

Quantitative risk assessment in practice

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SYNOPSIS. In 2004 the Interim Guide to Quantitative Risk Assessment for UK reservoirs was published. This document gives a methodology for evaluating the risk posed by the principal threats to dam safety within a common framework using a series of Excel worksheets. The probability of failure of the dam is estimated and compared with the likely loss of life to evaluate the risk posed by the dam, and whether this is tolerable.

This paper describes one of the first uses of this methodology in practice. The system has been applied to 6 reservoirs owned by British Waterways in the United Kingdom which feed the Leeds and Liverpool Canal as part of the regular 10 yearly review of reservoir safety under Section 10 of the Reservoirs Act 1975. The reservoirs are impounded by earthfill embankment dams constructed in the early 19th century and are all around 10 metres high.

The paper presents the results of the quantitative risk assessment and the criteria used to determine whether any works are required to improve dam safety. The benefits obtained from using quantitative risk assessment are evaluated from the perspective of both the dam inspecting engineer and the reservoir owner. The use of the quantitative risk assessment in reviewing the existing surveillance procedures for the reservoirs is also described.

The paper concludes with a review of the quantitative risk assessment methodology and identifies where there are opportunities for future improvement.

INTRODUCTION

Regulation of a high hazard civil engineering industry was first implemented through the Reservoirs (Safety Provisions) Act 1930. Although the Reservoirs Act 1975 added further measures to improve the management of reservoir safety, the system of reservoir inspection is largely unchanged since 1930 and has served the public well in this period, with no

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reservoir failures occurring which have resulted in loss of life. The inspection system places full reliance on the judgement, experience and knowledge of individual inspecting engineers. A consistent approach by different inspecting engineers has been promoted through a Government funded research programme of guidance documents. Prescriptive guidance is provided for two threats, floods and earthquake, with the remainder being open to wider interpretation.

In recent years four other high hazard industries have been regulated by the Health and Safety Executive; nuclear sites, onshore chemical plants, offshore and railways (HSE, 2000). The approach to regulation in these industries is broadly similar comprising four underlying principles which represent current best practice.

The most important principle is that the organisation which creates the hazard has a legal duty to manage the risk through the preparation of a safety case which describes how the risk is managed. The safety case involves the following steps:

- Identify the hazards
- Assess the risks
- Develop effective control measures in a coherent whole (i.e. an integrated approach)
- Keep a current documentary record.

The general approach to regulation is that a goal setting framework is preferable to defining prescriptive standards as it makes duty holders think for themselves. This flexibility leads to methods of risk control being tailored to particular circumstances.

Risk is the product of the probability of an event and its consequences. Quantitative risk assessment (QRA) allows risk to be quantified by assigning numerical values to both the probability and consequences to arrive at a risk value of £/annum and likely loss of life/ annum. QRA, as a tool for the safety management of high hazard industries, was pioneered in the nuclear industry but is now more widely used and facilitates preparation of a safety case.

The Interim Guide to Quantitative Risk Assessment for UK Reservoirs (Brown and Gosden, 2004) sets out a methodology for using QRA as part of the safety case for continued operation of a reservoir. This paper describes the application of that methodology

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DESCRIPTION OF RESERVOIRS

Quantitative risk assessment (QRA) has been used as part of the inspections under Section 10 of the Reservoirs Act for 6 reservoirs supplying water to the Leeds and Liverpool Canal to inform the findings and recommendations.

The principal characteristics of the reservoirs are summarised in Table 1 below. Both Whitemoor and Rishton reservoirs are formed by continuous embankments which cross the catchment watershed. Depending on the location of any breach, failure could take place into either one of two separate valleys. This was not recognized in the last Inspection Report where only a single flood hazard category was determined (presumably the more severe) but two Consequence Class assessments have been made as part of the QRA, which apply to particular lengths of the embankment.

Reservoir	Height m	Reservoir capacity m ³	Catchment area km ²	Dam	Flood hazard category	Consequence Class
Upper Foulridge	12	430,000	3.5		B	A2
Lower Foulridge	9	1,490,000	4.8		B	A2
Whitemoor	10	640,000	1.7	East	B	A2
				South	B	B
Slipper Hill	7	165,000	0.3		C	B
Barrowford	9	450,000	Non-impounding		n/a	B
Rishton	10	615,000	0.7	West	C	A2
				East	C	B

Table 1: Principal characteristics of Leeds-Liverpool canal reservoirs

In carrying out the Section 10 inspections the recommendations were deliberately not formulated until the QRA had been completed.

QUANTITATIVE RISK ASSESSMENT

Data

The data collected on the condition of the dam was little different from that obtained in a normal inspection, with the differences identified below. The condition of the dam was described in the Section 10 report and used to develop the annual probability (AP) of failure for the internal threats.

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In order to evaluate the AP of failure due to extreme rainfall, a level survey of the embankment crest is required to assess the extent of overtopping in order to derive the imminent failure flood. This has been carried out as standard practice in recent years in any case to check on crest settlement.

Greater attention was paid to visiting the downstream valley to assess flow routes, identify infrastructure which could reduce or increase the flood peak (in the event of failure) and potential properties at risk. In this case this was carried out during a second visit to the reservoirs to inspect them under high reservoir level when seepage was more likely to be evident. However what a number of recent inspections has shown is that a failure to properly consider the downstream valley has considerably underestimated the population at risk. We have found that carrying out a rapid dam break assessment forces this proper consideration to take place.

Results of QRA

The results of the QRA are shown on the Consequence Class diagram and FN chart in Figures 1 and 2.

Improvements to dam safety

For each of the dams the impact of the measures recommended in the interests of safety and the surveillance improvements on the annual probability of failure are shown in Table 2 below and also illustrated on Figure 2. The current AP of failure is shown in normal type and the AP of failure following the proposed works in italics. The principal measures recommended in the interests of safety are indicated in the final column.

Reservoir	Annual probability x E-05					Principal works recommended in the interests of safety
	Extreme rainfall	Upstream reservoir	Internal stability embankment	Internal stability appurtenant works	Total	
Upper Foulridge	0.1 <i>0.1</i>	n/a <i>n/a</i>	4.0 <i>0.6</i>	30 <i>0.3</i>	34 <i>1.0</i>	Repair draw-off upstream sluice gate CCTV survey of the draw-off pipe Fill crest depression; close gaps in crest kerb Seal leakage paths through spillway crest
Lower Foulridge	1.0 <i>0.1</i>	34 <i>1.0</i>	2.0 <i>0.6</i>	4.0 <i>0.1</i>	41 <i>1.8</i>	Repair bottom draw-off upstream sluice gate CCTV survey of upper draw-off culvert Clear strip along embankment d/s toe Reconstruct upper part of spillway chute Protect d/s toe from high spillway chute flow
Whitemoor	1.5 <i>0.1</i>	n/a <i>n/a</i>	4.0 <i>0.3</i>	3.0 <i>0.8</i>	8.5 <i>1.2</i>	East embankment minimum freeboard of 1.5m Increase spillway chute capacity Rebuild spillway chute floor
Slipper Hill	0.01 <i>0.01</i>	n/a <i>n/a</i>	0.2 <i>0.2</i>	10 <i>0.8 5</i>	10.2 <i>1.0</i>	Construct cut-off below spillway crest
Barrowford	Wind 5 <i>Wind 0.1</i>		10 <i>2.0</i>	10 <i>0.2</i>	25 <i>2.3</i>	Reduce current overflow level CCTV survey and repair draw-off pipework Review surveillance frequency
Rishton	0.05 <i>0.01</i>	n/a <i>n/a</i>	9.0 <i>0.3</i>	0.8 <i>0.8</i>	9.9 <i>1.2</i>	Investigate toe drains and measure flow Embankment minimum freeboard of 1.1m

Table 2: Impact of proposed works on the annual probability of failure

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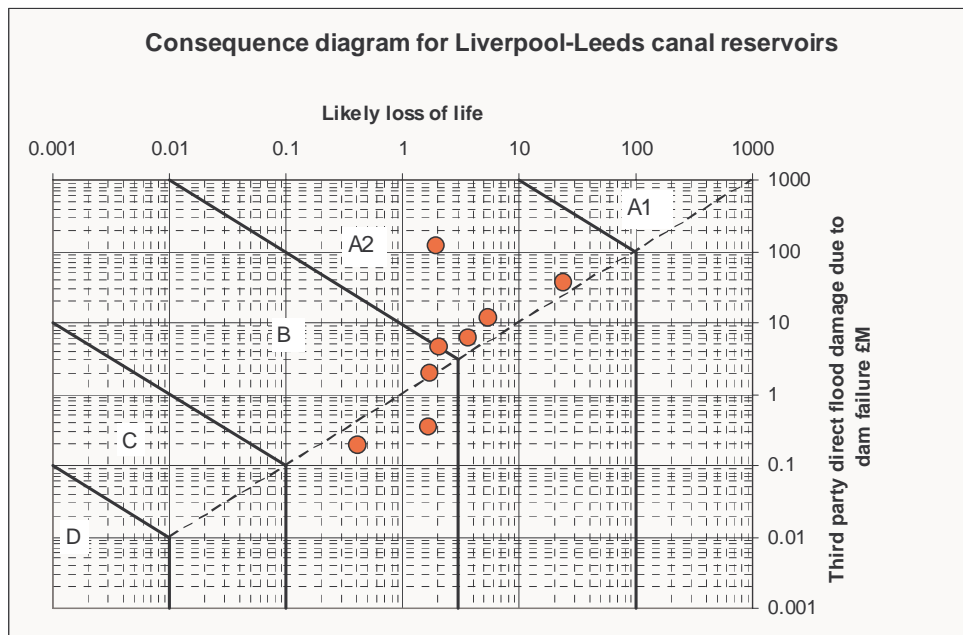


Figure 1: Consequence Class diagram for Leeds-Liverpool canal reservoirs

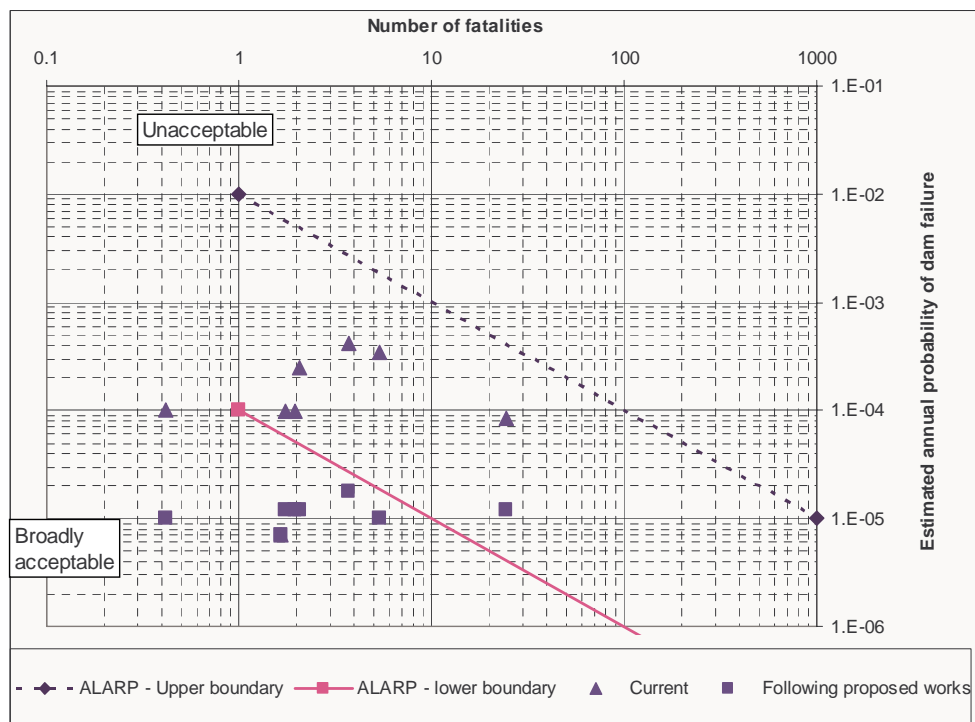


Figure 2: F-N chart for Leeds-Liverpool reservoirs

BENEFITS TO THE INSPECTING ENGINEER

I found the following benefits through carrying out the QRA as part of the Section 10 inspection:

- 1) Carrying out a rapid dam break assessment ensured that potential flow paths were assessed and a quantitative estimate of the depth of flow assisted the visual identification in the valley of potential properties at risk. This process highlighted for two of the reservoirs that were close to the watershed that breach flows would take very different paths depending on the breach location resulting in different Consequence Classes for particular sections of the embankment, as shown in Table 1. This resulted in different minimum freeboard requirements for the east and south embankments at Whitemoor reservoir and works only being required to raise the east embankment
- 2) Consideration of the event trains ensured systematic assessment of potential failure modes, including the addition of some not included as standard and helped to identify the most critical ones. This ensured attention was focused on where improvement was required. In particular this led to the identification of a failure mode at Lower Foulridge reservoir of erosion of the embankment downstream toe from the limited capacity of the spillway chute. Previous upgrading works had increased the spillway crest capacity to in excess of the 10,000 year flood while the chute capacity remained around the 100 year flood. It was estimated that the annual probability of embankment failure from this mode was 1×10^{-5} .
- 3) Repairs to some of the bottom outlets had been postponed for many years. The improvement in AP of failure resulting from a reliable bottom outlet demonstrated clearly the need to include these as measures in the interests of safety
- 4) The rapid dam break analysis demonstrated that the population at risk had been optimistically assessed in previous inspections. Using the guidance given in Floods and Reservoir Safety (ICE, 1996) significant improvements in the spillway capacity to provide the recommended wave freeboard would have been required at several reservoirs. I did not believe that this was the best use of funds rather than expenditure on other items where there is no prescriptive guidance. The QRA provided a rational, defensible basis on which to recommend that no further upgrading in spillway capacity was required. This approach was adopted at Lower Foulridge and Whitemoor reservoirs.
- 5) Recommendations for improving surveillance were justified on the basis of reducing the AP of failure. This was more easily accepted by the reservoir undertaker. Examples of this included the

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recommendation at Barrowford reservoir, which had suffered repeated embankment surface instability, to review the frequency of surveillance and nature of monitoring of the embankment to take into account the recommendations of the Early Detection of Internal Erosion research project, which are due to be published in 2006

- 6) The QRA provided a rationale for prioritising the required measures. The time suggested for completion of the measures in the interests of safety was judged from the absolute AP of failure and the extent of improvement required to achieve an acceptable condition. This resulted in the works at Upper Foulridge reservoir being prioritised ahead of the works at Lower Foulridge reservoir, despite Lower Foulridge reservoir having a higher AP of failure. Prior to carrying out any works the major contributor to the AP of failure of Lower Foulridge reservoir was the threat posed by failure of the upstream reservoir.

Overall the QRA provides an excellent audit trail establishing the basis on which recommendations have been made. This will have significant benefit to Inspecting Engineers in the future in our increasingly litigious society.

BENEFITS TO THE RESERVOIR OWNER AND SUPERVISING ENGINEER

Possibly the main benefits to the reservoir owner are that the QRA provides a consistent approach to the Section 10 Periodical Inspection, and makes transparent the reasoning behind the inclusion or exclusion of certain safety measures. Thus, for example, the owner is no longer faced with the dilemma of whether or not a particular inspecting engineer, relying on his own perception of risk, will insist upon the prescriptive use of Table 1 in the ICE Guide 'Floods and Reservoir Safety', or the provision of an upstream valve on a draw-off; the effect of the perceived shortcoming can be analyzed and arguments developed to justify particular recommendations which are proportionate in relation to the risk posed by the individual dam.

The QRA process provides the reservoir owner with a clearer understanding of where the risks to his reservoir lie and the potential hazard that the reservoir represents, both to his own undertaking and to others; in a business where there are competing claims on money, this proper appreciation of risk enables more realistic and responsible spending plans to be developed. The background knowledge that the QRA generates also allows the owner to comment authoritatively on others' proposals, for example planning applications, where responses often have to be made within a limited timescale. The undertaking of the dam breach analysis within the QRA of the Leeds and Liverpool Canal reservoirs has provided a salutary lesson on

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the likely level and extent of damage that would be caused in the event of a reservoir failure; the change in dam category that has been necessary at a number of these reservoirs suggests a certain lack of appreciation in the past.

Undertaking a QRA as part of the Section 10 Periodical Inspection provides a much more detailed record of the reservoir's condition than is normally given in inspection reports. This 'benchmark' information will be of benefit to both the supervising engineer and future inspecting engineers, as it allows the rate of change of any worrying or unusual feature to be readily assessed. Also, it can be used by the reservoir owner to set up a tailor-made surveillance regime, directing resources and attention in particular to those features which have a direct bearing on the safety of the dam.

The total cost of the six inspections including the QRA was £22,000. This is probably around 50% higher than the inspections alone would have cost. However this is an order of magnitude lower than the cost of potential spillway upgrading which might have been required without the QRA to support a different approach.

CONCLUSIONS

Quantitative risk assessment following the Interim Guide to Quantitative Risk Assessment for UK Reservoirs was successfully used during the Section 10 inspections of 6 reservoirs for British Waterways. It yielded a number of benefits for both the Inspecting Engineer and the reservoir owner, which have been outlined above, including a substantial cost saving by avoiding the need for further spillway upgrading works.

These assessments have demonstrated the robustness of the approach adopted by the Guide to QRA and have identified a small number of improvements which should be made when preparing the definitive guide.

The principal improvements proposed are:

- a) Revision to the rapid dam break routing, which in some situations underestimates the amount of flood attenuation occurring down the valley. At present this is implemented by selecting values of the attenuation parameter L_a which are below the recommended range
- b) Additional guidance on the scoring of current condition for the internal stability evaluation, in particular where indicators are either longstanding or have not been evident during surveillance visits since the previous Section 10 inspection

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