Comparison of methods used to determine the probability of failure due to internal erosion in embankment dams.

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SYNOPSIS. Quantitative risk assessment is a routine part of periodic safety reviews in Australia and the United States. Many dam owners have been using these techniques to produce Portfolio Risk Assessments of their dams for a number of years. The recent publication of the DEFRA Interim Guide to Quantitative Risk Assessments has increased awareness of such techniques in the UK. This paper describes the application of two methods used for quantitative risk assessments of internal erosion used in Australia and the United States to six pilot dams and compares the results with the DEFRA method of assessing the probability of failure due to internal erosion..

BACKGROUND

Interest in risk assessment of UK reservoirs followed the Report on the Water Industry by the House of Lords Select Committee on Science and Technology in December 1982 which recommended that "*research should be carried out into risk associated with reservoirs and the methodology for quantitative risk assessment, and as a result of that in the light of this research a wider spectrum of safety criteria should be introduced to take into account of the different degrees of risk in individual reservoirs.*" This resulted in a number of feasibility studies being undertaken by a variety of organisations (Clifton et al. 1985a & 1985b, Clark and Tyler, 1987, Water Research Centre 1987, and Cullen, 1990). The last in this series of reports (Cullen 1990) concluded that "*in the light of present knowledge probabilistic risk assessment is not yet a suitable tool for inspection work*".

In 2002 a DEFRA Research Contract was undertaken and published (DEFRA, 2002) aiming to "*Propose and demonstrate an Integrated System which provides a framework for decision making by Panel Engineers on the annual probabilities of occurrence, consequences and tolerability of all the various threats to safety*". This publication followed on from a draft report

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by DEFRA and Babtie giving Guidance on the Stability Upgrades to Embankment Dams (Anon, 2002). DEFRA have recently published an Interim Guide to Quantitative Risk Assessment to UK Reservoirs (Brown and Gosden, 2004, 2005). In a letter to Panel Engineers in July 2004 DEFRA state that *"The Interim Guide is a tool for the management of reservoir safety enabling a screening level assessment to be made to inform decision-making by dam professionals on the annual probability of occurrence of reservoir failure, the consequences and the tolerability of that risk."* and that *"The Guide is intended to assist both Panel Engineers, particularly those who design and inspect reservoirs, and reservoir owners. It is anticipated that risk assessments undertaken using the Guide would be carried out where concern over the safety of a reservoir has arisen, to inform inspections of high hazard reservoirs, and in connection with portfolio risk assessment to rank risks and prioritise expenditure on safety improvement works."*

A major UK dam owner has developed a Portfolio Risk Assessment (PRA), using Quantitative Risk Assessment (QRA) techniques to rank dams within the Portfolio. The QRA techniques for internal erosion were based on those developed at the University of Stanford (McCann et al., 1985) and the University of New South Wales (Foster et al., 1998, 2000a). The output is considered more as a ranking tool rather than reliable absolute values for each embankment.

Following the introduction of DEFRA Interim Guide the dam owner commissioned a study to compare the methods used in their PRA (based on those of the University of Stanford and the University of New South Wales) and those used in the DEFRA Interim Guide as part of the development of a methodology to investigate internal erosion in its stock of embankment dams. This was based on desk study assessments of six embankment dams selected as being relatively high on the PRA probability list and with a variety of perceived problems. The methodology was reviewed by a panel of independent experienced dam engineers. This paper summarizes the results of the comparisons of the different methods of assessment undertaken on the six pilot desk studies to give a better understanding of why the different methods at times gave differing results and to see if more weight can be given to any particular method.

The methods of the University of Stanford (UoS) and DEFRA Interim Guide are based upon historical data of dam safety events related to internal erosion, from which estimates of probabilities of failure have been derived for different dam conditions. The University of Stanford method (McCann, et al. 1985) uses a Bayesian probabilistic model to evaluate the probability of failure (PoF) for four modes of failure: piping, slope stability, piping associated with outlet works and foundation and miscellaneous failures. The model draws on US dam data and practices to estimate the frequency of failure for a number of dam conditions. The DEFRA Interim Guide uses data from the BRE/KBR National Dam Database (NDD), which classifies historical problems and incidents. Both methods require an engineering assessment of the current dam condition to be performed and scored on a scale of 1 (best condition embankment) to 10 (distressed embankment). Based on the current condition score, a probability of failure is 'read off' from the base data.

In the case of the DEFRA Interim Guide method, the 'base data' is the BRE/KBR National Dam Database, with typical probabilities of failure being adjusted to take account of the individual characteristics of the embankment under assessment.

The University of New South Wales (UNSW) method (Foster et al. 2000a and 2000b)uses data from reported dam incidents throughout the world (ICOLD, 1995) to make assessments of the likelihood of failure of embankment dams by three methods; piping through the embankment, piping through the foundation and piping from the embankment into the foundation. These historically determined probabilities of failure are then adjusted using weighting factors to take account of the characteristics of the dam under assessment, considering attributes such as core properties, compaction, conduits and foundation geology and also the performance of the dam in terms of seepage observations and pore water pressures. The frequency of monitoring and surveillance is also incorporated into the assessments. Each of these attributes is assessed as above or below a median probability of failure, representing a more likely and less likely condition to initiate failure. Appropriate weightings applied to give an overall probability of failure.

COMPARISON OF METHODS USED TO CALCULATE PROBABILITY OF FAILURE DUE TO INTERNAL EROSION.

General Comparison

The DEFRA Research Contract (2002b) produced a comparison of the various methods of calculating probability of failure by equating the maximum and minimum weighting in the University of New South Wales Method (UNSW) to the best and worst condition scores used in the University of Stanford (UOS) and DEFRA methods used at the time of publication (i.e. before the publication of the DEFRA Interim Guide). The comparison has been updated to include the new Guide as shown in Figure 1.

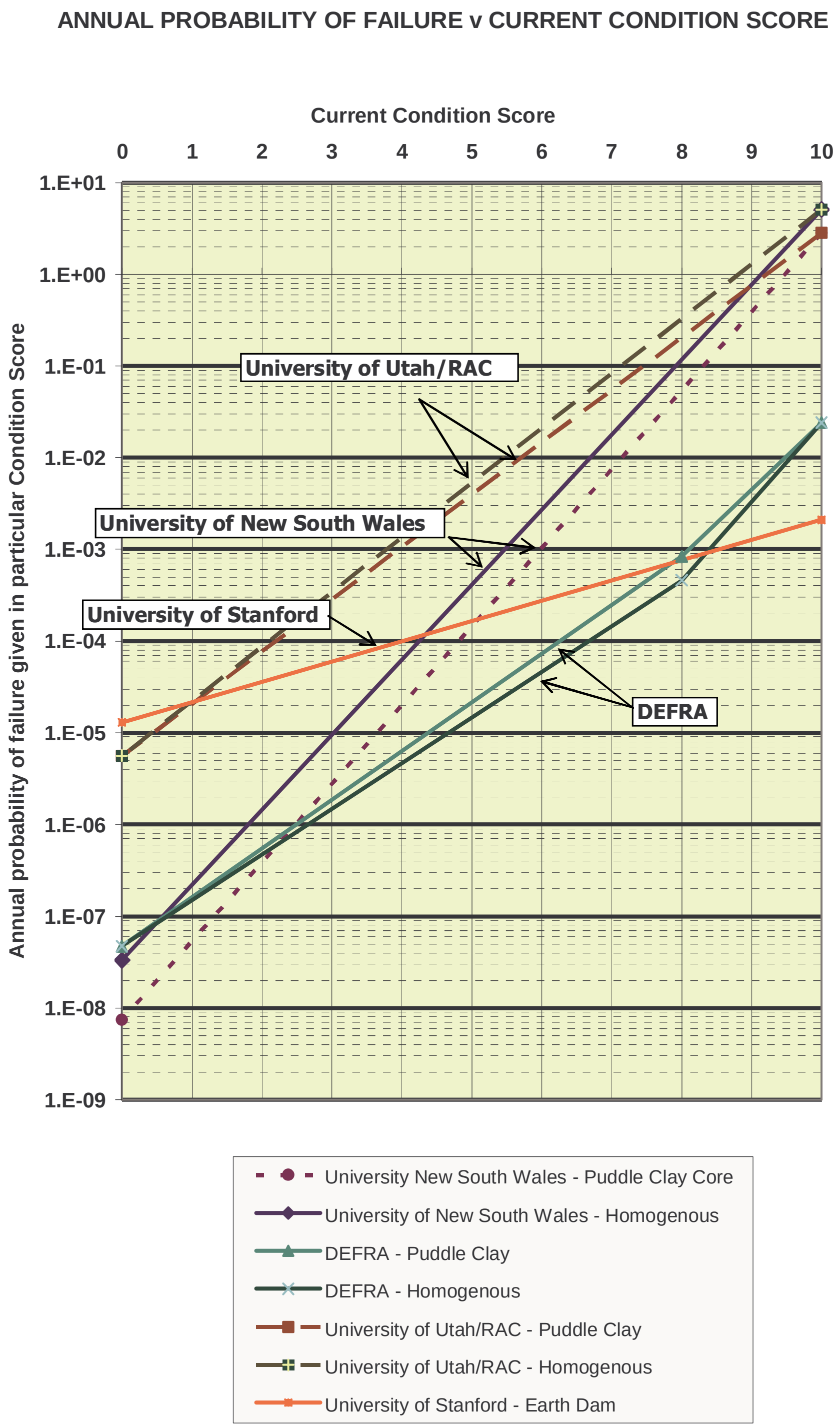

Figure 1 - Comparison of methods of evaluating Probability of Failure and Dam Condition Scores

A number of observations can be made from the above plot including:

- The wide variations in estimated PoFs for both good and poor condition dams by the various methods
- The UoS method shows the least degree of variation in PoF for differing Dam Condition Scores
- The UNSW Worst Case Probability of Failure is greater than one
- The UNSW method gives the lowest probability of failure for best condition dams
- The PoFs for best condition dams for the UoS and DEFRA methods are similar
- The fact that even for Condition Score 10 dams the PoF is still only 1 in 50 reflects the relatively high number of emergency draw downs due to internal erosion which have been reported since 1975, whilst there have been no corresponding reported failures due to internal erosion in the same period. It also assumes that similar surveillance and intervention would continue in future
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The value of PoF determined by any of the methods is dependant on a consistent evaluation of a Dam Condition Score. Experience in using the methods has shown that, for certain dams, the assessment of condition scores by the different methods gives widely differing values, but the calculated probabilities are similar. Conversely similar condition scores assessed by the different methods can give wide variations in calculated PoFs.

The application of all the methods and interpretation of the resulting PoFs requires considerable engineering judgement.

It is also of note that the incidence of failure of puddle clay core dams in the UK is greater than that for homogenous dams. The reverse is the case for the data from world dams used in the UNSW Method.

<u>Comparison based on application to Pilot Desk Studies</u>

The results of assessment of Probability of Failure and Dam Condition are presented in Table 1 and plotted in Figure 2.

The dams selected for study consisted of three traditional “Pennine” dams with puddle clay cores and three controlled seepage or “Canal” dams.

Looking at the estimated overall Probabilities of Failure it can be seen that there is a wide spread of results. The largest difference noted is for Dam 2 where the highest PoF assessed by the UNSW method was 34 times greater than that calculated by the DEFRA method. The differences ranged from between 1.5 and 34 with a mean variation of 9 i.e. nearly an order of magnitude different. In at least one case (DEFRA PoF $9x10^{-5}$ for Dam 1) the method gave a result contradicting the judgement of the Review Panel (and others) following review of the data and a site visit, the UOS and UNSW methods do however indicate a problem.

As would be expected Dam Condition Scores upon which the estimated PoFs are based, show a similar variation with none of the three methods giving consistently high or low values. This illustrates the very approximate nature of the derived values and the need to treat them in conjunction with engineering judgement rather than applying them as absolute values.

Table 1 - Assessed Probabilities of Failure and Dam Condition Scores for Pilot Dams

OVERALL SUMMARY OF PROBABILITY OF FAILURE								
	Dam 1	Dam 2	Dam 3 (with filters)	Dam 3 (without filters)	Dam 4	Dam 5	Dam 6 (Before Grouting)	Dam 6 (After Groting)
UOS								
Piping	9.5E-05	9.5E-05	2.5E-05	3.8E-05	1.0E-05	1.2E-05	6.9E-04	1.1E-05
Slope Stability	9.2E-06	5.9E-06	5.9E-06	5.9E-06	2.8E-05	2.1E-05	1.1E-06	1.1E-06
Piping/Outlet Works	6.6E-06	1.1E-05	8.0E-07	8.0E-07	7.9E-07	1.6E-06	1.2E-04	2.7E-05
Foundations and Misc	1.1E-05	3.6E-05	5.1E-05	5.1E-05	1.1E-05	1.1E-05	1.0E-05	1.0E-05
Total	1.2E-04	1.5E-04	8.3E-05	9.6E-05	2.6E-05	4.6E-05	8.2E-04	4.9E-05
UNSW								
Embankment Piping	7.4E-04	4.5E-03	5.8E-07	3.0E-04	8.3E-05	3.3E-04	3.6E-03	4.3E-04
Foundation Piping	6.2E-05	4.7E-05	2.1E-05	2.1E-05	2.0E-06	6.1E-06	1.4E-04	2.8E-05
Embankment to foundation	2.1E-04	3.1E-05	0.0E+00	1.0E-07	6.0E-07	3.1E-05	9.1E-05	1.8E-05
Total	8.1E-04	4.5E-03	2.1E-05	3.2E-04	8.6E-05	3.7E-04	3.8E-03	4.7E-04
DEFRA								
Embankment	8.90E-05	9.00E-05	8.6E-05	8.6E-05	1.7E-05	1.7E-05	1.0E-04	1.00E-04
Surface Structures	2.60E-06	-	1.0E-07	1.0E-07	1.0E-06	1.0E-07	4.2E-06	1.10E-04
Buried Structures	-	4.20E-05	9.4E-06	9.4E-06	6.3E-07	1.7E-05	1.0E-02	1.20E-05
Total	9.16E-05	1.32E-04	9.55E-05	9.55E-05	1.86E-05	3.41E-05	1.01E-02	2.22E-04
Max	8.1E-04	4.5E-03	9.6E-05	3.2E-04	8.6E-05	3.7E-04	1.0E-02	4.7E-04
Min	9.2E-05	1.3E-04	2.1E-05	9.6E-05	1.9E-05	3.4E-05	8.2E-04	4.9E-05
Max/Min	8.8	34.3	4.5	3.3	4.6	10.9	12.3	9.6

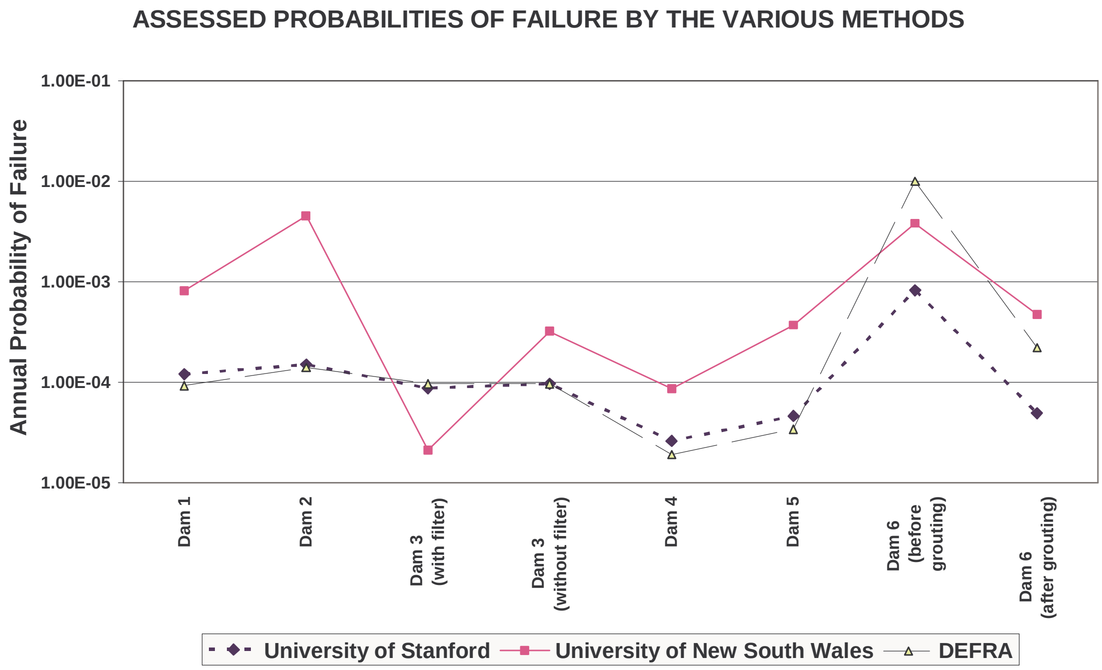

Figure 2 – Plot of Assessed Probabilities of Failure and Dam Condition Scores for Pilot Dams

Comparing the results where known influences occur the following can be highlighted:

Seepage carrying fines

Where seepage carrying fines is noted (as for Dam 6, before grouting) this is allocated a relatively high weighting in all methods and whilst the range of PoFs vary by an order of magnitude they are all generally in the $>10^{-4}$ within the HSE intolerable range. (N. B. General guidance issued by the Health and Safety Executive (2001, 2004) for industries imposing hazards on the public, suggests that annual probabilities of failure of less than 10^{-6} (1 in 1,000,000), are broadly acceptable. Probabilities between 10^{-6} and 10^{-4} (1 in 10,000), requires action to reduce risk to as low as reasonably practicable (ALARP) and probabilities above 10^{-4} are intolerable and require remedial action at any cost).

Conduits through embankment

In the cases where conduits pass through the embankment Dams 2, 5 and 6) an appropriately high weighting is picked up by the UNSW method

($W_{E(con)}$), in the buried structured part of the DEFRA appurtenant works assessment and in the Piping/outlet section of the UoS method. Whilst the PoF difference between the three methods for the case of Dam 2 vary by the highest order (34 times difference) the results all fall within the HSE Intolerable range indicating a potential problem. Similar PoFs are recorded for the influence of a conduit for Dams 5 and 6 by the DEFRA and UNSW methods. However the wide range of condition scores (4-7) and associated probabilities covered under a single description by the UoS method for pipes considered in "neutral" condition makes there assessment very much open to the interpretation of individual assessors.

Filters

The addition of stabilising berms, which may have been designed as filters, at the Dam 3 embankment allowed an evaluation of the effect of including a weighted filter. The effects of filters slightly reduces the PoFs estimated by the UoS method and by an order of magnitude with UNSW method. Surprisingly there is no apparent beneficial effect with the DEFRA method and only a very small benefit with the UOS method. Consideration of the method of evaluation (DEFRA Sheets 4.3 and 4.4) indicate that whilst the effect of filters is taken into effect in establishing the Intrinsic Dam Condition this is only used in the adjustment of the Best Condition Dam Anchor Point. This has little effect on dams with discernible defects. In the assessment of the Current Dam Condition Score used in the assessment of the PoF the effect of filters is related to seepage and only has a major effect when there is a "large amount of uncontrolled seepage discharging i.e. not discharging into a filtered drainage system". This is related to the calculation of a Seepage Index (Charles, 1993). This is clearly an area requiring further consideration in relation to determining the beneficial effects of remedial works using the ALARP methods recommended in the Guide.

Effectiveness of Remedial Works (Grouting)

Dam 6 had previously identified defects that were remediated by grouting. This allowed for the evaluation of PoF before and after the remedial works. Results before the remedial works were implemented by all methods indicated PoFs within the HSE Intolerable range. The DEFRA method gave a value of 1×10^{-2} indicating Condition Score 10 equating to a "Serious incident involving emergency action or drawdown" in accordance with the NDD Classification (see Table 2). Results estimated after grouting for the DEFRA and UNNSW remain in the intolerable range indicating that there are still potential problems within the embankment that still need to be addressed.

ADVANTAGES AND DISADVANTAGES OF THE METHODS

The advantages and disadvantages of the methods investigated to determine the PoFs against internal erosion may be summarised as follows:

University of Stanford	
Advantages	Disadvantages
• easy to use • largely based on visual evidence • can provide quick assessment for ranking a number of dams • covers a number of potential failure mechanisms • covers embankment and concrete dams	• evaluation scale difficult to interpret and sensitive to choice of Dam Condition Score • some descriptions for condition scores are not appropriate for large dams • does not distinguish between types of earth embankments • based on US data and practice

University of New South Wales	
Advantages	Disadvantages
• easy to use and apply • large range of factors considered • based on world dam incident data	• wide coverage makes interpretation to UK conditions difficult for some factors • does not give a Dam Condition Score

DEFRA Interim Guide	
Advantages	Disadvantages
• based on UK National Dam Database data • rigorous means of determining Dam Condition Score	• anchors to Category 3 NDD incidents only (incidents leading to work). It does not anchor to incidents leading to the involvement of an Inspecting Engineer • some double accounting of contributory scores (e.g. inspections) • zero anchor point adjustment does not have a noticeable effect on poor condition dams (e.g. absence or presence of filters, conduits) • sensitive to scoring of Dam Condition

CONCLUSION

The methods used to provide estimates of probability of failure due to internal erosion are useful values for initial screening purposes. It must be stressed that the calculated probabilities should not be taken as absolute values but to be used in conjunction with engineering judgement, particularly on issues not directly taken into account in the assessment (e.g. downstream consequences). Currently all three methods are used by the authors to make Probability of Failure assessments, the findings of which will assist in refining the current DEFRA Interim Guide as it develops into a national standard. Before being used in ranking and (potentially) decisions on remedial works, the authors recommend that the process be reviewed by an All Reservoirs Panel Engineer (under the Reservoirs Act 1975) working with the team undertaking the data gathering and inputting to the process which should include experienced Geotechnical Engineers, Dan Engineers Supervising Engineers and Reservoir Keepers.

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