Developments in management of reservoir safety in UK

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SYNOPSIS. The UK government funds a continuing programme of research and development on issues related to the safety of large raised reservoirs in the UK. This paper describes three recent projects carried out by KBR which are likely to have a significant effect on the way reservoir safety is managed in the UK.

The first project was to devise and trial a system for quantitative risk assessment of dams, to allow comparison of threats such as inadequate spillway capacity with other threats to the safety of a dam. This system is to be published in early 2004 as an Interim engineering guide for extended trial by dam owners and dam professionals. The second project arose out of the realisation that in UK there are typically about three incidents a year where emergency drawdown of a reservoir is required to avert failure. The project comprised a feasibility study into the content of an incident reporting and investigation system and how this might be established. The third project comprised a feasibility study to identify practicable means of early identification of internal erosion in old dams.

INTRODUCTION

There have been no dam failures involving loss of life in the United Kingdom since enactment of the first Reservoirs Act in 1930. One of the contributions to ensuring that this situation continues is a research and development programme funded by the UK government (Department of environment, food and rural affairs, Defra), to both carry out original research and disseminate current good practice to all those involved in the management of dam safety.

This paper describes three research projects carried out by KBR for Defra, and comments on how UK dam safety management practice may develop in future.

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

THE INTEGRATED SYSTEM

The prototype Integrated System of Quantitative Risk Assessment for dams (KBR, 2002) is summarized in Figure 1. The system is intended to be a rapid screening level assessment, suitable for use as part of the ten yearly safety review carried out under the Reservoirs Act 1975 or for a portfolio risk assessment.

The definitions used form the cornerstone of the system, and unfortunately there is currently no agreed common framework of definitions used in the dam industry. Some of the key definitions of the processes used in the System are shown in Table 1.

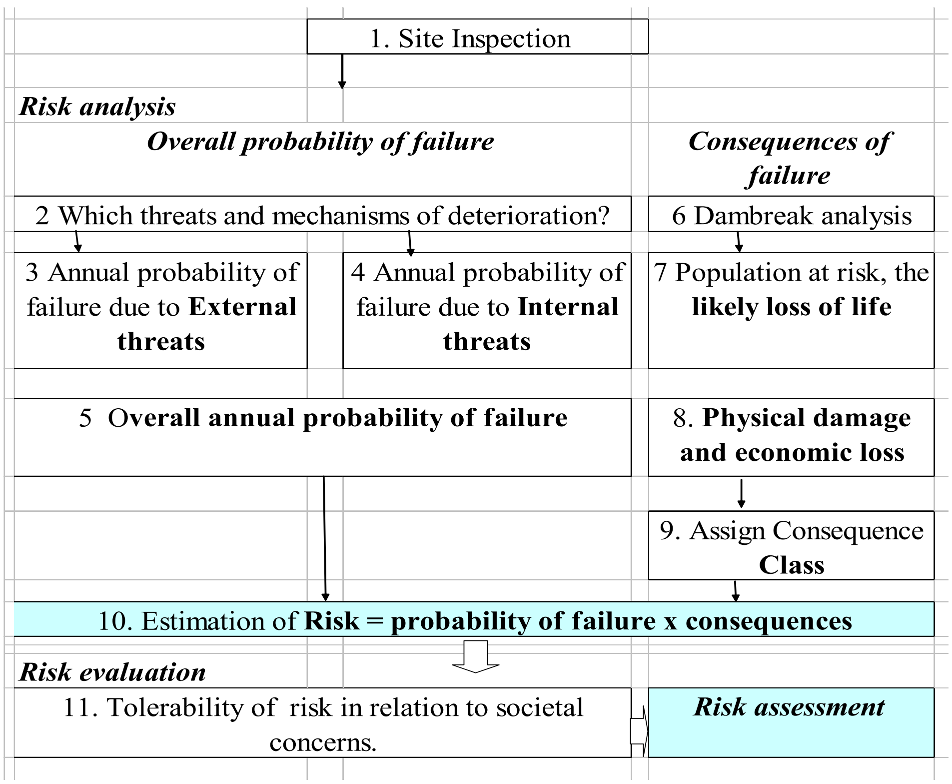

Figure 1: Process comprising the Integrated System

The selection of threats to quantify is one of the most difficult yet important steps. At the feasibility stage the System contains a methodology for estimating the AP of failure due to the most common threats (namely floods, upstream reservoirs, seismic, wind and internal threats), although it includes a requirement for the user to evaluate the significance of other threats at a particular dam and a facility to add these into the estimate of the overall probability of failure. This is carried out using an event tree similar to the Failure Modes and Effects analysis (FMEA) in BS 5760-5:1991.

Table 1: Key definitions used in the Integrated System

Term	Definition
Current Condition	Condition of a dam at a particular date as assessed from visual inspection and in some cases physical investigation
Indicators	Measurable outcome from the application of a mechanism of deterioration e.g. deformation, seepage, instrumentation results.
Intrinsic condition	Current physical property or dimension of the dam which can be measured and which affects the outcome of the application of a mechanism of deterioration. Although initially determined by design and construction details; this may change with time due to ageing, neglect, maintenance or upgrading.
Mode of failure	Means by which a failure (uncontrolled sudden large release of water) may occur; four modes are differentiated in the System namely external erosion (including overtopping), internal erosion, sliding and appurtenant works.
Mechanism of deterioration	Process by which the integrity of the dam is undermined. The mechanism can have a quantitative threshold above which deterioration is likely to occur e.g. slope protection designed to withstand waves due to 100 year wind
Threat	Random Event (External threat, such as floods and earthquake) or Potential Internal Instability (Internal threat) that poses a threat to the integrity of the dam.

Annual Probability of Failure

For external threats such as floods the system uses analysis, by adopting the concept of a "Critical" external event, which is an external loading of sufficient magnitude to just cause failure of the dam. The annual probability (return period) of this event is estimated from the relationship between magnitude and return period.

Estimating the probability of failure due to internal threats is difficult, as internal threats do not occur as independent events and it is often difficult to measure the occurrence of the threat. The preferred system for evaluating the probability of failure due to internal threats is to relate the dam condition, in terms of a Current Condition score of 0 to 10, to the annual probability of failure. The annual probability of failure of the worst condition dams due to internal threats is based on performance over the last 25 years (Brown & Tedd, 2003), while it is assumed that the best condition dams have an annual probability of failure due to internal threats of $1x10^{-7}$.

A critical element of this methodology is the system for assigning the Current Condition score, which is assessed from indicators of poor performance (e.g. seepage and settlement); the quality of ongoing surveillance; the ability to lower the reservoir rapidly in an emergency and the reservoir operating regime.

Consequences of Failure

It is necessary to quantify the consequences if the dam failed, firstly in terms of areas of inundation and structural damage, and then in terms of the likely loss of life and damage to infrastructure. The system uses published rapid methods of estimating the peak breach flow at the dam (Froehlich, 1995), and how this attenuates down the valley (CIRIA, 2000).

The relationship between the likely loss of life (LLOL) and PAR derived from dam failures and flash floods in the United States was used (Bureau of Reclamation, 1999, which includes allowance for the "forcefulness" of the flood wave and warning time.

The estimation of physical damage is as far as possible based on systems used by the Environment Agency for evaluating potential flood defence schemes; albeit some adjustment is required to take into account the higher velocities and thus greater destruction from a dam breach flood.

Tolerability of Risk

The System plots the probability of failure and LLOL on an FN chart, as both one technique for evaluating the tolerability of risk, and as a means of prioritising dams where several are being considered together (e.g. in a cascade). It also provides a spreadsheet to allow the user to carry out ALARP assessment. This estimates the cost to save a statistical life for a package of works. This value can be compared with the cost of the package of works to assess whether the expenditure is proportionate to the reduction in risk achieved.

Benefits

The following benefits are anticipated on application of the prototype system:

- Explicit consideration of the likely threshold of dam failure can help provide a more considered basis for decision making. It will assist understanding of the margin of safety that is available
- For the first time internal threats can be evaluated in a similar format to external threats
- Permits investment to be targeted where it will do most good i.e. achieve the largest reduction in risk
- ALARP analysis can be a useful tool in identifying the value obtained from proposed investments

An interim engineering guide to an integrated approach to reservoir safety will be issued in 2004 for an extended trial as a screening tool over a period of 5 years. Feedback should be provided to the authors or Defra who intend to carry out a review of the approach at the end of that period.

INCIDENT REPORTING AND INVESTIGATION SYSTEM

One of the contributions to managing dam safety is to learn as much as practicable from near miss incidents, which might have become a failure in different circumstances, and this is the objective of the proposed incident reporting and investigation system (Gosden & Brown, 2004).

Other industries were drawn on in defining the system for dams, where systems for reporting near miss incidents are well established although normally being a statutory requirement.

As part of devising a incident system for UK dams, questionnaires were sent out to a selection of dam owners and panel engineers to obtain their views on the various issues relating to such a system. A questionnaire was also sent out for the third research project described in this paper; devising a method for early detection of internal erosion.

Possible objectives and combinations of output and incident level

There is a wide range of possible combinations of level of detail of analysis and output from the data, and the level of seriousness of an incident which could be included in an incident database, as summarised in Table 2.

The levels of incident that were adopted are as shown in Table 3, being based on those used previously in the BRE database (Tedd et al, 1992) although with some tightening of definitions. The current best estimate of the likely average number of each level of incident per year is also included; being derived from the response to the questionnaire (other than Level 6 incident which is derived as shown).

The practicable options considered are shown in Figure 2, with selection of the preferred option based on the views of UK dam industry obtained from the questionnaire, the likely completeness of reporting, the cost of data collection and processing, and the value of the output in improving dam safety.

Table 2: Possible objectives and outputs from incident system

Objective	Output	Feedback from questionnaire to UK dam industry
Ensure best possible practice is applied to ensure the continuing safety of UK dams	II Lessons learnt	Highest support in principle, 69% of dam owners and 35% of others were prepared to contribute to cost.
	II Trends III Cause and feature of each incident	High support in principle but willingness to pay not tested explicitly
	IV Historic Annual probability	70% of dam owners and 30% of others were prepared to contribute to cost.
Minimise whole life cost of asset	VA Cost and duration of incident	62% of owners were prepared to pay for information on cost, but only 39% for the disruption arising from the incident
	VB Reliability database	44% of dam owners and 33% of others were prepared to contribute to the cost. Only 7% of dam owners strongly agreed that it was worthwhile
Data collection	VI Number of extreme events/yr	Low priority.

Table 3: Estimated number of incidents a year in UK, with 2600 large dams

Incident Level	Definition	Estimated No/ yr
1	Failure (uncontrolled sudden large release)	0
2	Emergency drawdown or works; serious operational failure in emergency	3
3	Precautionary drawdown, unplanned visit by Inspecting Eng, unplanned works; serious human error	10
4	Works in the interests of safety (Section 10 of Reservoirs Act)	60
5	Physical works not under a higher incident level. Investigation arising out of periodic safety review	30
6	Extreme natural event > 1% annual probability (1 in a 100 year return period)	78 (1% of UK dams/yr. x 3 threats)
7	Other e.g. operational failure	na

Output Table 2	Incident level (Table 3) -Y is combination which is practical, other combinations are not practical						
	1	2	3	4	5	6	7
I	***Option A***			-	-	-	-
II				***Option C***		***Option D***	*Y*
III	***Option B***						*Y*
IV							*Y*
V	-	-	*Y*	*Y*	*Y*	-	*Y*
VI	-	-	-	-	-	*Y*	*Y*

Figure 2: Options considered for combination of Incident level and output

A critical issue is the likely effectiveness of a voluntary reporting system. This was assessed from the responses to the questionnaire sent out to the dam industry. Of the 117 questionnaires, 43% responded to the questionnaire on the incident system and 34% to the questionnaire on early detection of internal erosion, although only 16% of recipients provided case history data for the latter. Of those that responded to the questionnaire on the incident system, 77% considered they would achieve a completeness ≥80% for a Level 3 incident (Precautionary drawdown of the reservoir) and 13% considered they would achieve a completeness ≥80% for Level 6 (Floods> 100yr).

It was concluded that a voluntary system would only attract a proportion of actual incidents, and that based on the response to the questionnaire the likely completeness of reporting of Level 2 and 3 incidents could be between 35% and 85%. Thus depending on the level of reporting, it may be difficult to reliably differentiate trends in safety from changes in reporting completeness. Hence any statistical analysis may be of uncertain value for Outputs 2 and 4, and biased for Output 3. Initially the system will be voluntary. However, depending on the effectiveness it may be appropriate that the system should become mandatory through new legislation.

It was concluded that, based on both the willingness to pay and likely completion of reporting, there is reasonable support in principle from the UK dam industry for Options A and B, but less so for Option C and none for Option D. Option B (which includes Option A) is taken forward as the information to be obtained from the incident reporting system.

Investigation of near miss incidents

For serious near miss incidents it is of value to investigate the incident to maximise what can be learnt, rather than just relying on an incident report. It is proposed that the purpose of the investigation is the same as for the various accident investigation bodies under the Department of Transport; namely to look for the root causes of accidents without apportioning blame or liability.

It was concluded (Gosden & Brown, 2004) that

- The system should investigate all Level 1 and 2 incidents, but the database manager will be given discretion to investigate other incidents that he believes merit investigation
- the investigator should be appointed by, and report to, an independent body. It is proposed that the independent body would not carry out the investigation themselves but appoint a civil engineer, qualified in accordance with the Reservoirs Act, to carry out the investigation

EARLY DETECTION OF INTERNAL EROSION

The objective of this research was to develop techniques for the early detection of progressive internal erosion (Brown & Gosden, 2004). Drivers for this research included recommendations from a recent research project into the feasibility of an Integrated System to assess all threats to dams (KBR, 2000), and a recent serious near miss incident involving an unprotected masonry culvert through an older embankment dam.

The project builds on the work of the European Working Group (Charles, 2001) as well as others (e.g. Vaughan, 2000a, 2000b). The project comprised data collection through both a questionnaire to dam professionals to obtain data on internal erosion incidents, and the use of expert elicitation to quantify parameters which are not readily measurable (Brown & Aspinall, 2004).

Long term strategy

The overall purpose of a strategy for the early detection of internal erosion is to obtain time

- in which mitigation actions can be taken to avert failure (which could include physical upgrading works), and
- if failure cannot be prevented, to warn and evacuate people from the dam break inundation zone

It is implicit that the importance of early warning is greater where the risk of loss of life and/ or damage resulting from a failure is high; namely that the amount of advance warning time should be greatest and the reliability of detection of defects highest where the risk to the public is greatest. This suggests that the strategy for early detection of internal erosion should be risk based. It is considered that in the long term detection should be one of a suite of three risk control measures to reduce risk from progressive internal erosion, namely

a) surveillance (detection);
b) planning of measures to be taken in the event that internal erosion is detected (emergency planning) and
c) the reduction of vulnerability through physical upgrades

<u>Rate of deterioration</u>

Data on the rate of deterioration is available from the questionnaire and expert elicitation (Brown & Aspinall, 2004); with the key variable being T_f, the estimated time from detection of the incident to failure if there had been no intervention. Figure 3 shows T_f by the location of the incident or the type of dam from the questionnaire. This figure shows that the respondents to the questionnaire considered

a) T_f varies by several orders of magnitude, from 1 to over 100 days,
b) incidents associated with culverts and pipes were much more likely to lead to a rapid failure. The median T_f (50% of incidents) for incidents at appurtenant works was 5 days, whilst the median for incidents in the body of puddle core dams was in excess of 365 days (a year).

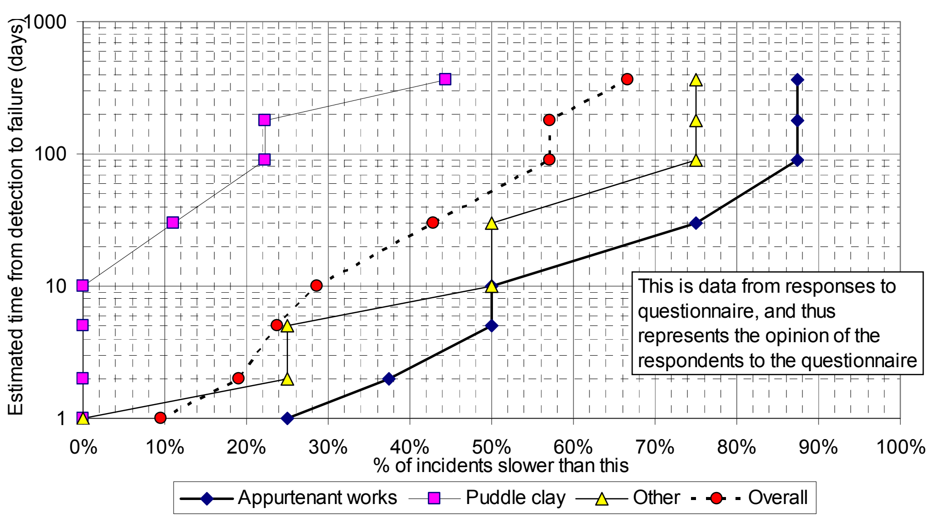

Figure 3: Variation of estimated time from detection of incident to failure (T_f) with incident location or embankment type

Further results from the project are given in Brown & Gosden (2004); with the overarching conclusion being that the understanding of internal erosion processes is still immature. Detailed conclusions include that the rate of deterioration due to internal erosion can be very variable, that there is a threshold leakage for erosion to commence and thus that leakage may occur without internal erosion, depending on issues such as the soil type and magnitude of leakage.

Interim Strategy

Currently there are significant uncertainties in relation to the proposed control measures. For example there are significant uncertainties in estimating the annual probability of failure due to progressive (rapid) internal erosion. Similarly there are a number of arguments against applying the approach of physical upgrades as a default at the present time (except for very high consequence dams):-

a) Currently it is not possible to reliably predict those dams where internal erosion would be rapidly progressive, rather than steady
b) Pipes and culverts appear to be the largest risk; it is more difficult to upgrade these than the body of the embankment
c) If the mechanisms of deterioration and singularities (e.g. construction features) present at a dam cannot be fully quantified, then upgrades could lead to a false sense of security if they were incomplete in not addressing all potential failure modes. (e.g. if carrying out an upgrade led to a reduction in surveillance this could increase the probability of failure due to progressive erosion)

It is therefore concluded that at present it is more appropriate to concentrate on surveillance, and to link the risk control measures to the consequences of failure, rather than risk, albeit with some provision for adjustment on the basis of an assessment of the vulnerability of a dam to failure. Those dams with higher consequences would justify higher expenditure than those dams where the consequences are limited.

Frequency of monitoring

Four general monitoring regimes are proposed to be applied as shown in Table 4. The proposed “Matrix” to define the monitoring regime, which depends on the consequence class and condition of the dam, is shown in Table 5, whilst the Consequence Class is shown on Figure 4.

The latter is based on the Dam Category for defining the design flood as given in Table 1 of Floods and Reservoir Safety (ICE, 1996); but made more quantitative by changing “could endanger life” to “likely loss of life” and requiring that damage be quantified in £M. It is recognised that the accuracy of the latter should be appropriate to the intended use and generally would only be an order of magnitude estimate.

Table 4: Suggested Guide for in-service dam base monitoring frequency

Parameter	Monitoring regime (Note 1)			
	α	β	γ	δ
Visual surveillance				
Exterior; including Exterior of culverts/ shafts (and Interior where no confined space)	Daily	Daily to Tri-Weekly	Twice Weekly to Weekly	Monthly
Interior of culverts/ shafts, where confined space	Weekly to monthly	Monthly to 3 monthly	3-Monthly to 6-Monthly	Ten yearly
Instrumentation				
Flow of water incl turbidity (Note 2)	As for visual surveillance of exterior			
Telemetry	Recommended	Recommended	Consider	Not applicable
Surface Movement	Yearly	2-Yearly	Consider	Consider
Pre-existing instruments	*For manual reading; where automated readings are available more frequent reading would be appropriate.*			
Piezometers	Monthly to 3 monthly	Monthly to 6-Monthly	3-Monthly to 6-Monthly	Consider
Internal movement/ stresses	Yearly	2-Yearly	Consider	Consider
Parameters required to adjust trigger level				
Rainfall	As for flow of water			
Reservoir level	As for flow of water			

1. These frequencies may need to be varied according to the conditions at, and the type, and size of the dam; these should be determined by the dam owner and his Supervising and Inspecting Engineers.
2. This applies to any flow of water that might be emanating from the reservoir. Where there is concern over the behaviour of the dam then periodic measurements of temperature and/or chemical analysis of the water may be helpful in improving the understanding of the sources of the water.

Table 5: Proposed "Risk Matrix" to define monitoring regime

Condition of dam	Consequence class of dam (From Figure 4)			
	A1	A2	B	C/D
Poor	α	β	β	γ
Average	β	β	γ	δ
Good	γ	γ	γ	δ

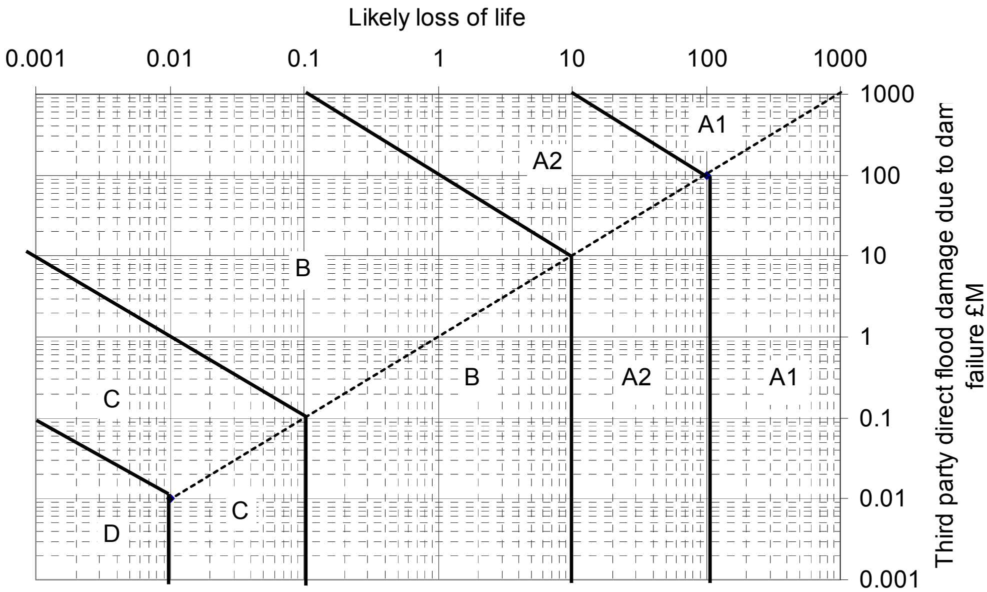

Figure 4: Proposed Consequence diagram for UK dams

DISCUSSION – THE FUTURE FOR DAM SAFETY MANAGEMENT IN THE UK

There is no reason to be complacent about the good public safety record of dams in the UK, and the projects described will contribute to continuous improvements in the safety regime. Quantitative risk assessment (QRA) is still in the early stages as a management technique, but is likely to have far reaching effects on how risk and uncertainty are perceived and managed, and thus on the nature and extent of physical upgrading works.

In a society which is becoming increasingly litigious it is important that safety management becomes more transparent, and that its application to dams is consistent with the approach in other high hazard industries. QRA should assist in informing the debate on these issues.

New legislation passed in 2003 (The Water Act) will change the enforcement of the Reservoirs Act in England and Wales to a single body, the Environment Agency, and also introduce the requirement for emergency plans for higher risk dams.

Implementation of the incident reporting and investigation system described in this paper should lead to more informed understanding of both the frequency and type of serious near miss incidents and prioritisation of areas for future research.

CONCLUSIONS

The UK government programme of research and development in relation to dam safety continues and provides useful output in terms of how the safety of UK dams is managed. Several recent research contracts have been described and a description of how safety management may change in future given. Further information on the projects described is given on both the Defra and British Dam Society websites. Feedback on the Interim Guide to QRA is welcomed and should be addressed to Defra. Readers are encouraged to use the Incident Reporting System, once in place. Similarly suggestions for future research are always welcomed and may be addressed to Defra.

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