Application of the Interim Guide to Quantitative Risk Assessment across multiple dam owners by multiple Jacobs offices

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SYNOPSIS. This paper describes a number of different quantitative risk assessments (QRA) analyses carried out independently by different Jacobs offices, for different clients, using the Interim Guide to QRA. It compares the results and suggests improvements to the Interim Guide which should be incorporated when it is finalised. It also comments on the insights from, and the strategic issues relating to the use of, quantitative risk assessment in dam safety management.

INTRODUCTION

The Interim Guide to QRA (Brown and Gosden, 2004) was published in 2004 for extended trialling, prior to finalisation about five years later. Jacobs has applied the workbook in the Guide to dams owned by a number of major dam owners and also by many small owners, the application being carried out independently by a variety of teams in different offices. This paper describes and comments on the results of these analyses as a means of assessing the value and repeatability of the Interim Guide and obtaining feedback on its use.

ANALYSES

The number of dams assessed represents about 5% of UK dams; the analyses being carried out under the direction of six separate Panel AR Engineers. Groups A to D are those owned by major dam owners, whilst Group E are a group of “small dams” owned by private owners, charities and local authorities. The range of dam height, reservoir volume and age are summarised in Table 1.

The reason for the analysis varied, from being an enhancement of a Section 10 Inspection by providing an auditable justification for any works in the interests of safety, through to more general risk management practices. Similarly the process for carrying out the QRA varied, from completion by a junior engineer with review and signoff by an All Reservoirs Panel Engineer, through to completion of the workbooks by a Panel AR Engineer. In general, involving the Supervising Engineer for the dam under consideration in the process was considered to improve the accuracy of the process, in terms of understanding and scoring appropriately indicators of current condition. Moreover the Supervising Engineer considered that this assisted in focusing surveillance.

For Group E use of the Interim Guide was limited to Consequence assessment only, to provide a more repeatable assessment of population at risk and likely loss of life (LLOL), and thus categorisation of both Consequence Class (as defined in the Interim Guide) and Flood Hazard Category (as defined in Table 1 of Floods and Reservoir Safety, ICE, 1996). These are a subset of the group of dams described in Brown and Gosden (2000).

Table 1: Range of height and age of dams, and size of reservoirs

	Groups A to D			Group E		
	10%	Median	90%	10%	Median	90%
Dam height (m)	6	12	40	3	5	8
Reservoir volume ($1000m^3$)	70	600	8,000	28	50	230
Date of construction	1810	1910	1960	1550	1790	1930
% of dams > 15m height (ICOLD "Large dams")		65%			0%	

Note Dimensions generally rounded to one significant figure, and dates rounded to nearest 10 years so data does not relate to specific dams

METHODOLOGY USED FOR QRA

The methodology used was the Excel workbooks accompanying the Interim Guide to QRA as published in 2004, in some cases using the following refinements

a) Supplement No 1 to the Interim Guide was published in June 2006 on the Defra website along with the draft Guide to Emergency Planning, providing extended guidance on the estimation of the consequences of failure
b) Extended guidance on scoring internal threats, as indicated in Brown and Peters (2007)
c) Extension of the Excel worksheets to include
   - automatic calculation of seepage and settlement index,
   - the effect of infrastructure embankments on rapid dam break.
   - Current Condition Score amended to be quoted to one decimal point

- Sheets 9 and 10 were also merged, so the same property data was used for both risk to life and cost of damage.

In some groups detailed dam break maps were available, but no consequence assessment, so the existing maps were used to denote the extent of flooding with the methodology in the QRA workbook used to estimate the population at risk, likely loss of life and property damage.

The time taken to complete the workbooks was assessed as typically 3 to 4 days where the user was unfamiliar with the system, but this typically reduced by over half once the user was familiar with the methodology.
Feedback from the users included

a) "Move summary sheet for each section at the end. Anything that would help make the method less intimidating would help. Once you get into the spreadsheets they are ok.
b) The spreadsheets are a lot simpler than expected; the most complex programming is an "If statement"!
c) Generally I think the process is understandable. If time is taken to source the information required, and understand the methodology, then on an overall basis not many more changes might be required to improve it
d) The event train spreadsheets did not add to the process
e) If there is limited information for a reservoir, and no adverse indicators I believe the studies may not provide significantly different results for different reservoirs. Especially if they are done or reviewed by the same person for consistency"

In regard to item 'd', Section 2.2 of the Interim Guide notes that, although the event trains are not essential for a quantitative estimate, the event trains prompt the user to consider failure modes (BSI, 1991), and confirm and document which are to be quantified. Item 'e' is an important issue. Where there is a lack of data on dam construction and its foundation this raises the question of whether Section 10 Inspections are similarly constrained, and thus the adequacy of Section 10 Inspections. In practice a certain amount can be inferred by experienced engineers from the date of construction and properties of geological materials in the vicinity of the dam, likely to have been used in the construction and present in its foundation, in the same way as for a statutory Section 10 Inspection.

RESULTS - SUMMARY

The results are summarised as shown in Table 2 and plotted on Figures 1 to 6. Identification of data is limited to maintain anonymity.

The estimates of consequences and annual probability of failure are discussed in the following sections, including a commentary on the absolute values, differences between groups, to what extent this is real, and suggested improvements to the Interim Guide that arise from experience in its use. Comment is also made on insights in relation to reservoir safety management, provided by the use of QRA.

The discussion of improvements commences with Consequence assessment as this influences the proportionate level of detail and effort in the assessment of annual probability of failure. This is followed by a section discussing the strategic issues that arise in relation to the use of quantitative assessment of risk

Table 2: Summary of summary plots of results of analysis

Fig.	Axes	Data fields
1	Consequences of failure (Likely loss of life (LLOL) vs. third party flood damage	Median for each group, and envelope of range of all results
2	Risk as FN chart of LLOL (with and without warning) vs. annual probability of failure (APF) of dam (excluding any upstream dams)	
3	Cumulative distribution of LLOL	All dams in Groups A to D (undifferentiated by group)
4	Cumulative distribution of APF	
5	Cumulative distribution of breach discharge at dam; and "depth" and "velocity x depth" at 1km downstream	Group E only
6	Cumulative distribution of two alternative methods of estimating length of dambreak impact	

In relation to the estimation of risk, Figure 2 shows both the existing median risk for each group of dams, plotted on a FN chart, and the reduction in risk where an effective warning is available. The figure also includes the zones for Acceptable, Tolerable if ALARP and Unacceptable, as defined in Clause 9 of the Annex to SPC/permissioning/09 (HSE, 2001). These lines relate to risk levels of LLOL of 1 in 100 per year (upper line) and 1 in 10,000 (lower line). It can be seen that the median values are all within the "Tolerable if ALARP" zone, which indicates that there should be a formal ALARP analysis on file to show why further risk reduction measures are disproportionate to cost. It can be seen that LLOL reduces by a factor of 5 to 10 where 60 minutes effective warning is available, the reduction being greater for higher consequence dams.

The practical outcomes from the analyses varied depending on the reason for carrying out the analyses. For Group E use of QRA provided a more realistic estimate of consequence class than that provided previously which was based on visual assessment of the dam and downstream valley.

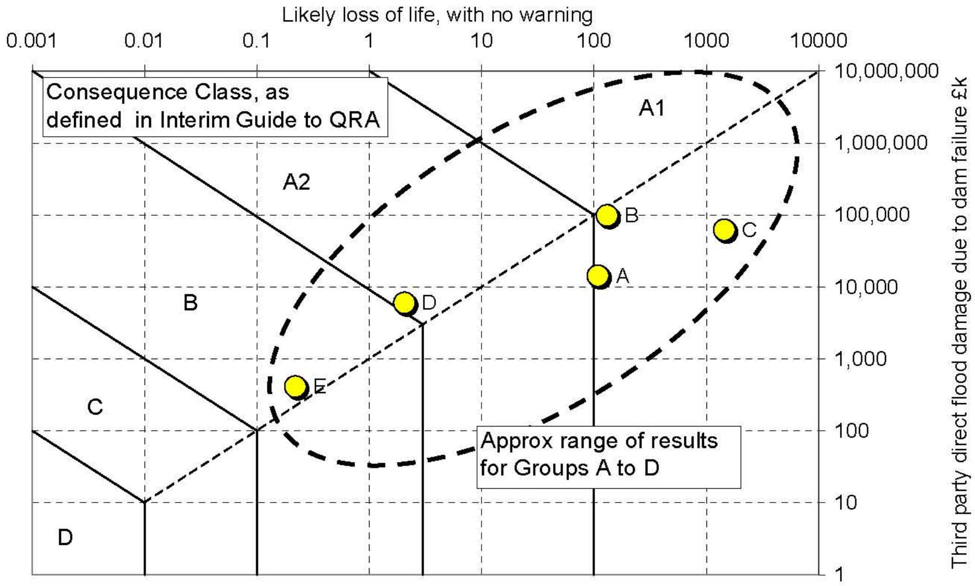

Figure 1: Consequences of failure (median for each group)

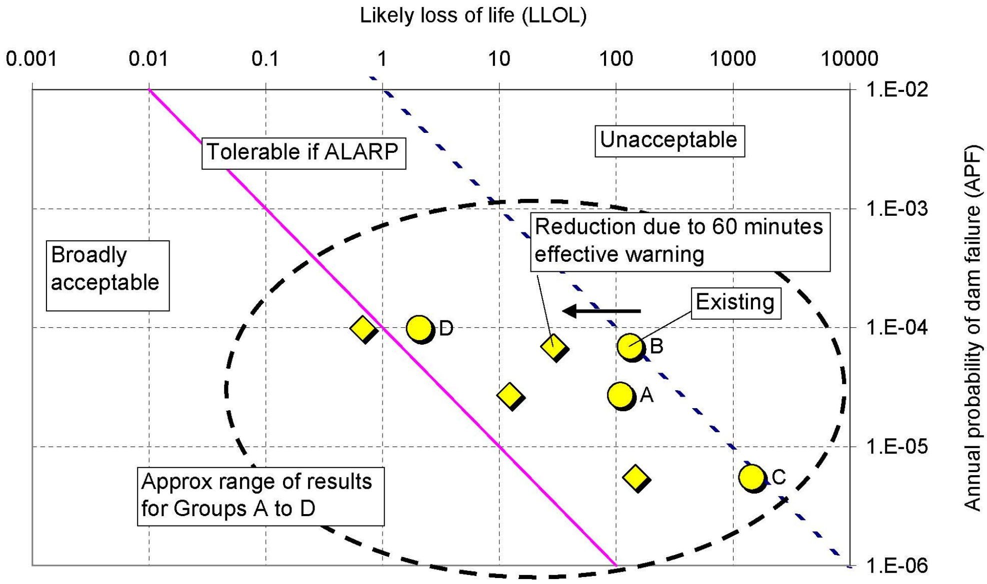

Figure 2: Risk from dams, with and without an effective warning (median for each group)

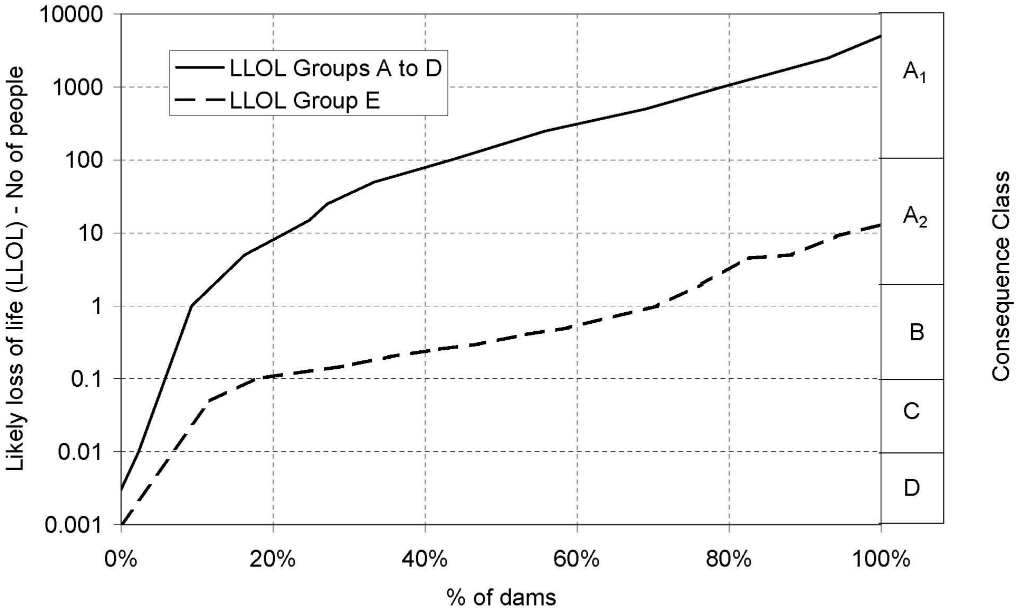

Figure 3: Cumulative distribution of likely loss of life

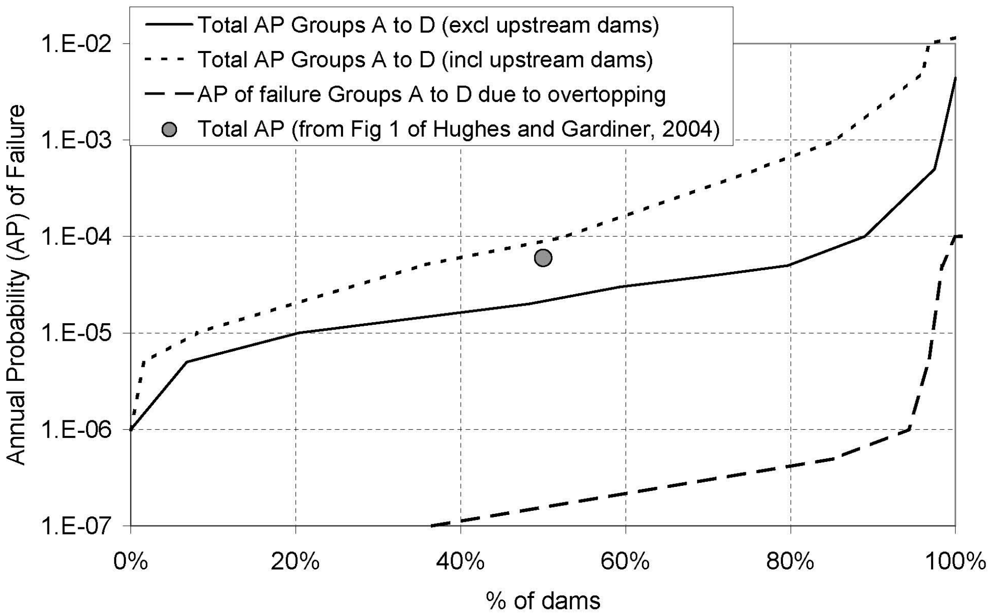

Figure 4: Cumulative distribution of annual probability of failure

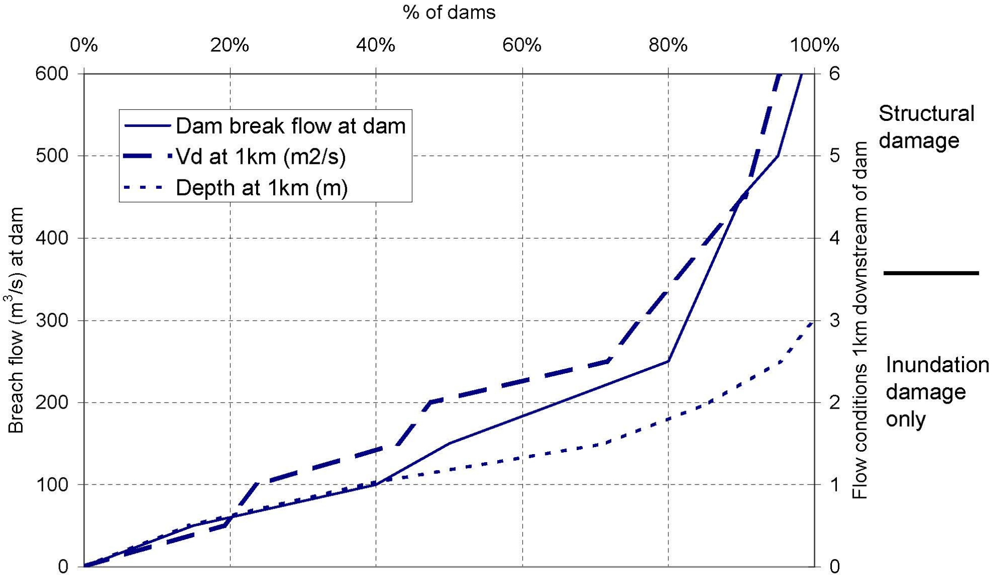

Figure 5: Group E: Distribution of dam break parameters

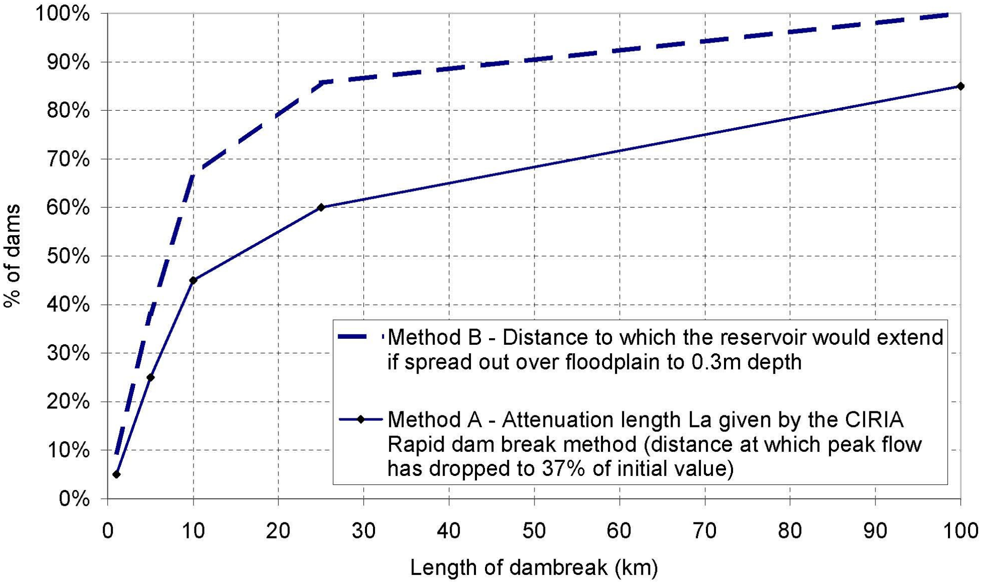

Figure 6: Group E: Alternative methods of estimating length of dam break impact

The expectations for the uses of the QRA included:

a) improved transparency and consistency in assessing the consequences of failure
b) assisting the Inspecting Engineer in deciding whether an issue was crucial to dam safety (could lead to failure), or whether it was an

operational issue which may lead to damage but unlikely to lead to release of the reservoir

c) identification of “quick fix” operation or capital investment that would materially reduce the AP failure
d) a tool which allowed an evaluation of whether the cost of candidate upgrading works were proportional to the reduction in risk achieved
e) assist in evaluating surveillance frequency, and effect of maintenance regime (e.g. grass cutting) on the probability of failure
f) prioritising works between different dams

The Interim Guide did not always fully meet these expectations as the terms of reference for its development were to compare the existing risk from floods with internal erosion, and did not include these other uses. For one group the scoring given to surveillance frequency and quality of monitoring was increased as the scoring in the Guide was considered too low. Nevertheless for all groups the analysis was felt to be of value in focusing thoughts on modes of failure, and “what really mattered”.

REVIEW OF ESTIMATES OF CONSEQUENCES

General

Figure 1 shows that the Consequence Class of the median of the various groups varies significantly, as might be expected. Third party property damage is typically about £1M per likely loss of life (LLOL). Groups A and C are large dams where the fatality rate is high, leading to a higher LLOL relative to property damage. Group D dams are located in more rural areas, remote from large urban development and thus pose a reduced risk to third parties in terms of both LLOL and property damage. The differences between groups are considered a reasonable reflection of reality.

Figure 3 shows the variation in LLOL. The wide range of the consequences of failure are noted, with LLOL varying by a factor of five orders of magnitude. A risk based approach to safety management would suggest that the resources to ensure dam safety would similarly vary by five orders of magnitude.

Rapid Dambreak assessment

A risk based approach requires a methodology for rapid dam break to screen out the low consequence dams, where the consequences of dam failure would be small, and thus where significant cost in risk management measures would be disproportionate. A particular problematic area is in differentiating between Class B and C dams. For these dams there are typically up to a few tens of houses downstream. However, the depth of flooding above the flood plain is typically just over one metre, so deciding which houses have a threshold level which would be inundated by a dam break flood depth can therefore only be indicative. In reality the main risk is to those exposed in the open, as those in two storey buildings can readily rise above flood level by going upstairs, provided the building is not upstream of a transportation embankment where water would pond to a greater depth.

A Rapid method is given in CIRIA Report C542 (2000); this being reproduced in the Interim Guide (2004) with some modest refinements. This method is now used routinely to estimate dam break characteristics for the Group E dams. Figure 5 shows that the median dam break flow is 150m^3/s, whilst by 1km downstream of the dam

- 80% of the dams have a median product of velocity and depth of less than 3.5m^2/s, where damage is anticipated as inundation damage only.
- The 50% and 90% depth of flooding above the floodplain are 1.1m and 2.2 m respectively

This is likely to be an overestimate, as in some cases the breach flows from these small reservoirs are overestimated by the Rapid method, since it neglects the effect that having a wide crest width in relation to dam height would have on the breach flow.

A separate issue relates to the distance downstream which would be affected by dambreak. The problems with the CIRIA (2000) C542 method in underestimating attenuation of the dambreak wave have been identified in Supplement Number 1 to the Interim Guide (Defra, 2006). Figure 6 shows two alternative simplified approaches to estimating the downstream extent of dambreak flooding:

A – Attenuation length L_a given by the CIRIA rapid dambreak method (distance at which peak flow has dropped to 37% of initial value; noting that it drops to 14% and 5% of initial flow at $2L_a$ and $3L_a$ respectively)

B - Distance to which the reservoir volume would extend if spread out over the floodplain downstream, to a depth of say 0.3m, as representing a residual flood depth due to ponding behind roads, hedges, debris, trees etc.

It can be seen that Method B suggests attenuation would occur faster than the CIRIA rapid dambreak. Although detailed dambreak would be required to confirm the validity of this, it does provide a useful indicative check for preliminary dam break assessment.

<u>Impact assessment</u>

The various analyses used Supplement No 1, which gave extended guidance on estimating the occupancy of buildings and cost of property damage. One of the main uncertainties is whether the occupancy rates quoted in non-residential property (average $40m^2$/ person, occupancy of 25% of time) are reasonable, or whether they overestimate the population likely to be present.

REVIEW OF ESTIMATES OF ANNUAL PROBABILITY OF FAILURE

General

The vertical axis on Figure 2 shows the median annual probability of failure (APF), which varies between 3 and 10 x 10^{-5}/ year, apart from the high consequence group where APF is 0.7 x 10^{-5}. The relatively modest differentiation between groups is probably a reflection that the data points are the median for each group, and that there is a greater differentiation within groups than between groups.

Figure 4 shows the distribution of APF across the dams considered in this paper. 90% of the dams considered have a probability of failure of less than 1 x 10^{-4}/ year, whilst the median probability of failure is 3 x 10^{-5}/annum. The latter is of the same order as the overall probability of UK dams of less than 2 x 10^{-5}, inferred from the lack of failures of dams in service under the Reservoirs Act since 1975 (KBR, 2002), and slightly less than the median shown on Figure 1 of Hughes and Gardiner (2004)

The small number of dams with an APF higher than 10^{-4}/annum is noted. Although some represent lower consequence dams where safety requirements have been relaxed following a risk based approach, there are also some where QRA has identified risks which had been overlooked by the last Inspecting Engineer.

Extreme rainfall

Figure 4 includes the contribution of the probability of failure from overtopping, which is less than 1 x 10^{-6} for the great majority of dams. The exceptions include lower Consequence Class dams, where the design standard is to pass a 1 in 150, or 1 in 1000 chance per year flood, and some dams where the QRA identified inadequacies in the existing arrangements, most commonly due to some combination of a constriction downstream of the weir, blockage of the weir by trees or other debris, or structural instability of the crest wall under wave/ water loading.

Although Sheet 2.3 of the Interim Guide requires the User to assess the criticality of failure due to erosion along the sides of the chute, or structural failure of the chute, it does not provide means of quantifying the APF due to these failure modes. Both of these failure modes have been highlighted by incidents at Boltby and Ulley and worksheets should be developed to quantify these, at the screening level of accuracy of the Interim Guide.

Upstream reservoirs

For the reservoirs owned by major dam owners 37% of reservoirs have reservoirs upstream of them retained by embankment dams, which when included in the overall APF typically increases the APF by a factor of about five. Difficulties were experienced in estimating the APF where the upstream dam was in third party ownership. This analysis neglects upstream reservoirs retained by concrete dams, as currently there is no methodology for estimating the APF of concrete dams. This confirms the increased risk of failure where dams are in cascade, due to the potential for the domino effect.

Internal stability (embankment and appurtenant works)

This element of the Interim Guide was the main novel section, and as such has attracted the greatest comment. The research project preceding the Interim Guide carried out a review of systems in use worldwide, identifying 12 different systems (Table 5.3 of KBR, 2002; Brown and Gosden, 2002). Evaluation of this international practice led to the Interim Guide using historical data from the BRE database (Brown & Tedd, 2003) to define “anchor points” for poor condition dams. It is implicit in this approach that the surveillance and intervention regime effective over the period over which the data was collected continues at the same level, so incidents continue to be detected at an early stage and appropriate action taken. It was also assumed that good condition dams have a probability of failure of 10^{-7} and a scoring system was devised to interpolate in-between these anchor points.

One of the early comments that emerged with use of the Guide was that the guidance on scoring allowed different interpretation by different engineers. In addition although Table 4.3 of the Guide noted that where the construction, or condition, of a particular element was unknown, a proportion of the total score should be assigned, some users failed to notice this and assigned zero, leading to the conclusion that their dams were very safe. This feedback led to issue of extended guidance on scoring (Brown & Peters, 2007), including suggested ways to include uncertainty and suggested scores related to the age of the dam, based on typical design details at the date the dam was built. Other issues relating to assessment of internal threats are summarised in Table 3, with comment on how the system could be refined.

The process of considering behaviour of the dam as part of scoring its Intrinsic and Current Condition led to a number of insights related to surveillance. One was that where the downstream toe of a dam (or downstream outlet from a culvert through the dam) is submerged by the reservoir of a downstream dam, there is significant uncertainty over its condition, which is reflected in a high Current Condition score. Another was where instrumentation readings were not systematically evaluated within a week, again reflected in an increased Current Condition Score. Although these were in retrospect obvious, the process of quantifying their impact on the APF was valuable in highlighting their importance to scoring the current condition of the dam.

Other threats

Other threats have been identified and considered in application of the Guide, including reservoir rim landslides and coal mining in the vicinity of the dam, but none was considered sufficiently high to materially affect the overall probability of failure.

DISCUSSION – STRATEGIC ISSUES

Experience with use of the Interim Guide has showed that a risk based approach is still a new technique to many dam engineers. There is often a lack of clarity over consequences if there were no intervention, in terms of whether it is damage which does not affect the structural adequacy of a dam, or whether it affects the ability of the dam to retain water. For this reason alone a QRA approach is considered valuable, as a means to encourage clarity of thinking in terms of modes of failure and consequences.

A second major issue is that the Reservoirs Act 1975 is indiscriminate in terms of the minimum reservoir safety regime required by Undertakers, and does not differentiate between small reservoirs where the probability of loss of life in the event of dam failure is less than 10%, and large reservoirs where the LLOL exceeds 1000. Application of QRA is of significant benefit in providing a transparent and robust methodology to differentiate the level of consequences in the event of dam failure, and thus inform a risk based regime for management of dam safety.

A third area where QRA provides benefits over qualitative assessment is in assessing when the cost of candidate structural works is disproportionate to the reduction in risk that would be achieved, and providing an auditable record of that assessment. This is of benefits to owners in providing a tool to prioritise works and to demonstrate that they have reduced the risk as low as reasonably practicable (ALARP) (www.hse.gov.uk/risk/theory/alarp.htm), and to panel engineers in providing a consistent methodology. As in any analysis, understanding the uncertainties in the analysis is important. As a screening level analysis the Interim Guide provides two sets of parallel calculations for internal stability, which allows sensitivity study. More explicit inclusion of uncertainties would significantly increase the complexity of the workbook and is probably inappropriate for a screening level assessment. Such addition would, however, be a useful additional tool where the screening analysis showed that further assessment was necessary.

Table 3: Possible refinements to methodology for estimation of APF due to internal threats

Assumption	Adopted in Interim Guide	Possible refinement
What score should be assigned where the construction is unknown, or there is no measurement of settlement or seepage?	Table 4.3. Assign a % of total score depending on what is likely, in the experience of the assessor	Extend guidance on scoring, to reduce variability between assessors, as described in Brown & Peters, 2007
What is the lowest APF that can meaningfully be estimated?	10^{-7}/ year (Table 4.6)	For extremely high consequence dams with LLOL of 1000, the overall APF must be below 10^{-7} for risk to be in the broadly acceptable zone. It is suggested that for a screening system such as the Interim Guide it is not meaningful to estimate APF lower than this
What relative importance should be given to Intrinsic and Current Condition, which relate to the form of construction and actual performance of the dam respectively?	Figure 4.1. Only a small weighting is given to Intrinsic Condition.	The weighting could be increased, for example the adjustment of Anchor Point 0 for Intrinsic Condition could be increased to a factor of 100, or 1000. However, the system would then need to be recalibrated, to ensure that it provided reasonable results for a range of dam conditions.
What is the probability of failure of a dam where emergency drawdown is considered necessary to avert failure?	Table 4.2 1.4×10^{-2} (1 in 71) for Condition Score 10; as inferred from BRE data	The estimate of the annual probability of a serious incident could be separated from the probability of failure given an incident. This would have the advantage of focusing attention on the adequacy of arrangements in an emergency, but would complicate the system.
How is the system calibrated?	Section 4.6.2 Poor condition dams based on historic data on frequency of incidents, calibrated by trial of prototype system	The Interim Guide allows the User to enter alternative values of probability for the anchor points; guidance on this could be extended. An alternative approach would be to provide an alternative method, such as event trees (e.g. Cyganiewicz, 2007). This would need significant additional guidance to achieve consistency.

One of the issues highlighted by use of QRA is the lack of information on construction and foundation of many dams, common to all the groups considered by this paper. It is suggested that as a minimum owners could carry out portfolio wide desk study summarising the information that is available, including construction drawings (although recognising that these may be unreliable), site investigation and published geotechnical data on geological deposits in the area which are likely to have been used in dam construction. For some very high consequence dams it may then be appropriate to carry out site investigation to establish, or confirm, dam construction details, including filtering ability of the downstream shoulder and erodibility of the core.

CONCLUSIONS

It is concluded that the Interim Guide is a good first step in introducing a screening level QRA as a tool to assist in dam safety management in UK. It is now in routine use to provide an improved assessment of the consequences of failure for dams which are not necessarily Category A1 or A2. The principles are also in use to apply the ALARP test, and to inform decisions regarding dam safety management.

Nevertheless, as with any new technique, a number of areas for improvement of the accuracy of the quantitative estimates have been identified, including

a) in relation to consequences of failure
   - the method for estimating the dam break flow should take explicit consideration of crest width in relation to dam height, and crest surfacing materials in relation to breach due to overtopping
   - further research is required into the rate of attenuation of the dam break flood, particularly for reservoirs between 3 and 10m in height, and reservoir volumes between 25,000 and 100,000m^3 (which form 50% of the reservoirs registered under the Reservoirs Act 1975)
   - research and updated guidance on average occupancy rates in non-residential property
   - research and guidance on the effect of transportation embankments on extent of flooding following dam failure

b) in relation to annual probability of failure
   - improved guidance on uncertainty, particularly how to score where the construction of the dam is unknown, or its condition is obscured (e.g. by water in a downstream reservoir, thick vegetation, or permeable foundation strata are obscured by superficial soil deposits)
   - separate out the annual probability of a Level 2 Incident (emergency drawdown) from the annual probability of failure

- add an event tree method to be carried out as well as the "historic data method", to make the uncertainties clearer and promote consideration of how to manage those uncertainties
- further research into methods of reliably estimating the annual probability of less than 10^{-6}, which is necessary if very high consequence dams are to fall into the ALARP or broadly acceptable zones

The quantitative estimation of risk is considered to be a valuable process, for the discipline it imposes in terms of clarity of thinking, for the insights it provides into "what matters" and also in providing a documented audit trail. It is therefore considered that QRA should be an essential part of the toolbox of those managing the safety of UK reservoirs, and that the Interim Guide should be updated to provide this tool.

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