conditions	Criteria for Probability of Failure	Equivalent Event
Earthworks	10^{-2}	1 in 100
Earth retaining structures	10^{-3}	1 in 1,000
Onshore foundations	10^{-3}	1 in 1,000
Offshore foundations	10^{-4}	1 in 10,000

Table 4. Acceptability Criteria - Santa Marina et al. (1992)

Conditions	Criteria for Probability of Failure	Equivalent Event
Temporary structures with low repair cost	10^{-1}	1 in 10
Existing large cut on interstate highway	10^{-2}	1 in 100
Acceptable in most cases except if lives may be lost	10^{-3}	1 in 1,000
Acceptable for all slopes	10^{-4}	1 in 10,000
Unnecessarily low	10^{-5}	1 in 100,000

Table 5. Acceptability Criteria - Rettemeiere et al.(2000)

Conditions	Criteria for Probability of Failure	Equivalent Event
Likely	10^{-1}	1 in 10
Possible	10^{-2}	1 in 100
Not Impossible	10^{-3}	1 in 1,000
Unlikely	10^{-4}	1 in 10,000
With a degree of probability verging on certainly unlikely	10^{-5}	1 in 100,000
Totally Unlikely	10^{-6}	1 in 1,000,000

Bridle (2000b) related Probability of Failure to the ALARP principle ("as low as reasonably practical") where risks are considered acceptable only if all reasonable practical measures have been taken to reduce risk.

Table 6. ALARP Criteria - Bridle (2000b)

Conditions	Criteria for Probability of Failure	Equivalent Event
Unacceptable	10^{-3}	1 in 1000
ALARP	10^{-3} - 10^{-6}	1 in 1000 to 1 in 1,000,000
Negligible	10^{-6}	1 in 1,000,000

Table 7. ALARP Criteria - HSE framework tolerability of risk, (2001)

Conditions	Criteria for Probability of Failure	Equivalent Event
Intolerable	10^{-4}	1 in 10000
Tolerable (ALARP)	10^{-4} - 10^{-6}	1 in 10,000 to 1 in 1,000,000
Broadly acceptable	10^{-6}	1 in 1,000,000

The published data indicates a considerable range of values where a balance is needed between both the probability of failure and consequence of failure using for assessment techniques, such as Failure Modes, Effects and Criticality Analysis (FMECA) or Location Cause and Indication methods (LCI) as outlined in the CIRIA report on "Risk management for UK Reservoirs" (Hughes et al, 2000a).

There is some consensus that a probability of failure of 10^{-4} (1 in 10,000) is considered a generally acceptable criterion for slopes where there is a potential for loss of life. Alonso (1976) equates this to the commonly accepted deterministic factor of safety of 1.5 for new build embankment dams. However Christian et al (1994) report probabilities approaching 1 in 1000 for a factor of safety of 1.5.

For a general and conservative approach, which could be considered in parallel with consequence of failure considerations, it is proposed that more stringent criteria be used in preliminary analyses as detailed in Table 8.

Table 8. Suggested acceptable values of Probability of Slope Failure

	Suggested Acceptable Probability of Failure
From desk study information	Less than 2×10^{-6} (1 in 500,000)
Measured dam specific parameters	Less than 1×10^{-5} (1 in 100,000)
Remedial works required	Greater than 1×10^{-4} (1 in 10,000)
Urgent attention required	Greater than 2×10^{-4} (1 in 5000)

These are currently suggested values only and are being evaluated along side the conventional deterministic factors of safety already in use in the existing methodology. It must also be borne in mind that shear strength is not the only parameter that should be considered when using probabilistic methods. Variations in groundwater conditions, inundation of downstream slope due to heavy rainfall, poor drainage or overtopping and the effects of climate change will all need to be taken into account.

PROPOSED METHODOLOGY FOR PROBABILISTIC SLOPE STABILITY ANALYSES

In order to evaluate the possible advantages of the use of probabilistic methods of slope stability analyses of embankment dams, a hybrid deterministic/probabilistic approach is being evaluated for the embankment dams currently under investigation as detailed below.

Choice of parameters

For each parameter (ϕ' and others as required) determine the mean and standard deviation from available testing information.

Probabilistic analysis (mean and standard deviation parameters)

Carry out slope stability analysis including the probabilistic approach to determine the Factor of Safety based on mean parameters.

Deterministic analysis (worst credible parameters)
For each parameter determine the worst credible value. As a guide the worst credible value is sometimes defined as:

mean – (1.64 x standard deviation).

This means that 5% of values are potentially lower than the selected worst credible value. This is similar to the approach used in structural design, in particular for concrete structures e.g. characteristic strength, and also discussed in Eurocode 7 (Driscoll and Simpson, 2001, Cardoso and Fernnandes, 2001, Hicks and Samy, 2002, Samy and Hicks 2002). It should be noted that the choice of 5% is arbitrary and should reflect the risk the designer is prepared to accept on the statistical parameters value, and a degree of engineering judgement is therefore required. Perform deterministic analysis for worst credible parameters and report factor of safety based on worse credible values.

Check slip surface between probabilistic and deterministic analyses
The slip surface geometry obtained from worst credible parameters could potentially be different to that obtained with the mean parameters. If so, re-run the probabilistic analysis with mean parameters on that particular slip.

Report Probabilities of failure and Factors of Safety
Compare and report results obtained.

- Probability of failure from Monte Carlo analysis
- Factor of safety based on worse credible values based on deterministic analysis

A flowchart summarising the proposed methodology is given in Figure 5.

CONCLUSION

The adoption by UU of a rigorous methodology for the seismic investigation of their embankment dams has afforded the opportunity to accumulate and collate a significant common data set for some of its stock of older embankment dams. This has allowed for a detailed comparison of the properties and performance of its assets to enable it to begin to align the findings of conventional deterministic slope stability analyses with probabilistic risk assessment methods. Such an approach allows dam owners to evaluate how safe their dams are in terms of probability of failure. If this is considered in conjunction with the consequence of failure, it will also allow a more rigorous review of the trade off between cost and risk which should improve dam safety management using techniques such as Portfolio Risk Assessments, as described by Hughes and Gardiner (2004).

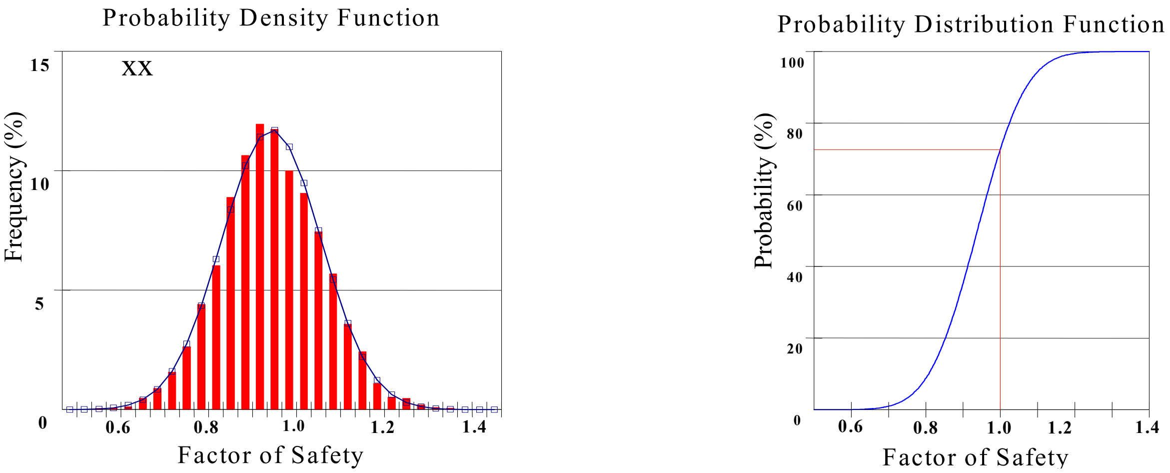


Figure 4a). Probability density/distribution function
Factor of Safety of 0.9, Probability of Failure Less than 1 in 1.4 (70%)

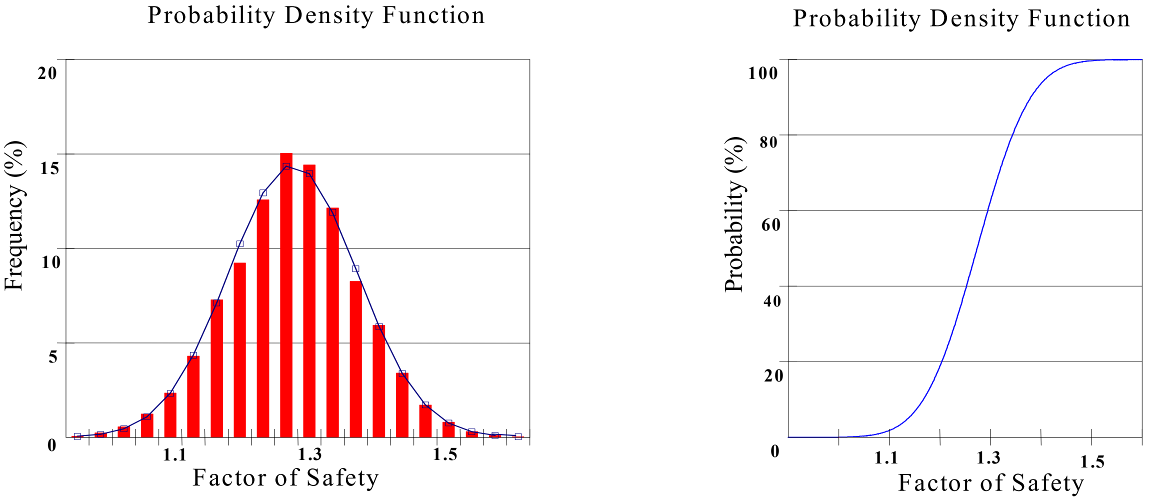


Figure 4b) Probability density/distribution function
Factor of Safety 1.3, Probability of Failure Less than 1 in 2000

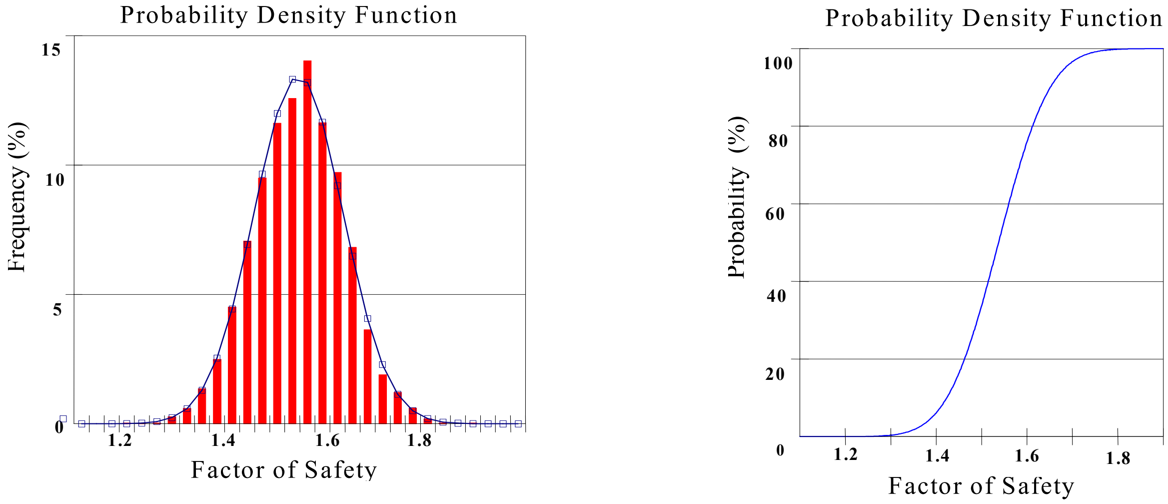
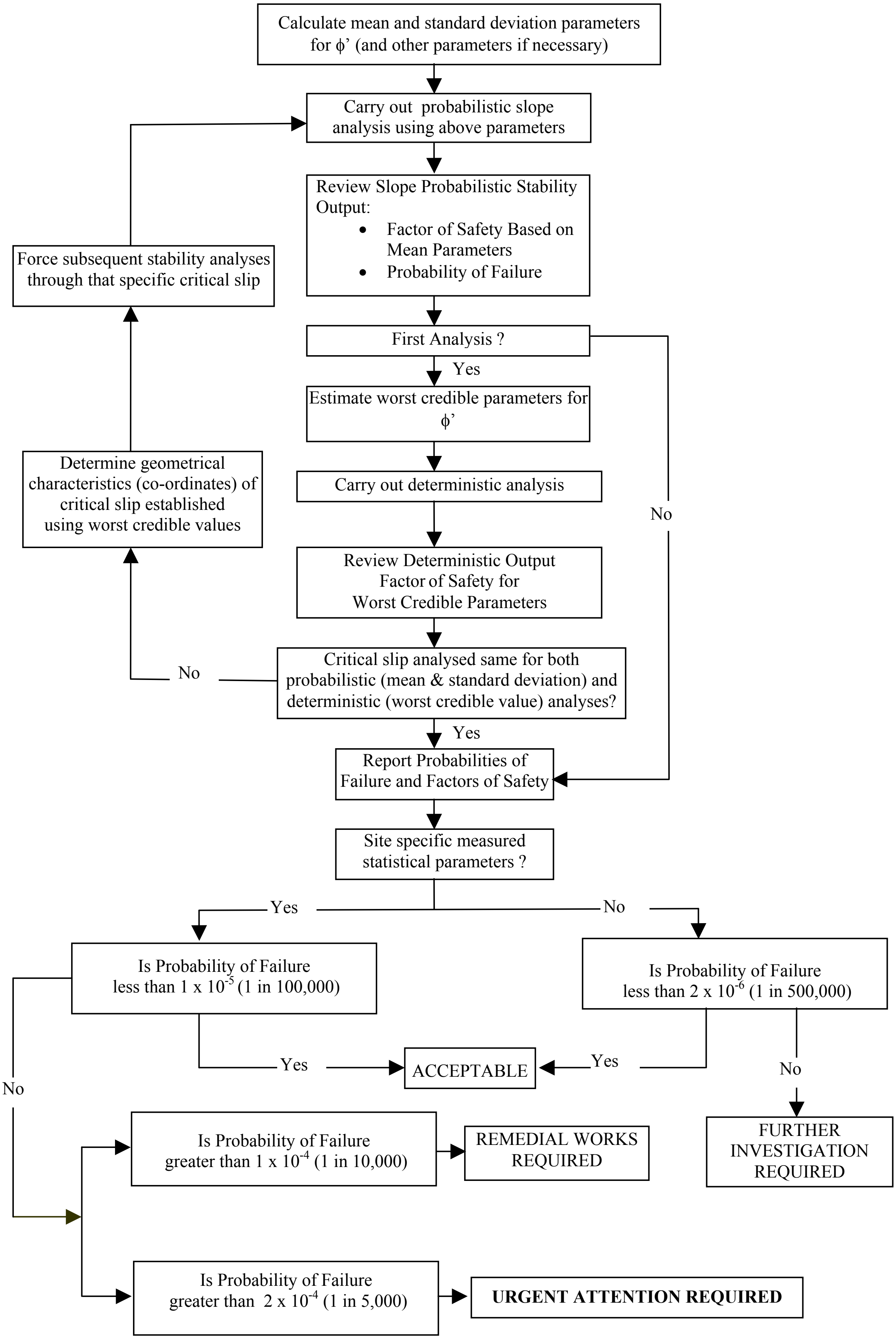


Figure 4c) Probability density/distribution function
Factor of Safety 1.5, Probability of Failure Less than 1 in 10,000,000

Figure 4 Typical Probability density/distribution functions


Calculate mean and standard deviation parameters for ϕ' (and other parameters if necessary)
Carry out probabilistic slope analysis using above parameters
Review Slope Probabilistic Stability Output:
• Factor of Safety Based on Mean Parameters
• Probability of Failure
Force subsequent stability analyses through that specific critical slip
First Analysis ?
Yes
Estimate worst credible parameters for ϕ'
Determine geometrical characteristics (co-ordinates) of critical slip established using worst credible values
Carry out deterministic analysis
No
Review Deterministic Output Factor of Safety for Worst Credible Parameters
No
Critical slip analysed same for both probabilistic (mean & standard deviation) and deterministic (worst credible value) analyses?
Yes
Report Probabilities of Failure and Factors of Safety
Site specific measured statistical parameters ?
Yes
No
Is Probability of Failure less than 1 x 10-5 (1 in 100,000)
Is Probability of Failure less than 2 x 10-6 (1 in 500,000)
Yes
ACCEPTABLE
Yes
No
No
FURTHER INVESTIGATION REQUIRED
Is Probability of Failure greater than 1 x 10-4 (1 in 10,000)
REMEDIAL WORKS REQUIRED
Is Probability of Failure greater than 2 x 10-4 (1 in 5,000)
URGENT ATTENTION REQUIRED

REFERENCES

Alonso, E.E. (1976). Risk analysis of slopes and it's application to slopes in Canadian sensitive clays. Geotechnique Vol. 26, 453-472.

Ambraseys, N.N. (1972). Behaviour of foundation materials during strong earthquakes. Proceedings 4th European Symposium on Earthquake Engineering, London, Vol 7, 11-12. Sofia, Bulgarian Academy of Sciences

Ambrayseys, N.N. (1998). Earthquake induced ground displacements. Earthquake Engineering and Structural Dynamics (Special Issue) Vol. 16, 985-1006.

Bridle, R.C. (2000a) Dams 2000, British Dam Society, 10th Biannual Conference, Bath, Discussion, 104.

Bridle, R.C. (2000a) Dams 2000, British Dam Society, 10th Biannual Conference, Bath, Discussion Conference Closing Remarks, 155.

Cardoso, D.A.M. and Fernandes M.M. (2001) Characteristic values of ground parameters and probability of failure in design according to Eurocode 7. Geotechnique 51(6) 519-531.

Charles, J.A, Abbiss, C.P, Gosschalk, E.M and Hinks, J.L. (1991). An engineering guide to seismic risk to dams in the United Kingdom. Building Research Establishment Report Publ. BRE, Watford.

Christian, J. T, Ladd C. C. and Baecher G. B. (1994) Reliability applied to slope stability analysis. Journal of Geotechnical Engineering, ASCE. 120(12) 2180-2207.

Driscoll, R. and Simpson, B. (2001) Eurocode 7: Geotechnical Design. Proc. ICE, Civil Engineering, Vol. 144 Special Issue 2. 49-54.

Gaba, A.R, Simpson, B, Powrie, W, Beadman, D.R. (2003). Design of retaining walls embedded in stiff clay. Construction Industry Research Information Association (CIRIA) Report No. C580.

Health and Safety Executive, (2001) Reducing Risks, Protecting People.

Hicks, M. A. and Samy, K. (2002) Reliability based characteristic values : A stochastic approach to Eurocode 7. Ground Engineering 39, No 12, 30-34.

Hughes, A.K, Hewlett, H. W. M, Morris, M, Sayers P, Harding A, and Tedd, P. (2000a) Risk Management for UK Reservoirs. CIRIA, Report C542, 213pp.

Hughes, A.K, (2000b) UK Developments in risk management for reservoirs. Transactions of the 20th International Congress on large Dams, Beijing, Vol. 1, 67-70. Invited contribution to Q 76:

Hughes, A.K. and Gardiner K. (2004) Portfolio Risk Assessments in the UK; A perspective. Dams 2004, Thomas Telford, London.

ICE/DETR (1998). An Application Note to An Engineering Guide to Seismic Risk to Dams in the United Kingdom. The Institution of Civil Engineers. Thomas Telford Ltd, London.

Kreuzer, H. (2000) The use of risk analysis to support dam safety decisions and management. General Report. Transactions of the 20th International Congress on large Dams, Beijing, Vol 1. Q76 –R41, 769-896.

Johnston, T. A. (2000) Binnie Lecture "Taken for Granted", Dams 2000 British Dam Society, 10th Biannual Conference, Bath, Discussion, 143.

Johnston, T.A, Millmore J.P, Charles, J.A. and Tedd, P. (1999) An engineering guide to the safety of embankment dams. BRE Report 363, Watford.

Padfield, C.J. and Mair, R.J. (1984). Design of retaining walls embedded in stiff clay. Construction Industry Research Information Association (CIRIA), Report No. 104.

Peterson, J.L. (1999). Probability analysis of slopes. MSc Thesis University of West Virginia.

Rettemeie, K., Falkenhagen, B. and Kongeter, J. (2000) Risk Assessment – New Trends in Germany. Transactions of the 20th International Congress on large Dams, Beijing, 625 - 641

Rigby, P.J, Walthall, S and Gardiner, K. D. (2002) A methodology for seismic investigation and analysis of dams in the UK. Reservoirs in a changing world, Thomas Telford, London, 126-140.

Samy, K. and Hick, M. A. (2000) A numerical solution to characteristic values for geotechnical design. Proc. 10th UK Conference of the Association for Computational Mechanics in Engineering. Swansea, 137-140.

Santa Marina, J. Altschaeffi, A. and Chameau, J.(1992). Reliability of slopes incorporating quantitative information. Transport Research Record 1343, 1-5.

Smith, G.N. (1986). A suggested method of reliability analysis for earth retaining structures. TRRL Report No. 46.

Swannell, N.G. (1994) Simplified Seismic safety evaluation of embankment dams. Dams and reservoirs Oct. 4(3), 17-19.