

UNDERSTANDING AND MANAGING THE RISKS OF AGING DAMS:
PRINCIPLES AND CASE STUDIES

David S. Bowles¹, Loren R. Anderson², Terry F. Glover³,
and Sanjay S. Chauhan⁴

ABSTRACT

Risk management can enhance all aspects of the management of aging dams. Risk analysis can strengthen the identification and understanding of dam safety issues. Risk assessment can provide valuable information on the risk reduction characteristics and benefits of structural and non-structural risk reduction options. In addition, to being useful for technical purposes, risk assessment outcomes can strengthen the case for funding capital improvements, additional investigations, and on-going dam safety activities, such as monitoring and surveillance and emergency management. A portfolio risk assessment and an individual dam risk assessment, which the authors have completed for owners and a regulator, are summarized to provide specific examples of the use of risk analysis, risk assessment and risk management in gaining insights, exploring options, and justifying safety improvements at aging dams.

INTRODUCTION

The challenge of managing aging dams is rapidly becoming a principal focus of dam engineering throughout the world. At least a quarter of the dams listed in the U.S. Army Corps of Engineers (USACE 1997) National Inventory of Dams are more than 50 years old. The fact that these dams are the products of a different generation of design standards and construction practices is generally of greater concern than the aging process itself. The risks associated with aging dams are typically of low probability but high consequence. They usually affect third parties, which in many cases may not realize that they are at risk. The underlying dam safety issues are usually technically complex and information about foundations, and even the materials from which the dam itself is constructed, is less than desirable. Typically, justifications for expending large sums to reduce dam safety risks have been based mainly on non-compliance with engineering standards, and are found to be unconvincing by non-technical decision makers (Bowles et al 1997 and 1998a).

¹Professor of Civil and Environmental Engineering, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah 84322-8200; and Principal, RAC Engineers & Economists, 1520 Canyon Road, Providence, Utah 84332-9431.

²Head and Professor of Civil and Environmental Engineering, College of Engineering, Utah State University, Logan, Utah 84322-4110; and Principal, RAC Engineers & Economists, 1520 Canyon Road, Providence, Utah 84332-9431.

³Professor of Economics, Colleges of Agriculture and Business, Utah State University, Logan, Utah 84322; and Principal, RAC Engineers & Economists, 1520 Canyon Road, Providence, Utah 84332-9431.

⁴Research Assistant, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah 84322-8200; and Staff Engineer, RAC Engineers & Economists, 1520 Canyon Road, Providence, Utah 84332-9431.

A primary objective of dam owners and regulators should be to ensure that aging dams “do not create unacceptable risks to public safety and welfare, property, the environment, and cultural resources” (USBR 1993). The manner in which dam safety decisions are made varies from one owner to another, but increasingly these decisions are being made by non-engineers [“From engineers on top to engineers on tap” (Haisman 1998)]. In this setting, engineering inputs are considered along with a multitude of other business-related considerations. Thus, simply requiring that dams meet engineering standards is often not the most effective way to manage the safety of aging dams (Bowles et al 1998a and 1998b). The risk-enhanced approach is an alternative that is being increasingly used. When properly implemented, it can result in a more rapid and more cost effective achievement of risk reduction at aging dams. This approach seeks to a) develop an thorough understanding of the dam safety risks, and b) explore the options and provide a basis for managing these risks in the context of the owner’s business.

This paper is divided into four main major sections. The next two sections summarize ways in which risk management can be used to better understand and manage dam safety risks. In the following section we summarize a portfolio risk assessment and a risk assessment for an individual, which we have completed for owners and a regulator. These case studies provide specific examples of the use of risk analysis, risk assessment and risk management for gaining insights, exploring options and justifying safety improvements at aging dams. The paper closes with a summary and conclusions section.

UNDERSTANDING THE RISK

Qualitative Insights - Risk Identification

One of the first steps in performing a dam safety risk analysis is the identification of potential failure modes over full ranges of flood and earthquake loading and also for normal operating conditions. Risk identification is a qualitative process of listing potential failure modes as sequences of events or combinations of conditions, which are considered to be necessary for dam failure to occur. This process is driven by repeatedly asking the simple question, “If a certain range of loading were to occur, what would be the resulting effect on and response of the dam-spillway-foundation-abutment-reservoir system?” The outcomes of the risk identification process can improve the recognition and understanding of dam safety issues even before quantitative risk analysis. Risk identification can aid with the recognition of cases in which, even though conditions may exist for an incident to occur, other conditions that are necessary for dam failure to result may not be present. For example, earthquake-induced localized liquefaction may not be of sufficient severity and extent to lead to a deformation on a scale sufficient to lead to a loss of the reservoir contents. Even if significant deformation occurs, reservoir levels may or may not be high enough to lead to an immediate overtopping dam failure (e.g. Lower San Fernando Dam) and delayed failure modes may be avoided by an emergency drawdown of the reservoir pool.

In our experience, with risk assessments on almost 150 dams, we have seen many cases in which application of a systematic risk identification process has lead to the recognition of failure modes that had previously been missed (see Pykes Creek case study in this paper). Although there is no guarantee that all failure modes will be identified, the likelihood that all

significant failure modes will be recognized should be improved when a systematic risk identification process is properly applied by experienced dam safety engineers.

The insights gained through the risk identification process can be most valuable in positioning the engineer to design against specific failure modes. They can also lead to ideas for effective risk reduction measures, which might not otherwise have been suggested. Risks associated with human errors, communications and access problems, or institutional arrangements associated with operations and maintenance and monitoring and surveillance activities may be recognized for the first time; thus positioning the owner to take actions to lessen these risks. The potential for human intervention to reduce the likelihood of dam failure during an incident, or to mitigate its consequences, might be recognized. Valuable ideas for contingency planning may be developed. The vulnerability of a structure to malfunctioning of spillway gates may be better understood.

The identification of specific failure modes frequently leads to the recognition of gaps in the information that is needed before a quantitative assessment can be performed. Such gaps may be filled through field investigations, materials testing, engineering analysis or seeking expert inputs. Traditionally, the scoping of dam safety investigations and evaluations has been heavily influenced by the identification of deficiencies defined with respect to engineering standards. Efforts are sometimes allocated disproportionately to those deficiencies which are most amenable to analysis, and not necessarily to those which pose the greatest risk, or offer the greatest opportunity for cost effective risk reduction. Ideally, efforts invested in investigations should be justified by the reduction of uncertainties or the improvement in the confidence in engineering and other inputs to dam safety decisions.

The insights gained from risk identification may lead to shifts in the emphasis of investigative programs. For example, there may be a shift from focusing on spillway deficiencies for very rare floods, to concerns about piping or seepage, which are associated with much more frequent loading conditions and which could lead to a sudden and possibly undetected failure. In one of our early risk assessments (Bowles 1988), the shift was from performing a dynamic seismic stability analysis, to better defining the problems associated with evacuation of a large metropolitan area in the event of an upstream dam failure.

Quantitative Risk Assessment

Moving from the qualitative step of risk identification to quantitative risk assessment enhances the insights and other benefits that can be developed during risk identification. To obtain quantitative estimates of the risks associated with an existing dam requires that flood, earthquake and static loads be described using probability distributions. It also requires that the system responses, which comprise failure modes, and which were identified as part of the risk identification step, be characterized using conditional probabilities, and that consequences be estimated, together with exposure conditions that affect life safety risks. Thus the estimated risk is represented in terms of probabilities and consequences of failure for various failure modes of the existing dam. Similar estimates are made for structural and non-structural risk reduction measures. For each measure, appropriate changes are made to the system response characteristics and other relationships, such as, reservoir stage-annual exceedance probability (AEP), stage-discharge, and consequences.

Uncertainty is intrinsic to dam engineering and can be quantified using uncertainty analysis in conjunction with risk analysis. If uncertainty about foundation conditions or materials properties are considered to be too large to proceed with confidence, the value of obtaining

additional information through investigation, testing, and analysis can be assessed, and used as a basis for deciding if these efforts are worthwhile.

MANAGING THE RISK

Exploring Options

Risk assessment provides a valuable framework within which to compare a range of risk reduction measures. It provides insights into the unique risk reduction characteristics of each measure in a form that has been found useful to engineers and understandable to non-engineering decision makers. For example, increasing spillway capacity by lowering the spillway crest would be expected to increase the frequency of operational flood damages while decreasing the probability of dam failure. Raising a dam would reduce the probability of failure, but in the event of a failure the extent of damages will likely be increased. An emergency warning system may not provide an opportunity to reduce the probability of dam failure, but should decrease the potential for loss of life. If spillway gates are present, the many factors, which affect their operational reliability, can be explored so that the most effective means of improving reliability can be formulated. Figure 1 illustrates the differing life safety risk reduction characteristics of some different flood risk reduction measures.

The insights obtained through the qualitative and quantitative aspects of risk assessment can improve the range of risk reduction measures, which are identified. In some cases combinations of structural and non-structural measures may be significantly more cost effective, or even the only way to reduce risks to tolerable levels. We have seen several dams for which even a state-of-the-art structural fix is not sufficient to reduce risk to tolerable levels where a dam is located immediately above a populated area.

Justifying Actions

The need for better justification of both capital works and on-going dam safety management activities has probably never been greater than it is in these days of privatization, deregulation, and reinvention of government. Traditionally, a deficiency with respect to an engineering standard was considered to be sufficient justification for proceeding with a dam safety fix. Today, a strong business-related justification must frequently be made. Such a justification should include an explanation of the risks, including the consequences for the owner and third parties, for the existing dam and for various risk reduction alternatives. It should include an assessment of the implications of each alternative for such business processes as capital budgeting, due diligence and liability, contingency planning and business criticality, and loss financing and insurance coverages. In addition, a firm basis should be provided for monitoring and surveillance, operations and maintenance, and emergency preparedness planning.

Various criteria have been developed for use in evaluating dam safety risk assessment results. Amongst the most important are tolerable risk-to-life criteria. These are generally based on the probability and consequences associated with the failure (performance) of a dam. Risk and safety levels can be compared with those expected for other types of facilities, such as hazardous industry siting and nuclear power plants. Thus, by supplementing engineering standards with information obtained from risk assessment, the risk-enhanced approach can avoid the shortcomings of an engineering standards-only approach, while better

communicating the significance of dam safety issues and justifications for actions to lay decision makers.

In addition to life safety criteria, other criteria which can be useful for justifying dam safety actions can include estimates of financial liabilities for comparison with insurance coverages, rate of return and benefit:cost information, and estimates of the cost effectiveness of risk reduction actions. The role of cost effectiveness, including cost-per-(statistical) life-saved (CPLS), for prioritizing dam safety risk reduction measures is further discussed in the following subsection. CPLS can also be useful for benchmarking the level of expenditure by other dam owners in protecting public safety.

By obtaining estimates of dam safety risks, a basis can be established for comparing risk reduction decisions within and between portfolios of dams. These benchmarking exercises are becoming of great interest to dam owners, especially in times of deregulation and increasing competition. They should also be of interest to regulators. Such comparisons can provide a relatively objective measure of due diligence and might be used in an adversarial setting in the event of a dam failure, or if third parties were to question the adequacy of an owner's dam safety program.

Prioritizing Actions

Actions to reduce the risk associated with existing dams can be prioritized in various ways. Traditionally hazard ratings have been used to sort dams into different groups. Greater effort is then invested in dam safety management for high hazard dams than for low hazard dams. However, hazard rating systems are typically of little use for prioritization of a group of dams because hazard categories lump many dams into a single high hazard category (Bowles et al 1995). Also, hazard, as defined by these rating systems, has no relationship to the probability of failure and little relationship to the consequences of failure.

Risk-based approaches for prioritizing dam safety improvements can be based on the level of existing risk, the amount of risk reduction, or the cost effectiveness of risk reduction (i.e. risk reduction per dollar expended or "bang for the buck"). To maximize the rate of risk reduction for a single dam or over a portfolio of dams those risk reduction actions with the greatest cost effectiveness should be given the highest priority. This is clearly demonstrated in the portfolio risk assessment case study presented in the following section.

The most cost effective actions may include low cost measures, such as emergency preparedness planning or a parapet wall. These measures may not be complete fixes, and their implementation might be only a first phase or an interim measure in a multi-phased dam safety improvement program. The Pykes Creek Dam case study illustrates a phased approach for addressing flood deficiencies. When risks are high, relatively expensive measures can be cost effective if the resulting risk reduction is large. The as-low-as-reasonably-practicable (ALARP) condition can be considered to be satisfied when actions are no longer cost effective, as indicated by a very large cost for a very small risk reduction (e.g. a very large CPLS).

CASE STUDIES

Two risk assessment projects, which the authors have performed for clients in Australia, are summarized in this section. The first project is a portfolio risk assessment of 17 large dams.

The second project is for individual dam, and was a demonstration project sponsored by the owners and the regulator in the State of Victoria in south-eastern Australia. The regulator is developing and promoting a Business Risk approach to dam safety regulation and management (Watson 1998). These demonstration risk assessments were part of a program for implementing the approach throughout Victoria in response to the Victorian Review of Headworks (SMEC/RAC 1995), which recommended that “a staged risk assessment approach should be thoroughly integrated into the practice of dam safety evaluation ... in the State of Victoria ...”. Each case study is summarized in the following four parts: a) purpose and overview, b) results, c) outcomes and d) benefits of using a risk-enhanced approach to evaluating and managing the safety of existing (aging) dams.

Portfolio Risk Assessment

a) Purpose and Overview

The South Australian Water Corporation (SA Water) changed from a state government department to a public corporation in July 1995. It provides water and wastewater services to a population of more than 1 million people throughout South Australia. SA Water operates and maintains 16 large dams as part of the bulk water system and one flood control dam. It is self-regulated with respect to dam safety and has a good dam safety record. However, more than half its portfolio of large dams is older than 75 years, and in many cases they do not meet modern engineering standards. A number of dams are located on streams that run through metropolitan Adelaide where the consequences of a dam failure would be catastrophic.

SA Water will need to make some important choices on how much dam safety improvement is justifiable at each of its dams, how to prioritize these improvements, and at what rate to proceed. Such decisions will be made within the framework of expectations of long term profitability and improving the Corporation's business value. To provide inputs to these important decisions, and in view of the move to risk-based dam safety decision making in Australia, SA Water commissioned an initial portfolio risk assessment (PRA). The PRA was designed to provide a baseline assessment of the existing dams and an initial prioritization of future investigations and possible risk reduction measures. The PRA comprised a reconnaissance-level engineering assessment and risk assessment. These assessments were performed for flood, earthquake, and static loading. Various structural and non-structural risk reduction measures were developed and evaluated. Bowles et al (1998c) provides additional details on this study.

b) i) Results – Existing Dams

Results from the engineering and risk assessments of the existing dams are summarized for each type of loading, as follows:

- Floods: Over the portfolio, flood failure modes account for more than 90% of the probability of failure and about 80% of the total risk costs, but only about 30% of the life loss risk. Only one dam is expected to meet ANCOLD flood guidelines.
- Earthquakes: Earthquake failure modes are estimated to contribute about 1% or less to the portfolio probability of failure, total risk costs, and life loss risk. Current practice for earthquake resistance is expected to be met by five dams.
- Static: Over the portfolio, static loading (normal operating conditions) failure modes appear to contribute less than 10% to the probability of failure and less than 20% to the

total risk costs, but almost 70% to the life loss risk, due to the lack of warning time needed for evacuation. Current practice for static loading is expected to be satisfied by 14 dams.

For ANCOLD (1996) revised interim societal (life safety) risk criteria, five existing dams do not appear to meet the limit criterion, and an additional six dams do not appear to meet the objective criterion.

b) ii) Results - Risk Reduction Measures

A total of 23 structural risk reduction measures were formulated at a reconnaissance level as logically separable construction packages. Each measure was developed with the intent of meeting an engineering standards level of risk reduction. Even so, some are not expected to meet ANCOLD or other societal risk criteria for life loss, due to their close proximity to a population at risk.

Benefit:cost ratios greater than one were identified for only two structural measures: installing external back-up seals on the upstream face of a concrete faced rockfill dam (approximately 2:1); and stabilizing a free standing crest structure used for raising another dam (greater than 40:1). Net present value is estimated to be positive for only the second of these structural measures.

Four ALARP (as low as reasonably practicable) justification ratings (“very strong”, “strong”, “moderate”, and “poor”) were proposed for use in the SA Water PRA based on increasing order of magnitude of cost-per-life-saved (CPLS), which is a measure of the cost effectiveness of improving life safety. Of the 23 structural measures, there are three “very strong” ALARP justification ratings, three “strong” ratings, three “moderate” ratings, and 14 “poor” ratings. These ratings were used in developing implementation phases, which is described in the next subsection on outcomes.

c) Outcomes

The Dam Safety Improvement Program (DSIP) component of SA Water’s overall dam safety program will comprise further engineering evaluations and the implementation of structural and non-structural risk reduction measures. Evaluations will include engineering investigations and detailed risk assessments. These will be of sufficient depth to achieve a “sign off” level confidence in dam safety evaluations and decision making, and to provide sufficient information for design of structural and non-structural measures.

An initial priority for implementing the 23 structural risk reduction measures was developed to maximize the rate of estimated risk reduction for the expenditure of capital funds for dam safety improvement. First priority was given to reducing life safety risks until a point of diminishing returns is reached after the first eight measures, which have the smallest CPLS values. Second priority was given to reducing total risk costs (i.e. direct SA Water and third party). The resulting prioritization is referred to as “the PRA prioritization”.

The estimated rate of life safety risk reduction is significantly greater for the PRA prioritization than for the current SA Water program prioritization (Figure 2). It is estimated that the proposed DSIP would achieve 98% of the total life loss risk reduction for about 15% of the total capital costs, compared with about 75% of the total capital costs to achieve the same level of risk reduction under the current SA Water prioritization. Risk reduction

measures were assigned to four implementation phases based on the PRA prioritization and various risk-based ratings thresholds. These are described in Bowles et al (1998c).

On the basis of the PRA, a number of recommendations were made so that SA Water can effectively integrate and apply the PRA findings within its existing dam safety program. Key actions that SA Water is, or will be taking, include the following:

- High priority is being given to establishing and implementing a risk-based DSIP comprising further investigations, implementation of all reasonable and practical structural and non-structural measures with the goal of reducing risks to tolerable levels, and consideration of emergency preparedness plans (EPP) and early warning systems (EWS) for all dams.
- The PRA indicated that at some dams there are high life safety risks or a high probability of failure. High priority is being given to evaluating the need for short term measures to reduce risks in these cases.
- Existing dam safety management program activities and contingency planning will be reviewed based on insights developed in the PRA.
- Consistent with the baseline nature of the initial PRA, it is intended to regularly update the PRA as additional information becomes available.
- Based on the PRA, it is expected that detailed risk assessments will be justified at a number of dams. As a minimum, the initial risk identification step of detailed risk assessment will be applied to all dams.

d) Benefits

Many useful insights into dam safety issues, which might not otherwise have been obtained, were provided by the PRA process. SA Water now has an overall picture of the current dam safety status of its large dams from both a standards-based perspective and a risk-based perspective. The proposed phased implementation of structural measures and further evaluations is proving useful for prioritizing and managing dam safety evaluation and improvement efforts, and importantly, is regarded as a defensible strategy for reduction of risk.

Another significant benefit of conducting the PRA is that it identified a more rapid approach to risk reduction than the existing dam safety program prioritization, which was based on traditional approaches. By taking a risk-based approach to prioritizing dam safety evaluations and improvements, SA Water has obtained information that is useful for integrating dam safety issues into overall business planning. However, the owner can still choose whether or not to adopt a standards-based or risk-enhanced approach to establishing safety targets for long-term risk reduction at each dam.

The close partnership between the consultant and SA Water technical staff and the periodic involvement of SA Water executives and the Board contributed to the effective conduct of the PRA. This level of interaction is clearly an essential ingredient for maximizing the value of a PRA process to the owner and achieving rapid acceptance of PRA outcomes.

Pykes Creek Dam

a) Purpose and Overview

Pykes Creek Reservoir is located west of Melbourne, Victoria, Australia, in the 121 km² Werribee Basin. It supplies irrigation water and some supplemental urban water. Rapid urban development is expected to continue and has encroached on the floodplain. The original embankment dam was completed in 1911 with a 3.35 m raise in 1930 resulting in its present reservoir capacity of 23,900 ML. Recent safety reviews had identified a number of dam safety issues, as follows:

- A spillway capacity estimated to have an AEP of 1 in 16,000, but which was less than that called for in ANCOLD flood guidelines for this dam.
- An intake tower that only just passes the 1 in 1,000 AEP design seismic event, although the embankment dam should withstand the 1 in 10,000 AEP design seismic event.
- The inability to inspect the intake tower guard gates and outlet conduit due to excessive leakage past the remaining guard gate.

The owner, Southern Rural Water (SRW), initiated a risk assessment of the dam with the stated objective, “to identify those deficiencies ... which present an unacceptable liability to SRW and to recommend prioritized cost effective remedial measures.” The risk assessment addressed potential flood and earthquake failure modes and possible internal failure modes in the dam or its foundation under static loading.

The main components of Pykes Creek Dam are as follows (see Figure 3):

- Embankment: A zoned embankment with a central puddle clay core supported by shells of stony material with rockfill toes. In 1967 a highway embankment was constructed on the downstream toe of the dam and crosses over the dam crest near the spillway on the right abutment. The highway embankment divides the dam into two parts, which we refer to as embankments 1 and 2 (see Figure 3).
- Outlet tower: The unreinforced concrete tower is 29.2 m high with a low level inlet and four operating inlet ports. Problems with the tower include an inability to dewater for guard gate maintenance, the condition of the guard gates, concrete structural integrity under seismic loading, and siltation. Up to 15% material loss through graphitic corrosion of the guard gate has been found, although the gate is considered to retain sufficient structural strength to withstand full storage hydrostatic loads.
- Outlet works: The outlet works consist of a 900 mm diameter reinforced concrete encased outlet conduit with two downstream control valves.
- Spillway: The spillway consists of a mass concrete ogee fixed crest 4.3 m high and 92 m long. The spillway chute is in competent rock and is unlined, except for the apron and training wall along part of the left abutment. There is an approximate 10 m vertical drop to the natural stream bed below.

Existing information was reviewed and some additional analyses were performed. Potential failure modes were identified and formed the basis for an event tree risk model. System response probabilities were estimated for various ranges of inflow floods and earthquakes that might lead to dam failure. Dam breach analyses and flood routings were completed and were used to estimate the consequences for each failure mode. The principal identified flood failure modes were:

- Overtopping and erosional failure of embankment 1 and the highway embankment – the role of the highway embankment as a “second line of defense” had not been accounted for in previous dam safety reviews.

- Overtopping and erosional failure of embankment 2 – the lesser consequences associated with failure of this lower section of embankment had not been recognized previously.
- Overtopping of left spillway training wall leading to erosional failure of embankment 2 – this failure mode had not been previously recognized and was identified through the systematic risk identification process.

Identified earthquake failure modes were:

- Embankment 1 deformation leading to overtopping erosional failure and failure of the highway embankment.
- Embankment 2 deformation leading to overtopping erosional failure.
- Outlet works rupture leading to piping failure due to loss of upstream control.

Potential internal (normal operating conditions) failure modes under static loading were:

- Piping of embankments 1 and 2.
- Slope instability of embankments 1 and 2.
- Piping along the outlet works.

In the event of failure of embankment 1 by piping or slope instability it would be necessary for the highway embankment to fail before there would be a release of the reservoir contents.

b) i) Results – Existing Dam

The existing Pykes Creek Reservoir has a relatively high probability of dam failure (3×10^{-3} per year) and economic risk cost (\$137,000 per year), but a relatively low annualized incremental life loss totaled over flood, earthquake and internal failure modes (7×10^{-5} lives per year). Financial loss was estimated at AU\$50M (plus personal injuries and losses downstream of Melton Dam which were not assessed in this study) with approximately 40% of this amount being direct losses to the owner.

Approximately 95% of the probability of failure and risk costs were attributed to an erosional failure of the embankment initiated by overtopping of the training wall of the emergency spillway. Overtopping is estimated to begin during relatively minor flood events (with an approximate AEP of 1 in 15) and has been confirmed by observation. This potential failure mode had not been recognized in previous dam safety evaluations but was identified through the risk identification process.

For best estimates of warning time, the existing dam satisfies the ANCOLD (1994, 1996) amended interim societal risk objective criterion, individual at greatest risk limit criterion (3×10^{-5} per year compared with the criterion: 1×10^{-4} per year), and individual risk objective criterion averaged over the population at risk (PAR) (1.5×10^{-7} per year compared with the criterion: 1×10^{-5} per year). The existing dam also satisfies the Tier 1 USBR (1997) Public Protection guidelines and B.C. Hydro (1993) interim criterion for annualized incremental life loss. However, it does not satisfy ANCOLD's individual at greatest risk objective criterion. Also, considering the magnitude and likelihood of economic consequences for flood-induced failures, the New South Wales (NSW 1993) Total Asset Management example guidelines would suggest that "corrective action (*is*) required in a reasonable time frame" based on the best estimate and that it is "imperative to suppress risk to lower level" based on the high confidence estimate.

Sensitivity of existing dam risk assessment results to a one hour reduction in warning time for flood failure modes, showed that annualized incremental life loss would increase by more than two orders of magnitude. At this level it would not meet the Tier 1 USBR Public Protection Guidelines or the B.C. Hydro societal risk interim criterion. The limit values of the ANCOLD interim societal and individual risk criteria would no longer be met. Thus it is very important to develop sufficient confidence that the warning time for flood-induced failure modes of the existing dam can be achieved.

b) ii) Results – Phase 1 Risk Reduction

A significant risk reduction can be achieved by raising the spillway training wall to protect against erosion of embankment 2. This relatively inexpensive measure was considered as a Phase 1 risk reduction measure with all other risk reduction alternatives being considered under Phase 2. Based on best estimates, Phase 1 risk reductions from the existing dam, are as follows:

- Probability of failure: from 3×10^{-3} to 1.5×10^{-4} per year
- Annualized life loss: from 7×10^{-5} to 2×10^{-5} lives per year
- Average individual: from 1.5×10^{-7} to 4.9×10^{-8} per year
- Most exposed individual: from 3×10^{-5} to 1.1×10^{-6} per year

The Phase 1 benefit:cost ratio is estimated to be about 12.5 and hence the CPLS is zero. Clearly Phase 1 measures are justified economically. With Phase 1 risk reduction, the NSW (1993) Total Asset Management example risk category would change from “medium” for the best estimate and “major” for the high confidence estimate, to “low” for flood loading with both best and high confidence estimates. In the low category, “corrective action (*is recommended*) where practicable”. Phase 1 appears to satisfy all the risk-based criteria, which were considered in this study, except for the Tier 2 USBR Public Protection Guideline (1.5×10^{-4} per year compared with the guideline: 1.0×10^{-4} per year).

Sensitivity studies on loading and system response probabilities did not change the outcomes of the evaluations of the Phase 1 measure against any of the risk-based criteria. Decreasing warning time by one hour was shown to change only one evaluation against risk-based criteria: the ANCOLD (1996) interim societal objective criterion would no longer be met. However, it was recommended that a more detailed assessment of the effects of warning time should be conducted to develop the necessary confidence in warning time estimates used in this study.

b) iii) Results – Phase 2 Risk Reduction

Phase 2 risk reduction measures were examined to determine if they can be justified by ALARP using CPLS estimates or “de minimis” risk considerations. The following nine alternatives were considered:

- AR-1: Flood early warning system
- AR-2: Convert highway embankment into a retention dam
- AR-3: Decommission
- AR-4: Raise embankment
- HR-2: Lower spillway crest

- HR-3: Hydro Plus spillway gates
- ER-2: Increase stability of downstream embankment slopes
- IR-1: Replace guard gate
- IR-2: Raise clay core to the dam crest

Justification for risk reduction measures was examined against the existing dam including the Phase 1 risk reduction. With the exception of the flood early warning system, none of the Phase 2 alternatives were estimated to have a strong economic (i.e. benefit:cost ratio) or life safety (i.e. ALARP based on CPLS cost effectiveness considerations) justification. It appears that business considerations related to loss financing or public trust may dominate a decision on Phase 2 measures. Also, some Phase 2 alternatives may be justified based on the “de minimis risk” principle, which tends to support implementing low cost risk reduction measures even though other justifications may be lacking.

c) Outcomes

Even before the draft report to SRW was finalized, they engaged an engineer to design the Phase 1 raise of the spillway training wall. Considering the relatively high probability of dam failure (3×10^{-3} per year or an AEP of about 1 in 330) and economic risk cost (\$137,000 per year), especially compared with the earlier estimates of an imminent failure flood with AEP of 1 in 16,000, such prompt action was justified.

Phase 2 risk reduction alternatives have less justification than Phase 1. Nevertheless, it may be appropriate to implement some Phase 2 measures at Pykes Creek Dam. However, it was recommended that SRW conduct a PRA of their portfolio of eight dams so that they could prioritize risk reduction opportunities across all their dams. SRW has now completed a PRA.

d) Benefits

Benefits of this risk assessment are summarized as follows:

- A better overall understanding of failure modes including the role of the highway embankment in dividing the dam into two sections of embankment with one having a “second line of defense” provided by the highway embankment and the other having a much lower breach flow potential since it is a lower section on a rock foundation.
- The previously unrecognized spillway training wall deficiency was identified as a result of the systematic risk identification process carried out at the beginning of the risk assessment.
- Concerns about the performance of the outlet tower and outlet works during earthquakes were shown to be very minor risks in comparison to flood risks and yet engineering effort had been focused on the outlet tower prior to performing the risk assessment.
- Risk assessment outcomes were valuable in developing a phased approach to risk reduction and relating the implications of dam safety risks to the owner’s business. In contrast the traditional safety review approach did not provide any prioritization between deficiencies nor did it provide information needed for evaluation of the business risk associated with the *do nothing* scenario.
- The critical role of warning time for evacuation was recognized - a more in-depth evaluation of warning times for various failure modes was recommended to develop sufficient confidence that warning times estimate for the risk assessment could be achieved in practice.

- After completing the Pykes Creek Risk Assessment, the client recognized the value of the risk assessment process. As a result SRW decided to conduct a PRA of their portfolio of eight dams to pursue similar benefits for their other dams and to prioritize risk reduction measures across their portfolio.

SUMMARY AND CONCLUSIONS

Through discussion of principles and cases studies, we have sought to present some of the benefits of the risk-enhanced approach to managing the safety of aging dams. When properly applied by experienced dam engineers, risk assessment procedures can provide qualitative insights and quantitative estimates of risk and risk reduction. These can be valuable to engineers and to non-technical decision makers. For owners of many dams a good starting point is an initial portfolio risk assessment, to prioritize future efforts across all aspects of their dam safety program. Individual dam risk assessments should be carried out to a level of detail justified by the decisions that will depend on them. This typically should involve a staged approach in which additional effort is expended on developing risk assessment inputs only as justified by the degree of confidence and defensibility needed for the decisions that are to be made. It is therefore important that the uncertainties associated with risk estimates be carried through the risk assessment and presented to decision makers in a manner that is understandable and useful to them.

The challenge of managing aging dams is not just a technical matter, it should also be seen in the overall context of the owner's business with manifold considerations such as customer service and business criticality, contractual obligations, capital budgeting, improving business value, legal implications, emergency and contingency planning, loss financing and insurance, public perception, and many others. To fail to see this threatens our ability to win the necessary financial and other resources necessary to achieve and maintain safe aging dams. Through the systematic approach of risk assessment, technical and business understanding can be improved and strategies for cost effective risk reduction through structural and non-structural means can be formulated, explored, justified, and prioritized.

Risk analysis should not be an end in itself. It should serve the purpose of better understanding and managing the risks; or as a recent National Research Council (NRC 1996) report puts it, "Risk characterization should be a decision-driven activity, directed toward informing choices and solving problems."

Although risk assessment has sometimes been criticized as a tool for justifying less safety, we submit that the opposite should be true. The proper motivation for dam safety risk assessment and risk management should be to achieve:

- More safety
- More rapidly
- More cost effectively, with
- More understanding by all stakeholders, and
- More integration across all aspects of the dam safety program.

Engineering standards have played a useful role in our profession and should not be displaced by risk assessment. However, by supplementing engineering standards with information obtained from risk assessment, the "risk-enhanced" approach can avoid the shortcomings of the "engineering standards only" approach, while providing ways to better communicate

problem understanding and justifications for actions to lay decision makers. As such we believe that an appropriate level of risk assessment should become the cornerstone for all dam safety programs. As Bowles stated in the oral presentation of Bowles et al (1998a), "I can foresee the time, when dam safety evaluation will not be best practice, unless a properly conducted risk assessment is included."

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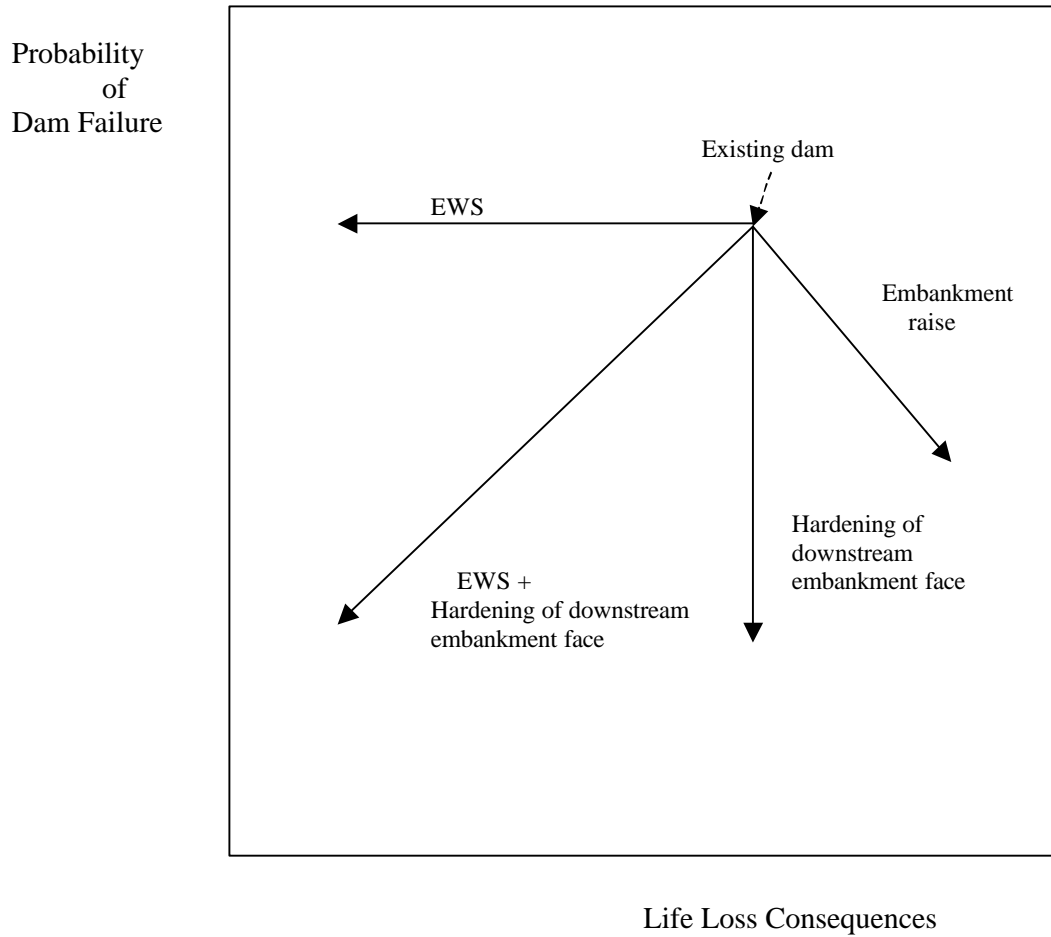


Figure 1. Differing life safety risk reduction characteristics of some flood risk reduction measures.

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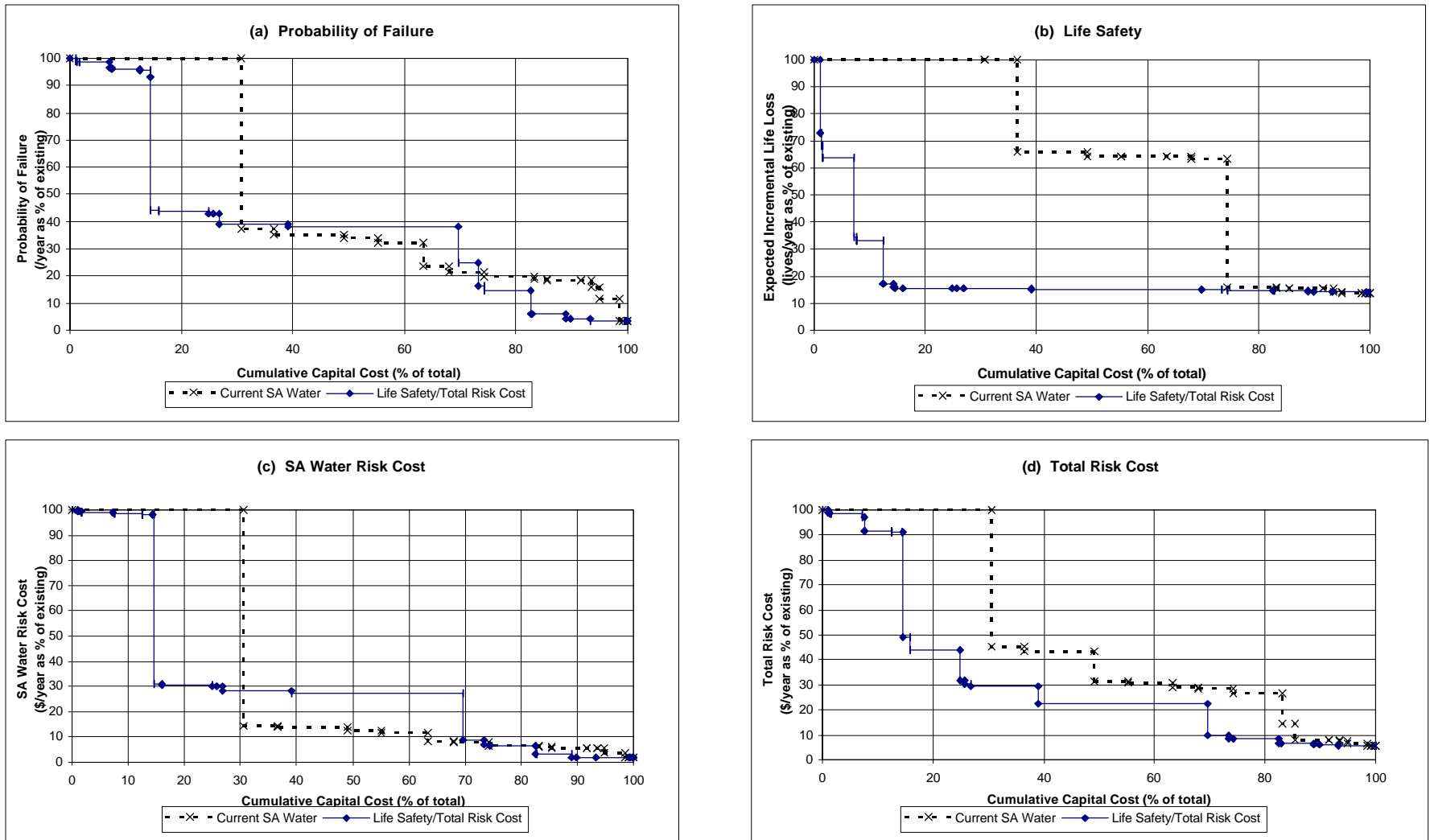


Figure 2 Comparison of residual risks based on PRA prioritization and the current SA Water program

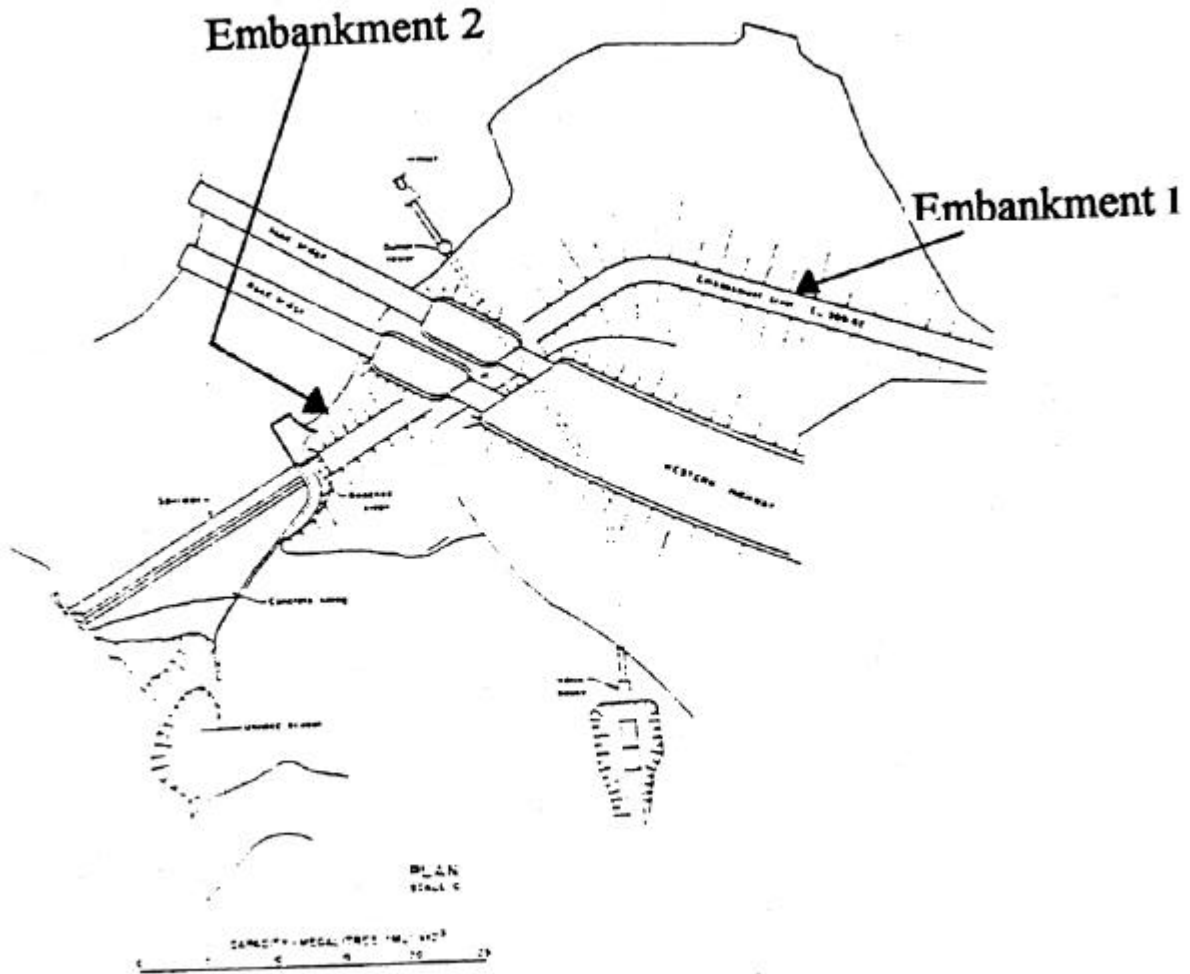


Figure 3. Pykes Creek Dam