INCORPORATING UNCERTAINTY INTO DAM SAFETY RISK ASSESSMENT

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ABSTRACT

Risk assessment is becoming more widely used to supplement traditional approaches to dam safety decision-making. Dam owners throughout Australia, the U.S. Army Corps of Engineers, and the U.S. Bureau of Reclamation are using risk assessment as a decision support tool.

This paper summarizes an approach to incorporating input uncertainties into risk analysis model. Input uncertainties are captured by using probability distributions, and their influence on risk assessment results can be expressed in terms of the confidence associated with meeting tolerable risk guidelines.

This paper presents a framework and procedure for uncertainty analysis in dam safety risk assessment, and demonstrates some useful formats for presenting results.

INTRODUCTION

Throughout the world, the management of the safety of existing dams has become the principal focus of dam engineering. The risk-enhanced approach is increasingly becoming recognized as a way of combining the benefits of the time-tested traditional approach to dam safety and those of risk assessment. Through the systematic procedure of risk assessment, dam engineers can develop an improved understanding of the technical aspects that affect the safety of a dam, and dam safety managers can obtain valuable inputs for dam safety decision-making.

Space does not permit a presentation of the principles and procedures of dam safety risk analysis and risk assessment. Therefore, the reader is referred to Bowles et al (1998a and 1999) and Bowles and Chauhan (2001). For discussions of risk management the reader is referred to Bowles et al (1997) and for portfolio risk assessment to Bowles et al (1998b and 1998c) and Bowles (2000). These papers draw from the authors' experience of working on individual and portfolio risk assessments for more than two hundred dams in Australia, North America, Asia and Europe.

Uncertainty is intrinsic to the various inputs used in both the traditional standards-based approach to dam safety as well as the risk-enhanced approach. Figure 1 is a schematic representation of some of the factors that result in uncertainties in various risk analysis inputs. Up until now

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most dam safety risk analyses have been conducted using only the best estimates of the inputs and a sensitivity analysis in which the upper and lower bound estimates of the inputs are explored to assess sensitivity of the decisions based on the best estimates values to the input uncertainties. However, the sensitivity analysis approach is severely limited in that it does not provide a picture of the entire distribution of outputs that would result from the joint distribution of input uncertainties. Thus, when performing a sensitivity analysis one has little, if any, idea of the relative likelihood associated with the outputs that are obtained from a particular combination of inputs. In contrast uncertainty analysis provides this additional valuable information about relative likelihoods of the outputs for dam safety decision-making as demonstrated later in this paper. For an authoritative reference on the topic of uncertainty in quantitative risk and policy analysis the reader is referred to Morgan and Henrion (1990).

This paper is divided into three major sections. The next two sections summarize uncertainty analysis approach and results of uncertainty analysis performed on a hypothetical dam. The paper closes with a summary and conclusions section.

UNCERTAINTY ANALYSIS APPROACH

General

As shown in Figure 1, inputs to a dam safety risk analysis model can be grouped into the following categories: loadings, system responses, and consequences. All of these have uncertainties associated with them. The uncertainties may be intrinsic to the underlying physical and anthropological processes (aleatory uncertainty), which affect dam performance, operation, and emergency management or they may result from our present inability to accurately estimate or model these processes (epistemic uncertainty). In uncertainty analysis these inputs are characterized using probability distributions of the risk analysis model inputs as described in following sub sections. Typically the risk analysis model is in the form of an event tree. For a discussion of some of the practical considerations in using event trees for dam safety risk analysis, the reader is referred to Hill et al (2001b).

Methodology

Figure 2 is a flow diagram for performing an uncertainty analysis for an existing dam and risk reduction measures. The @Risk, risk analysis and simulation add-in for Microsoft Excel (Palisade Corporation 1996), was used to perform the uncertainty analysis runs. The risk analysis model, containing the flood, earthquake and static (Normal Operating Conditions) event trees, was prepared in Microsoft Excel. VBA macros, which were used to run the risk assessment model, were linked with @Risk such that the macros were executed after each sampling of input probability distributions and recalculation of the worksheets.

For performing the uncertainty analysis on the existing dam by itself, as shown on left side of Figure 2, random inputs were generated using the @Risk Latin Hypercube (LHC) sampling technique (Iman, Davenport, and Zeigler 1980). This technique is more efficient than Monte Carlo sampling in that it achieves a given level of precision with a smaller size sample. The random input was passed to the risk model for the existing dam through the input sheet. The risk model was run by the VBA macros linked with @Risk, and the output was transferred to the output and result summary sheets. For each realization and for each loading interval-failure mode-exposure scenario, represented by pathways through the event tree models, f-N-$ data (pathway probability of occurrence, incremental number of fatalities and incremental economic losses) were transferred from the output sheet and stored as f-N-$ output. Flood, earthquake, static, and total probabilities of failure, risk costs, expected incremental life loss etc., were calculated and stored as @Risk outputs for each LHC realization.

For performing an uncertainty analysis on the risk reduction alternatives, the existing dam and a risk reduction alternative were run simultaneously in a parallel construct, as depicted in Figure 2. For risk reduction alternatives, two additional outputs, benefit/cost ratio and cost-per-(statistical)life-saved, were calculated and stored as @Risk outputs. It was necessary to run the existing dam and risk reduction alternatives in parallel, so that all outputs for the existing dam and an alternative are calculated using the same randomly sampled input values. In this way estimates of risk reduction are not subject to differences due to “sample error” or variability between different sets of randomly generated realizations. Therefore the same random number generator seed and the same number of realizations was used for the uncertainty analyses conducted on all risk reduction alternatives. The number of iterations should be determined through trials to achieve the desired precision of key output variables that influence key decision variables.

Specifying uncertainty distributions

In order to perform uncertainty analysis, the uncertainty associated with the inputs must be specified using probability distributions. Strictly speaking, a joint probability distribution of all inputs is needed so that the correlation structure of the inputs is captured. However, in practice important cross correlations between inputs of different types and between different levels of inputs of the same type are preserved through specifying cross correlations as an option within @Risk. The uncertainty distributions may be specified in one of the following two ways, depending on the level of details required for the study.

For the first level of detail, simplified probability distributions using general forms such as those illustrated in Figure 3, may be used to represent uncertainties in the estimates of direct inputs to the risk analysis (e.g. flood and earthquake loading-AEP relationships, system response probability relationships, and consequences relationships). Probability inputs to risk analysis are typically obtained using procedures summarized by Fell et al (2000) and consequences inputs are estimated using procedures summarized by Hill et al (2001a). Often upper and lower bounds are estimated as well as best estimates. In such cases, a triangular distribution shown as a) or b) in Figure 3 can be used depending on whether the uncertainty distribution is considered symmetric or asymmetric around the best estimate value. In some cases, confidence limits instead of upper and lower bounds are estimated. For such cases a probability distribution such as that shown as c) in Figure 3 may be used. If the estimator cannot distinguish a more likely range of values, a uniform distribution between the upper and lower bounds may be an appropriate way to represent the uncertainty distribution as shown in d) in Figure 3.

For a detailed level of uncertainty analysis, the uncertainty distributions on the risk analysis inputs may be derived by taking into account the underlying input process uncertainties and performing Monte-Carlo type simulations to derive estimates of the uncertainty distributions on the direct risk analysis inputs. Our current research is developing procedures for this more detailed level of uncertainty analysis approaches. However, in the work described in this paper we used the first approach based on assigning simplified distributions to the direct risk analysis inputs.

Uncertainty distributions were specified for flood and earthquake loading and for various failure mode system response inputs. The distributions used on some of the inputs are shown in Figures 4, 5, and 6 for the following cases:

- Peak outflow – AEP (Figure 4a)
- Peak ground acceleration (PGA) – AEP relationship for various earthquake magnitude ranges, as shown in Figure 4b was used. The upper and lower uncertainty bounds were set equal to the PGA multiplied by a factor ___, which was assigned a triangular distribution having 0.5 as its minimum value, 1.0 as its mode, and 2.0 as its maximum value.
- Flood overtopping failure system response – overtopping depth (Figure 5)
- Incremental economic losses – peak outflow rate (Figure 6a)

- Fatality rate (life loss/population at risk)– warning time (Figure 6b). The data used by DeKay and McClelland (1993) to develop their equation for estimating loss of life including various percentiles based on best estimates and 95 percent confidence limits estimated for the high force case by Dr. Mike DeKay (1997) and presented in Australian National Committee on Large Dams (1998b) were used to develop these uncertainty distributions. It was considered that population at risk can be estimated with high confidence, but warning time can be quite uncertain. Therefore, uncertainty associated with warning time was represented using a triangular distribution with the maximum at the upper bound, the mode at the best estimate, and the minimum at the lower bound of the warning time estimates.

In this work, we specified perfect correlations between different levels of inputs of the same type. For example, the three triangular distributions shown in Figure 5 were perfectly correlated so that the percentiles in each of the three distributions were identical. We did not specify any cross correlations between inputs of different types.

UNCERTAINTY ANALYSIS RESULTS

The results of uncertainty analyses can be presented as probability distributions of risk analysis results (i.e. estimates of failure probabilities and levels of consequences). More importantly, uncertainty analysis results can be displayed as levels of confidence in meeting various tolerable risk guidelines [USBR (1997), and ANCOLD (1994 and 1998a)] or strength of justifications measures to proceed with remedial works [e.g. ALARP (as low as reasonably practical), benefit/cost ratios, and cost per statistical life saved] as an aid for dam safety decision-making. For a discussion of the use of risk information and risk evaluation in dam safety decision-making see Bowles (2001).

Examples of results from the risk analysis and risk assessment steps are presented graphically for the following cases:

- Distribution of probability of failure estimates for existing dam and risk reduction measure (Figure 7a)
- Distribution of incremental risk cost estimates for existing dam and risk reduction measure (Figure 7b)
- Distribution of F-N relationships for existing dam (Figure 8a)
- Confidence in meeting the ANCOLD (1998a) interim objective life safety guideline for existing dam and risk reduction measure as a function of incremental life loss (N) (Figure 8b)

SUMMARY AND CONCLUSIONS

Uncertainty analysis can provide estimates of uncertainty distributions for selected risk analysis outputs such as probability of failure, annualized incremental life loss, risk cost, etc. This is very useful additional information compared with using only best estimate inputs or sensitivity analyses. Best estimate inputs, even though they represent the best judgment of experienced dam engineering professionals, provide just a single point on the spectrum of possible outcomes and will not in general corresponds to the best estimate of the output variables. Sensitivity analysis takes a step further and provides the range around the best estimate results, but it has a severe limitation in that it cannot provide the measure of confidence in the results that are obtained from best estimate inputs or the variability that exist about those results.

Bowles (2001) states that “The risk assessment framework can be used to capture the judgments of dam engineering professionals, and providing that information to decision makers along with information from other sources, in the form of a business case for addressing dam safety issues”. The use of uncertainty analysis provides an enhanced way to present the outcomes of risk assessment to decision makers by carrying forward through the process representations of the level of uncertainty in risk analysis inputs and hence the level of confidence in risk assessment outcomes.

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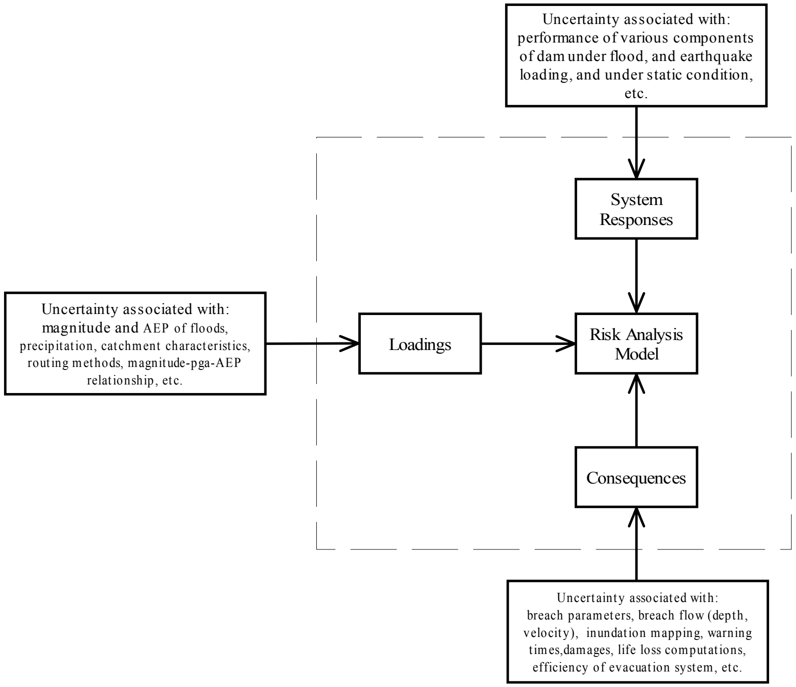

Figure 1. Uncertainty associated with direct risk analysis inputs.

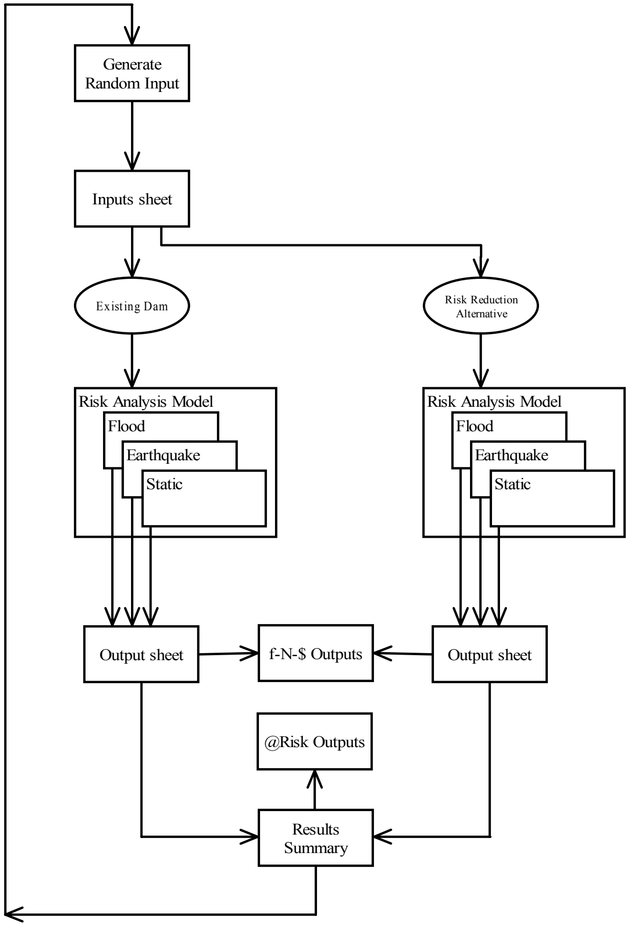

Figure 2. Uncertainty analysis flow chart for existing dam and a risk reduction alternative.

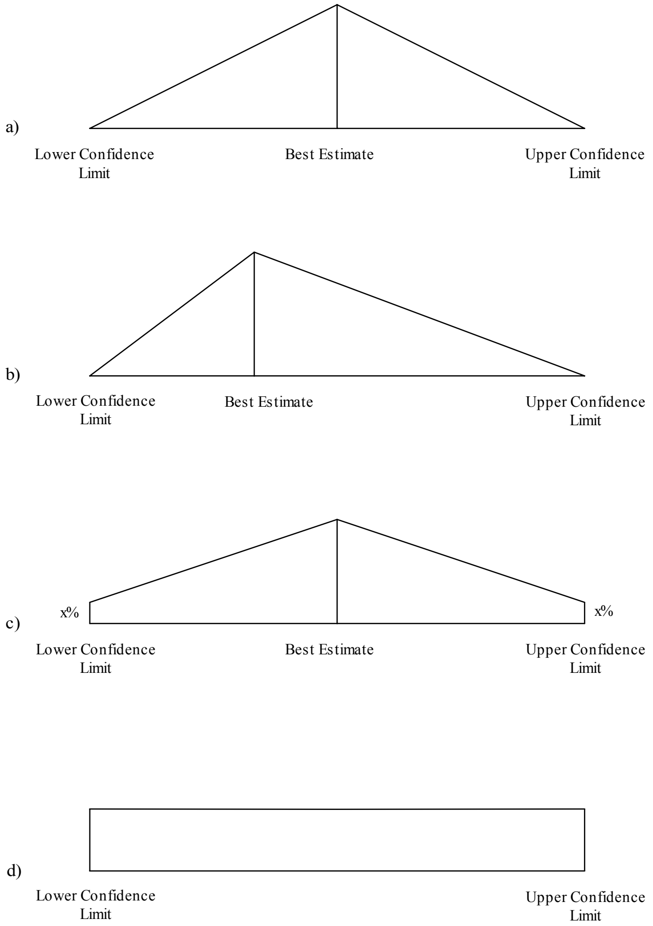

Figure 3 Some typical simplified uncertainty input distributions.

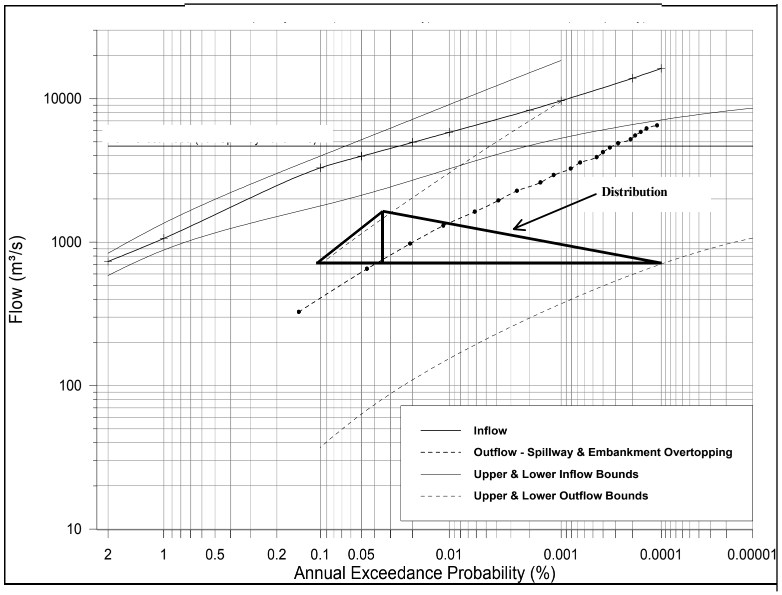

Figure 4a Uncertainty input distribution on flood loading (peak reservoir outflow).

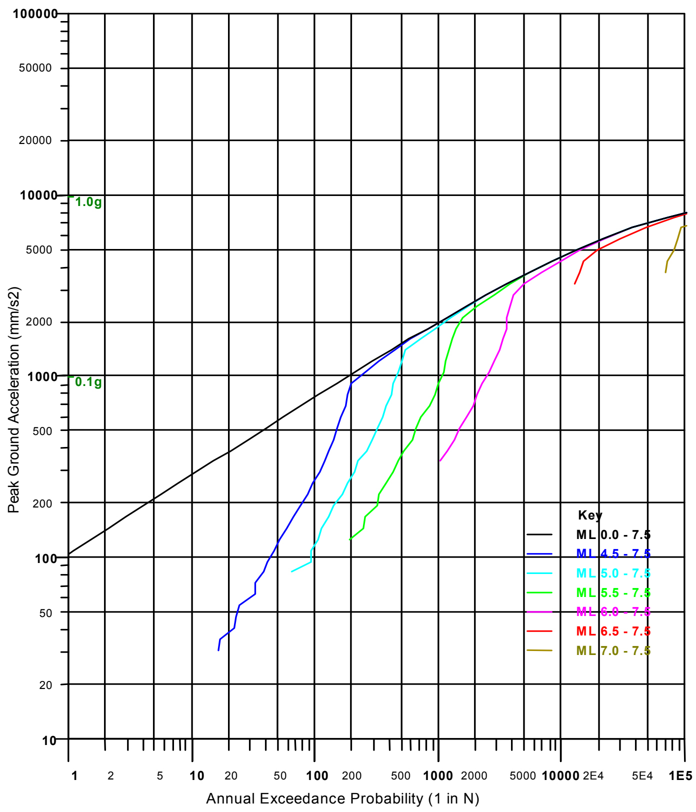

Figure 4b Uncertainty input distribution on earthquake loading.

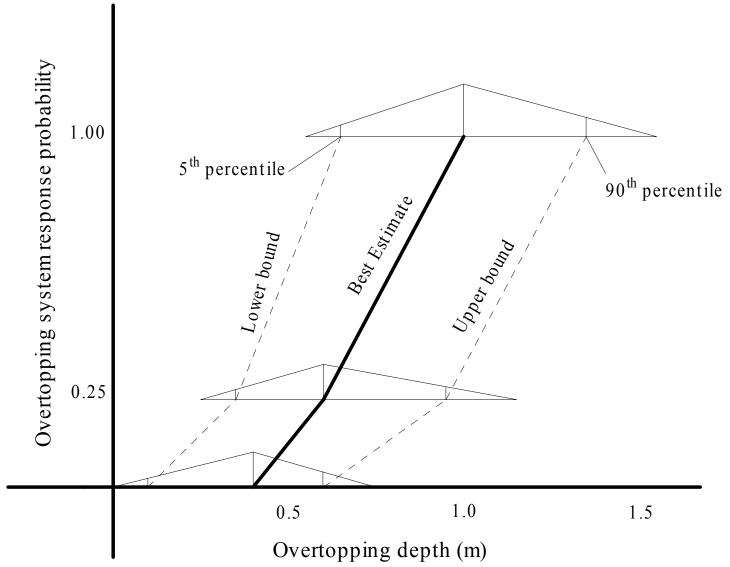

Figure 5 Uncertainty input distribution on flood overtopping failure system response.

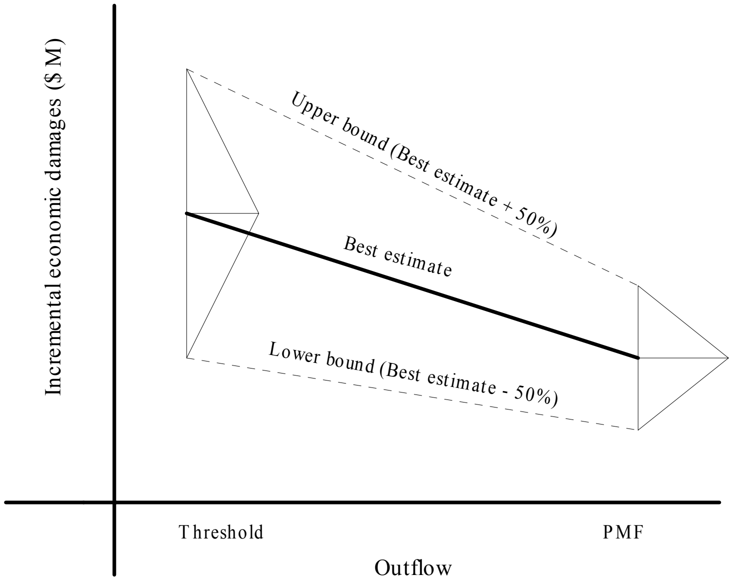

Figure 6a Uncertainty input distributions for economic losses.

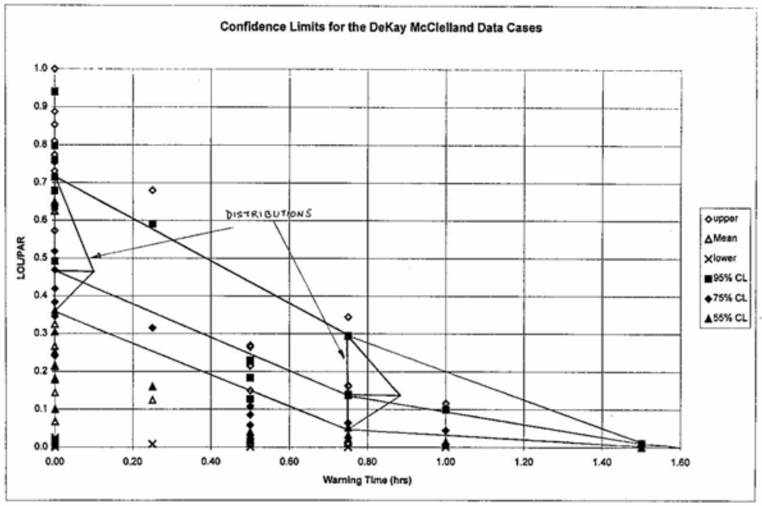

Figure 6b Uncertainty input distributions for fatality rate.

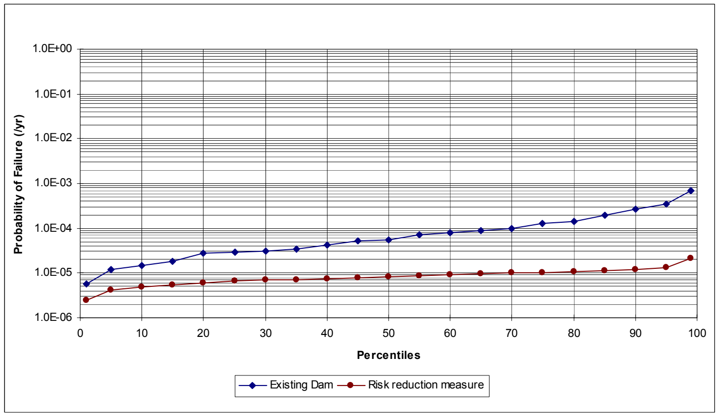

Figure 7a Distribution of probability of failure estimates for existing dam and a risk reduction alternative.

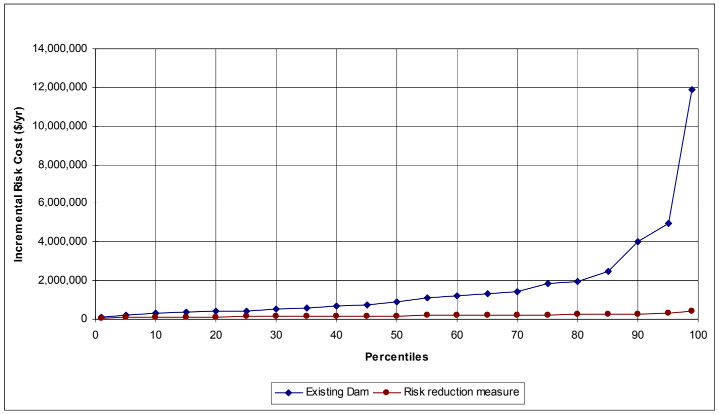

Figure 7b Distribution of incremental risk cost estimates for existing dam and a risk reduction alternative.

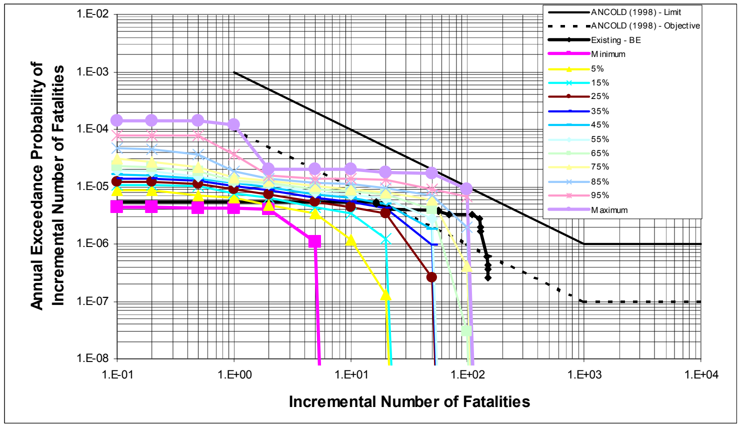

Figure 8a Distribution of F-N relationships for existing dam.

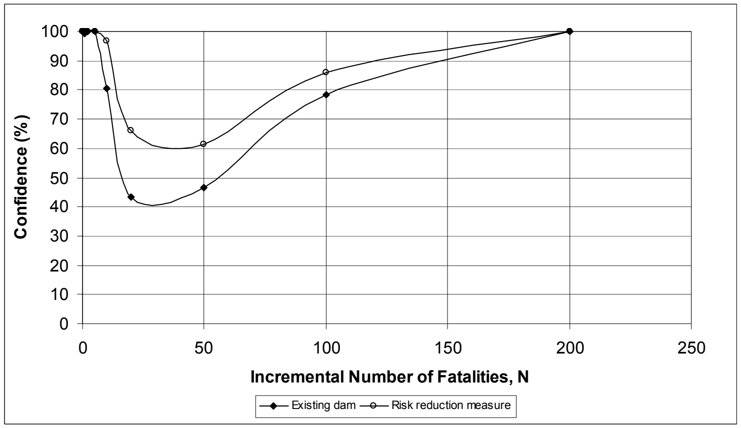

Figure 8b Confidence in meeting ANCOLD (1998a) interim objective life safety guideline for existing dam and a risk reduction alternative.

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