A COMPUTATIONAL FRAMEWORK FOR DAM SAFETY RISK ASSESSMENT

WITH UNCERTAINTY ANALYSIS

by

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ABSTRACT

A Computational Framework for Dam Safety Risk Assessment with Uncertainty Analysis

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The growing application of risk analysis in dam safety, especially for the owners of large numbers of dams (e.g., U.S. Army Corps of Engineers), has motivated the development of a new tool (DAMRAE) for event tree based dam safety risk analysis. Various theoretical challenges were overcome in formulating the computational framework of DAMRAE and several new computational concepts were introduced. The concepts of Connectivity and Pedigree matrices are proposed to quantify the user-drawn event tree structures with proper accounting of interdependencies among the event tree branches. A generic calculation of Common-Cause Adjustment for the non-mutually exclusive failure modes is implemented along with introducing the new concepts of system response probability and consequence freezing. New output presentation formats such as cumulative risk estimate vs. initiating variable plots to analyze the increase of an incremental (annualized) risk estimate as a function of initiating variable are introduced. An additional consideration is given to the non-breach risk estimates in the risk modeling
and new output formats such as non-breach F-N and F-$ charts are included as risk analysis outputs.

DAMRAE, a Visual Basic.NET based framework, provides a convenient platform to structure the risk assessment of a dam in its existing state and for alternatives or various stages of implementing a risk reduction plan. The second chapter of the dissertation presents the architectural framework of DAMRAE and describes the underlying theoretical and computational logic employed in the software. An example risk assessment is presented in the third chapter to demonstrate the DAMRAE functionalities.

In the fourth chapter, the DAMRAE framework is extended into DAMRAE-U to incorporate uncertainty analysis functionality. Various aspects and requirements reviewed for uncertainty analysis in the context of dam safety risk assessment and theoretical challenges overcome to develop the computational framework for DAMRAE-U are described in this chapter. The capabilities of DAMRAE-U are illustrated in the fifth chapter, which contains an example dam safety risk assessment with uncertainty analysis. The dissertation concludes with a summary of DAMRAE features and recommendations for further work in the sixth chapter.

(157 pages)
PUBLIC ABSTRACT

A Computational Framework for Dam Safety Risk Assessment with Uncertainty Analysis

by

Anurag Srivastava, Doctor of Philosophy

Event tree analysis is a commonly-used method in dam safety risk analysis. Event trees are used to obtain quantitative estimates of the probability of dam failure and its associated consequences. This can be done to evaluate the safety of an existing dam or to provide insights into the choice between risk reduction alternatives. In the past, the calculations have been performed using either generalized software developed primarily for business applications or purpose-built spreadsheets. However, these approaches lack generality, can require substantial effort, can be fragile, and are difficult to modify to represent risk reduction measures or to update using new information from investigations. These limitations can lead to using event tree structures that do not properly represent the failure modes and poor numerical precision in risk estimates. To overcome these limitations, the US Army Corps of Engineers (USACE) sponsored the development of a computational framework for efficient, flexible and generalized event tree analysis called DAMRAE (DAM safety Risk Analysis Engine). DAMRAE is now being used by the USACE and the Tennessee Valley Authority (TVA) while continued development takes place at Utah State University.

The supporting research and development of DAMRAE was carried in two stages. First, a deterministic (or non-stochastic) version was formulated and developed and then,
uncertainty analysis functionality was formulated and included. DAMRAE includes a graphical user interface (GUI) for developing and populating event tree inputs and functionalities for calculating and post-processing results. It provides estimates of the probabilities of various failure modes and their associated consequences for an existing dam. The post-processing step allows the user to combine results for various loading types (e.g. flood and earthquake) and to make comparisons against USACE tolerable risk guidelines. It can be applied to analyze structural and non-structural risk reduction measures, considered as alternatives or staged measures, including obtaining estimates of the risk reduction and the cost effectiveness of risk reduction.

Various theoretical challenges were overcome in formulating the computational framework of DAMRAE and new computational concepts were introduced. These include: Connectivity and Pedigree matrices to quantify the user-drawn event tree structures; Common-Cause Adjustment for the non-mutually exclusive failure modes along with the new concepts of system response probability and consequences freezing; and separation of uncertainties in logic and event trees. Several new output presentation formats including the tolerable risk evaluation under uncertainty were introduced as risk analysis outputs.

The developed computational framework was extensively verified using several risk analyses performed by USACE and by Dr. David S. Bowles and his group.
Dedicated to all DAMRAE users...
ACKNOWLEDGMENTS

I express my sincere gratitude to my major advisor, Dr. David S. Bowles, for his valuable advice, patience, constant support and encouragement throughout my graduate studies. It was an honor to be his student and to have an opportunity to work under his able guidance. He is truly an exceptional mentor and certainly, one of the best persons to work with.

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I am grateful to my dissertation committee members, Drs. James Bay, Arthur Caplan, Terry Glover, Mac McKee, and John Rice, for their interest and involvement. I especially thank Dr. Glover for his kind review and sincere comments on my proposal document.

I would like to acknowledge the support of the U.S. Army Corps of Engineers and the Utah Water Research Laboratory at Utah State University in funding the research and development work on DAMRAE. I also thank the DAMRAE users in the U. S. Army Corps of Engineers and the Tennessee Valley Authority for their invaluable suggestions towards the improvement of DAMRAE.

Anurag Srivastava
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CHAPTER 1
INTRODUCTION

1. Risk analysis in dam safety

In the context of dam safety, risk analysis integrates the scientific and dam engineering principles, the experience and judgment of dam safety professionals, with probability theory and mathematical statistics to obtain qualitative insights and quantitative estimates of the risk of dam failure. These outcomes can be obtained for a dam in its existing condition and for a range of risk reduction alternatives to explore equitable, efficient and reasonably practical resource allocations for structural safety, and operational and emergency planning to improve the safety of persons, property and the environment that are at risk from dam failure. Risk analysis, which involves both the risk identification and risk estimation, is embedded within a structured framework of dam safety risk assessment and risk management [1, 2].

The process of dam safety risk analysis is commenced with a defined scope and context for the risk assessment. A well-defined scope helps in setting the level of sophistication and rigor in the analysis efforts to optimize the use of the available study resources (e.g., human skills, time, and technical capabilities) and to achieve adequate outputs for the decision making purpose. The scope and context of risk analysis must originate mainly with the decision-maker(s), including various stakeholders in the decision process; although it is often necessary for the risk analysts to be involved to ensure that this critical initial step is clearly and thoroughly completed. Outcomes from this initial step should include a list of all types of outputs that will be needed as inputs to the decision processes that will be informed by the risk assessment, and a list of all life
safety tolerable risk guidelines and other types of criteria or guidelines against which risk estimates will be evaluated. An understanding of the context will also help to identify who the decision makers are and the extent to which other stakeholders are to be included. Stakeholders can include a dam safety regulator, an economic regulator, cost-share partners, water users, environmental groups, and downstream (and sometimes upstream) populations at risk.

Based on the identified purpose and context for the analysis, event tree forms of risk models are set up to delineate the “source-pathway-receptor” scenarios of the analysis, and the quantification efforts are put forth to obtain inputs and risk estimates. In the deterministic form of the analysis, knowledge uncertainties associated with various events are either ignored and reasonable best estimates, as judged by subject matter experts, are used to assign the inputs, or a deliberately conservative position may be taken in estimating inputs in the case of a screening risk assessment, for example. An uncertainty analysis approach can be used in risk analysis to explicitly characterize the knowledge uncertainties in the event tree model inputs and to obtain the uncertainty distributions of the risk estimates. “Uncertainty analysis provides an enhanced way to present the outcomes of risk assessment to decision makers by including estimates of the level of confidence in risk assessment outcomes based on uncertainty in risk analysis inputs” [3].

Risk estimates obtained for the baseline analysis of the dam in its existing condition are evaluated against tolerable risk and other guidelines as part of the process of formulating decision recommendations regarding the following:

a) The need to conduct further investigations to better understand and reduce
uncertainties about apparently significant dam safety issues;

b) To explore, or not to explore, risk reduction options; or

c) To strengthen various aspects of on-going dam safety management activities.

When uncertainty analyses are conducted the evaluation against tolerable risk limit guidelines is changed from a relatively straightforward assessment as to whether risk estimates are above or below limit guidelines to an assessment of the degree of confidence that the estimated risk is above or below a limit guideline. Such evaluations should also consider the limitations in the analysis and the extent to which any key variables were not included in the analysis.

Tolerable risk guidelines (TRG) for dam safety have been developed by various organizations. Typically, in countries with a common law legal system, these guidelines follow a two-part evaluation process as established by the UK Health and Safety Executive [4]. The first part compares total estimated risk for all failure modes against the tolerable risk limits for Individual Risk (IR) expressed as a probability of life loss for the identifiable person(s) most at risk and for Societal Risk (SR) expressed as a limit of tolerability line on a cumulative probability distribution (F-N chart) of exceeding various magnitudes of (random) life loss as a measure of life-safety risk. Variations of TRGs used for dam safety also consider tolerable risk limits for Annual Probability of Failure (APF) as a measure of the performance of the dam and Annualized Life Loss (ALL) as the average magnitude of life loss from the probability distribution of life loss for Societal Risk.

The second part of the risk evaluation process is a determination of whether risks have been reduced to be as low as reasonably practicable (ALARP). To conduct an
ALARP evaluation requires that practical options for reducing the risk through structural and non-structural means are identified and evaluated. This evaluation is both qualitative and quantitative in nature and typically, it should take the following into account [5]:

a) The level of risk in relation to the tolerable risk limits,

b) The disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk-reduction measures and the subsequent risk reduction achieved,

c) The cost-effectiveness of the risk-reduction measures,

d) Compliance with established good dam safety practice, and

e) Societal concerns as revealed by consultation with the community and other stakeholders.

The consideration of the cost effectiveness or “disproportionality” associated with the cost of achieving life-safety risk reduction relative to the life-safety benefit achieved is a quantitative aspect of an ALARP evaluation. This introduces the consideration of cost, but only to justify further incremental risk reduction below the tolerable risk limits, and not to justify achieving those limits in the first place. Hence, there is normally no consideration of “balancing” the economic impacts of operating restrictions and reductions in life-safety risk in meeting the tolerable risk limits.

In a risk reduction analysis, the entire risk and uncertainty analysis is reiterated, with changed values of event tree branch variables and their uncertainty specifications to represent a proposed risk reduction plan, and possibly with a modified event tree structure if needed to represent the risk reduction measures. Some types of uncertainties about the dam system performance may be significantly reduced or perhaps eliminated by
engineering out certain failure modes in conjunction with the opportunity to exercise a high level of quality control during construction of a risk reduction measure and also with the possibility of more fully exploring foundation conditions during the remedial construction process. The residual risk estimates are then evaluated against the tolerable risk limit guidelines and other guidelines and a level-2 TRG evaluation is conducted considering the degree to which ALARP consideration are satisfied. Based on these evaluations and the engineering and other understandings that are typically strengthened through the risk and uncertainty analysis process, decision recommendations are made by the risk analysis team, together with the supporting case for these recommendations, and passed onto decision makers.

In preparation for conducting an uncertainty analysis, it is useful to perform sensitivity analyses on a preliminary deterministic event tree model as part of the process of selecting which input variables to treat as uncertain variables and which are appropriately considered as deterministic variables. Where there is little sensitivity of all key decision (output) variables to changing an input variable across the entire range of uncertainty associated with its magnitude, then that variable can be treated as a deterministic variable although interactions with other variables should be carefully considered. By minimizing the number of variables that are treated as uncertainty variables the computational time needed to complete uncertainty analyses can be kept to a minimum.

It may also be valuable to perform uncertainty reduction analyses to explore the potential value of conducting investigations that are designed to better understand existing conditions or key parameters that affect apparently significant dam safety issues.
2. Research objectives

The objectives of this dissertation work are outlined in Figure 1.1. The dissertation work is oriented to provide a comprehensive analytical tool to efficiently address the practical aspects of risk analysis specific to dam safety. The surging acceptance of formal risk analysis in dam safety and the emerging requirements of portfolio risk assessment from the owners of many dams, such as the US Army Corps of Engineers (USACE), have motivated the development of this new software for event tree based dam safety risk assessment - first, to overcome the limitations of commercial riskwares, and second, to serve the requirements of a database-compatible computational core engine in a portfolio risk assessment and management system.

DAMRAE is developed using the Visual Basic.NET environment. In addition to

![Figure 1.1. Research objectives](image)
the very significant challenges of designing and programming the DAMRAE software for
dam safety risk assessment, some significant conceptual issues were addressed which
represent specific contributions of this work, as follows-

a) Refinements to the evolving risk analysis modeling framework were made to
develop a generic tool that is suited to dam safety risk analysis.

b) The concepts of Connectivity and Pedigree matrices are introduced to
quantify the user drawn event tree structures with proper accounting of
interdependencies among the event tree branches.

c) System response probability (SRP) and consequence freezing concepts are
introduced along with a generic implementation of the Common-Cause
Adjustment (CCA) for the non-mutually exclusive failure modes.

d) Non-breach risk estimates are included as standard risk analysis outputs.

e) New output presentation formats, e.g. cumulative risk estimate vs. initiating
variable plots are introduced.

f) Monte Carlo simulation based generic computational logic for uncertainty
separation is introduced with the consideration of correlations among
uncertain variables.

g) Computational logic of uncertainty analysis for risk reduction measures is
implemented.

h) New output presentation formats incorporating uncertainty are introduced
for the tolerable risk guidelines evaluations.

The research work was pursued in two stages. In the first stage, a review of dam
safety risk analysis literature was completed to investigate and formulate the conceptual
design for DAMRAE in a deterministic mode, that is, without uncertainty analysis. The formulated conceptual design was implemented to develop DAMRAE as a GUI-based user-friendly computational tool. The results from several existing risk analysis studies, which were performed using spreadsheet calculations, were replicated to verify the DAMRAE software. Several hypothetical risk models were set up to demonstrate the application capabilities of the new DAMRAE software. Based on the work of the first stage, the following two research papers were prepared and included in this dissertation as Chapters 2 and 3, respectively: 1) DAMRAE - A Computational Framework for Event Tree Based Dam Safety Risk Analysis; and 2) DAMRAE - Application for an Example Dam Safety Risk Assessment.

In the second stage, the DAMRAE framework was extended to incorporate uncertainty analysis. A literature review of uncertainty analysis and Monte Carlo simulation were performed to understand the state of the art. A generic conceptual framework for uncertainty analysis for dam safety risk analysis was proposed and implemented in the DAMRAE-U software. Based on the work of the second stage, the following two research papers were prepared and included in this dissertation as Chapters 4 and 5, respectively: 1) Uncertainty in Dam Safety Risk Assessment: Theoretical Concepts and A Developed Framework with the description of the conceptual and computational concepts of DAMRAE-U; and 2) DAMRAE-U Application for an Example Dam Safety Risk Assessment with Uncertainty Analysis as an illustrative example of risk assessment with uncertainty analysis.
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CHAPTER 2

DAMRAE: A COMPUTATION FRAMEWORK FOR EVENT TREE BASED DAM SAFETY RISK ANALYSIS

ABSTRACT

Although several risk analysis tools are available commercially, there is still a lack of generic software that can efficiently address the specific requirements of dam safety risk analysis. The surging acceptance of formal risk analysis in dam safety and the emerging requirements of portfolio risk assessment from the owners of large numbers of dam (e.g., USACE) have motivated the development of a new software for event tree based dam safety risk analysis, which can overcome the limitations of commercial riskwares and can serve as a database-compatible computational core engine in dam safety portfolio risk assessment and management systems. This paper presents the architectural framework of this new software and describes the underlying theoretical and computational logic employed in the software.

1. Introduction

The long-established science of risk analysis has been adapted for application in the field of dam safety management. In the context of dam safety, risk analysis integrates the scientific and dam engineering principles, the experience and judgment of dam safety professionals, and probability theory and mathematical statistics to obtain qualitative insights and quantitative estimates of the risk of dam failure. These outcomes can be obtained for a dam in its existing condition and for a range of risk-reduction alternatives to explore equitable, efficient and reasonably-practicable resource allocations for
structural safety, and operational and emergency planning to improve the safety of people, property and the environment that are at risk from dam failure. Risk analysis, which includes both risk identification and risk estimation, and risk evaluation comprise risk assessment, which can be embedded within a structured framework for dam safety risk management [1, 2]. Risk Assessment (RA) of individual dams can be incorporated in a systematic approach of Portfolio Risk Assessment (PRA) to serve as a decision-support tool for Portfolio Risk Management (PRM) to provide an improved management scheme for the owner’s entire dam safety management program [3]. RA combined with traditional engineering standards evaluations forms a risk-informed approach [4]. The accumulated experience of almost three decades of experience with applying risk analysis to dam safety problems have guided the evolutionary process from single dam RA to PRA to the integrated PRM framework with risk analysis at the core of the framework.

Along with theoretical advances, developments in computer-aided technical resources and computational methods have contributed to incorporating PRM at the enterprise level. Various dam owners and agencies are now seeking computer-supported risk assessment and management tools. These tools help to architect a comprehensive Management Information System (MIS) to fulfill the organizational requirements of analysis, notification, updates, reports and planning dam safety activities among engineers and decision-makers [3, 5]. ResRisk, a portfolio risk management tool developed by Utah State University and RAC Engineers & Economists for a large UK dam owner [6], and PAMS (Performance-based Asset Management System) developed for the Department for Environment Food and Rural Affairs (Defra) and Environmental Agency [7] for flood risk management in the UK are prime examples of such endeavors.
There are numerous commercially-available riskwares that could provide risk analysis engine functionality to these management systems [8], but generally, these proprietary riskwares are developed for business applications and lack the features needed for dam safety applications, with the result that substantial effort is required to apply them to dam safety risk assessments. Some of the drawbacks of these riskwares, in context of dam safety risk analysis, are as follows:

i. **Inefficient modeling features**: Event trees are the most commonly used risk models in dam safety risk assessment [1]. Most software tools provide user-friendly features to construct event tree diagrams; however they lack the convenience of including continuous initiating events such as needed to represent flood and earthquake loading as annual exceedance probability distributions. To achieve numerical precision in risk estimates numerous identical event trees must be constructed to cover a wide range of loading values and this is a tedious and highly repetitive task. In addition, the resulting event tree diagrams can be difficult to readily understand and cumbersome to modify, which can discourage making changes that are needed to adequately represent failure modes or for addressing a full range of sensitivity cases in a risk assessment.

ii. **Inadequate calculation options**: Most of these tools lack the capability to readily assign branch probabilities and consequences to the numerous event tree branches and for considering the interdependencies among the variables in the event tree. Also, variable step size, which is desirable for continuous events to achieve numerical precision, and a common-cause adjustment [9,
to properly treat non-mutually exclusive events are not available options in these software.¹

iii. **Insufficient analysis outputs**: Typically, output from these riskwares is available only as expected values or annualized estimates of risks, with poor flexibility to obtain breakdowns of total risk estimates by failure modes or exposure scenarios, for example. There is also often no straightforward way to track and obtain probability-consequence pairs with their associated state values to prepare graphical displays for the evaluation of tolerable risk guidelines, such as those used by ANCOLD [11], NSW DSC [12], Reclamation [13], and USACE [14].

iv. **Incompatibility with custom database**: The input-output format of these riskwares is not designed in a compatible configuration to link with a specific custom database or to serve as a core engine in a dam safety portfolio management information system. Other requirements such as the model-reusability (i.e., the reuse of the same event tree model structure or input modifications for risk reduction measures and sensitivity studies), model scalability (i.e., developing a more-detailed model from a less-detailed preliminary model), automated batch processing (e.g., for long dams, uncertainty analysis applications, or automated model verification) and

¹ The common cause adjustment (CCA) is an approach to adjust the conditional probabilities for the failure modes that are not mutually exclusive. The non-mutually exclusive failure modes, also referred as common cause failure modes, are failure modes that can occur simultaneously at a single dam section or at multiple sections of a dam due to a single initiating event. In the context of dam risk analysis, either the uni-modal bounds theorem or the physical dominance approach is used for the CCA. The reader is referred to Section 3.2 and Bowles et al. [9] for a detailed description on the CCA.
obtaining risk reduction estimates are at best awkward and in many cases infeasible in the available riskwares. To attempt to adapt existing riskwares is thwarted with problems of software incompatibility or requirements for necessary software modifications and adjustments, which brings in additional complexity of computer coding, source code availability, programming environment compatibility, etc.

Therefore, although most of the riskwares offer the flexibility needed for applications of risk analysis in some fields [8], they have severe limitations for application to dam safety risk analysis. These limitations have led to using oversimplified risk model structures and to obtaining poor numerical precision in risk estimates. To overcome these limitations, the USACE has sponsored our development of a generic risk analysis tool – DAMRAE (DAM safety Risk Analysis Engine). The DAMRAE concept is founded on a generalized event tree analysis algorithm and its overall design is formulated to serve the requirements of dam safety risk assessment and risk management.

This paper presents the architecture of the DAMRAE framework including the underlying computational algorithm for the event tree analysis. Brief introductions of dam risk analysis and event tree analysis are included in subsections 1.1 and 1.2, respectively. The overall DAMRAE framework, associated generalized event tree algorithm, and framework outputs are described in sections 2, 3 and 4, respectively. A summary of the unique contributions of this work are presented in section 5 and section 6 contains some concluding remarks.
1.1. Dam safety risk analysis

The process of dam risk analysis should always commence with a defined scope and identified context for the risk assessment. A well-defined scope is important in setting an appropriate level of sophistication and rigor for the analysis effort and to achieve the desired outputs for use in supporting the identified decision-making purposes.

The risk analysis process includes risk identification including identification of the dam system scope, loading types, failure modes, exposure scenarios and consequences, risk model development, and risk model quantification. The risk analysis is initially conducted on the current baseline or existing condition of the dam system and can be used to evaluate risk reduction measures that can be structural (e.g., raise dam crest elevation, increase spillway capacity, or add a stability berm and filter) or non-structural (e.g., increase warning time, enhance evacuation planning, or implement a reservoir operating restriction) in nature. Individual risk reduction measures are combined into risk reduction plans and evaluated as alternatives or for staged implementation. On the other hand, each risk analysis performed for a baseline or a risk reduction state can be updated with improved inputs based on completing investigations or analyses that are designed to reduce the knowledge uncertainty in the inputs and hence to justify greater confidence in the risks assessment outcomes.

Initially, a more simplified risk analysis may be performed for a screening purpose, such as when initiating a portfolio risk management (PRM) program for a group of dams belonging to the same owner. One of the purposes of PRM is usually to develop and maintain a defensible basis for iteratively improving risk and uncertainty reduction pathways to efficiently allocate limited resources [15]. Though there is a tendency to
adopt a simple and unified risk analysis model structure in support of an initial portfolio risk assessment, it is important to realize the limitations of such an approach and to scale up the model to a more detailed model structure if needed to achieve adequate confidence in risk estimates to support final risk reduction alternatives selection or other detailed design choices. The portfolio risk assessment approach can be incorporated in a portfolio risk management information system as a decision-support tool [3]. Such a system can be centered on a database with other inputs, modeling, and reporting tools to collectively form a systematic and streamlined means of supporting dam safety management decisions for an entire portfolio of dams. The risk analysis engine is an essential component of such a system and can be run to support the evaluation of management options.

1.2. Event tree analysis (ETA)

Dam risk analysis is commonly based on event tree models for qualitative representation and quantitative assessment of the safety of the dam-reservoir system and to associate consequences with system performance. In general, an event tree is a graphical and mathematical model that is used to represent cause-and-effect (or event-outcome-consequence) relationships in a complex system, where, often, but not necessarily, relationships are arranged in a temporal sequence. Branch levels in the event tree can represent combinations of quantifiable intermediate events, such as the dynamic response of a dam-foundation system to an earthquake including the effects of liquefaction as modeled using FLAC [16] or a similar model.

The events forming the first level or the beginning of an event tree are referred to as Initiating Events. Each event in an event tree is represented by a branch dividing
further into as many branches as outcomes in the corresponding event-outcome space [17]. In the context of dam safety, initiating events are usually some type of annual peak loading event. For example for floods attributes such as peak annual inflow or peak annual reservoir pool elevation vs. annual exceedance probability (AEP) are often used. For seismic events the earthquake loading may be characterized as peak (annual) ground acceleration (PGA) vs. AEP either disaggregated over earthquake magnitude ranges or totaled over all magnitude ranges depending on whether magnitude in addition to PGA needs to be considered to characterize system performance.

The specific attributes of the initiating or loading events should be determined based on those needed to represent the likelihood of different dam system failure modes occurring over the entire range of loading variables. The failure modes leading to a dam breach outcome may be represented by one or more levels of branches following the initiating event branches. The event tree may be extended to represent consequences, including economic and life loss at remote locations from the dam due to dam break flooding.

The inputs to event tree branches are estimated from a combination of many sources of evidence including the following: available site-specific historical data (such as for flood or earthquake frequency curves); traditional and customized structural and other reliability analysis methods for structural (system) response probabilities; statistical, semi-empirical and simulation models (e.g. for estimation of dam failure consequences [17]); and expert elicitation based on professional knowledge, experience and judgment [18].

ETA is a well-established modeling approach in risk analysis systems. In any
field, the probability assignments and quantification involved in ETA follows the general concept of probability theory; however, the design or layout of event tree structure is site- and problem- specific. A conceptual article by Papazoglou [19] describes the mathematical foundation of event trees and proposes automated algorithms for event tree construction and some general simplifications. Many examples exist of event trees for dam safety risk analysis applications [15, 20-23].

Dams are complex systems that are located in unique settings. While some failure modes, such as failure induced by overtopping during a very extreme flood, are common to many dams, others are a unique result of the design and construction details and their relationship to the geological setting. Therefore event tree construction cannot be generalized or automated but must be the result of the analyst capturing the essential characteristics of system performance in relation to the external loading events or internal flaws that may exist in the structure. The initial conceptualization of an event tree is a result of the understanding, experience and knowledge of the analyst, or the team that is involved in the risk assessment, and should be tailored for the scope and context in which the risk assessment is conducted.

Event tree analysis can be divided into the following phases: i) construction, ii) quantification, and iii) post-processing and reporting. This paper describes a generalized systematic approach to support these three phases of ETA in the context of dam safety risk assessment.

1.3. USACE tolerable risk guidelines

The USACE tolerable risk guidelines [14] are incorporated in DAMRAE to evaluate the significance of the estimated risks for the Baseline case and for risk reduction.
measures. These guidelines include a two-part evaluation process. In the first part the total estimated risk for all failure modes is compared against the following USACE tolerable risk “limit values”:

a) An Annual Probability of Failure (APF) limit value of 1 in 10,000 /year as a measure of the performance of the dam (see the horizontal limit line at 1 in 10,000 /year on Figure 2.1).

b) An Individual Risk (IR) limit value 1 in 10,000 /year as a measure of life-safety risk expressed as the probability of life loss for the identifiable person(s) most at risk (see the point at 1 in 10,000 /year on Figure 2.2).

c) A Societal Risk (SR) expressed as a limit of tolerability on a cumulative probability distribution (F-N chart) of exceeding various magnitudes of life loss as a measure of life-safety risk to non-identifiable or random persons (see the

**Figure 2.1.** $f$-$\bar{N}$ charts showing USACE APF and ALL tolerable risk limit guidelines (where $\bar{N}$ = weighted average annual life loss estimated as ALL/APF)
d) An Annualized Life Loss (ALL) of 0.001 lives/year as the average magnitude of life loss from the probability distribution of life loss in 3) as an average measure of societal life-safety risk (see the sloping limit line at 0.001 lives/year on Figure 2.1).

The second part of the risk evaluation process is a determination of whether risks have been reduced to be as low as reasonably practicable (ALARP). This evaluation is both qualitative and quantitative in nature and should take the following into account: the level of risk in relation to the tolerable risk limits; the disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved; the cost-effectiveness of the risk reduction measures;
compliance with essential USACE guidelines; and societal concerns as revealed by consultation with the community and other stakeholders.

The consideration of the cost effectiveness or “disproportionality” associated with the cost of achieving life-safety risk reduction relative to the life-safety benefit achieved is a quantitative aspect of an ALARP evaluation and is included in DAMRAE. This introduces the consideration of cost, but only to justify further incremental risk reduction below the tolerable risk limits, and not to justify achieving those limits in the first place. Hence, there should be no consideration of “balancing” the economic impacts of operating restrictions and reductions in life-safety risk in meeting the tolerable risk limits.

2. DAMRAE framework

DAMRAE is a graphical user interface (GUI) based analytical framework for dam safety risk analysis. Figure 2.4 shows the main interface of DAMRAE. The analytical

![Figure 2.4. DAMRAE main interface](image)
architecture includes the following three objects, i) DAMRAE Project, ii) Run Case, and iii) Event Tree (ET), arranged in a tiered system as shown in Figure 2.5.

A DAMRAE project is a risk analysis project for a single dam and it comprises one or more run cases. A run case represents a safety state of a dam and the scope of the run cases in a project is determined by the user, but could, for example, be for a dam in its existing condition and a proposed series of risk reduction measures to be implemented in a staged manner. Any proposed structural modification to the dam structure or its appurtenances or non-structural actions that reduce the failure probability or the probability or consequences of failure is referred to as a risk reduction measure (RRM). Combinations of RRMs are referred to as a Risk Reduction Plan (RRP). The following four types of run cases are illustrated in Figure 2.6 and are defined in DAMRAE as follows:

i. **Initial Stage:** A new DAMRAE project begins with an Initial Stage, which...
ii. **Risk Reduction Stage (RRS):** The safety state of a dam following implementation of a proposed risk reduction measure (RAM) is represented by a risk reduction stage. Incremental risk reduction and benefits for a RRS are estimated with reference to the preceding safety state, which could be an Initial Stage or a previous RRS, and which is also referred to as the baseline state for the RRS.

iii. **Risk Reduction Alternative (RRA):** A run case representing an alternative risk reduction measure for a safety state (i.e. Initial Stage or an RRS) is referred to as a risk reduction alternative. Multiple risk reduction alternatives can be included in a DAMRAE project following any safety state. For each alternative the incremental risk reduction and benefits are calculated with respect to the previous safety state, which is referred to as
its baseline state.

iv. **Sensitivity Safety State (S):** The effect of changes in the event tree structure and inputs can be studied by defining Sensitivity Safety States in the project. Any number of sensitivity safety states can be included. Each safety state is associated with a base safety state which can be an Initial State, RRS or RRA. Changes in risk estimates for each sensitivity safety state are calculated with reference to its respective base safety state.²

A run case can combine contributions to total dam failure risk from more than one loading type, each represented in a separate event Tree. Examples of event trees that may be included within a run case could be, for example, winter and summer season flood loading cases [20], or different ranges of earthquake magnitude for earthquake loading [23]. An event tree (ET) object, which is the inner-most object in the DAMRAE framework, holds the user-drawn graphical representation of the event tree and associated event tree inputs. The ET object is integrated with a generalized event tree algorithm (described in the following section 3) to perform the event tree calculation for the following two options: a) Base Run Calculation, and b) Without Common-Cause Adjustment Sensitivity. The sensitivity calculation option b) can be selected for any run case and should not be confused with the Sensitivity Safety State (S).

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² The “base” and “baseline” safety states are different. The base safety state refers to the same safety state as a sensitivity run is made for with the difference being that the base run uses “base” input values and the sensitivity runs uses deviations from these base values. Sensitivity run risk estimates are compared with the base run estimates to assess the degree of sensitivity. The baseline safety state refers to the previous safety state against which risk reduction is calculated.
3. Event tree algorithm

A generalized algorithm to transform the user-drawn event tree structure into a matrix format and expand the matrix to cover the range of loading intervals is a key element in the DAMRAE computational approach. The matrix format is used as the basis for performing the event tree calculation by which quantitative risk estimates are obtained. We have also made some refinements to the traditional ETA terminology to tailor this generalized algorithm to dam safety risk analysis. The details are discussed under the stages of event tree analysis in the following subsections.

3.1. Event tree construction and input assignment

Probabilistic risk assessment of a dam system is commonly based on the event tree form of risk model. The generalized computational framework of DAMRAE supports the deterministic form of event tree calculations. The word ‘deterministic’ is used in the sense that the branch probabilities and state values assigned to different branches in the event tree are either fixed values or non-stochastic relationships. The natural variability (aleatory uncertainty) in the outcomes of random events (state variables), such as flood inflow to a reservoir, seismic ground acceleration, spillway gate reliability, the likelihood and extent of spillway plugging with debris, population exposure scenarios, and the timing of warning and evacuation, can be represented by a discrete probability distribution group using a group of discrete branches emanating from a node on the event tree.

The group of events represented by the branches must be mutually exclusive and collectively exhaustive. The first condition is often met by defining events as non-overlapping ranges of values, and the latter condition is met by ensuring that the
collection of all ranges of values completely covers the range of possible values for the particular state variable. For the case of between zero and five out of a total of five spillway gates failing to open on demand, the use of discrete branches matches the discrete count of spillway gates that malfunction. Under the full assumption of independence the binomial probability distribution can be used to assign probabilities to each of the six branches in the group; although the failure of spillway gates to open on demand can involve more complicated issues of common cause failures to open of subgroups or all gates and issues of the duration that a gate is unavailable and timing of repair, which are better represented in a fault tree model. However, some state variables are by their nature continuous rather than discrete. Inflow floods to a reservoir or seismic hazard are examples. In these cases the continuous probability distribution of annual peak inflow rates or peak ground acceleration are represented using a group of discrete branches, where the number of branches is best determined by meeting a numerical precision criterion similar to the approach used in numerical analysis.

In DAMRAE we have introduced a “continuous” branch to represent a continuous range of state values. In reality the continuous branch is a group of discrete branches where the number of branches is variable and can be determined by the user to meet numerical precision requirements and in the case of large event trees computational time may also be a consideration.

The first step in DAMRAE computation requires the user to manually set up the event tree model on the DAMRAE interface with branch inputs assigned appropriately. To support a generalized event tree calculation in DAMRAE, six types of branches are defined as follows: i) Discrete, ii) Continuous, iii) State Function, iv) Failure, v)
Exposure, and vi) Consequences. This branch type classification was developed specifically for the needs of dam safety risk modeling.

A discrete branch represents a discrete random variable (e.g., the number spillway gates that open on demand) that can take on only a finite number of state values. A continuous branch represents a continuous random variable such as flood (e.g., peak pool elevation) or earthquake [e.g., peak ground acceleration (PGA)] loadings, for example, which can take on values over a continuous range of values. A state function branch represents a deterministic relationship among variables in the event tree, such as reservoir stage-discharge or reservoir stage-duration relationships, or vertical and horizontal deformations of an embankment dam as a function of earthquake magnitude, PGA and reservoir pool elevation [23]. Failure branches are included in the event tree to represent the events of non-breach and the occurrence of one or more failure modes that lead to a reservoir breach. Failure branches are characterized by the failure mode names assigned to each failure branch, and the probabilities [system response probabilities (SRPs)] that each failure mode will occur conditioned on one or more of the preceding events (variables) that are represented by branches to the left of the failure branch. Exposure branches represent different exposure cases (e.g., summer and winter, or day and night) and are assigned the fractions of the time for which the respective exposure case occurs. The estimated magnitudes of economic and life-loss consequences for combinations of the various types of initiating events, failure modes, exposure conditions or other preceding events are assigned to the consequence branches. A summary of these branch types is included in Table 2.1.
The input method to assign the probability or state values as branch attributes can be selected as a fixed value, tabular interpolation or a relational equation. The tabular interpolation or relational equation options express the probability as a function of the state value of that branch or preceding branches or the state value as a function of the state values of preceding branches. Also, unique branch name and branch code are assigned by the user as branch identifiers. These are used by the DAMRAE computation logic to designate a unique identity to each branch in the event tree. The code can be used as a variable name in relational equations and the name is used in output tables and plots.

Event tree diagrams can become very large if they are fully developed for all ranges of state values at all levels of the event tree. To reduce the effort required to construct the complete event tree diagram, DAMRAE includes a collapsed node feature. A collapsed node, which functions as the “Host Node,” takes on the sub tree structure and the input relationship of another node, which serves as the “Donor Node.”

### Table 2.1. Types of event tree branches in DAMRAE

<table>
<thead>
<tr>
<th>Branch Type</th>
<th>Description</th>
<th>Branch Input</th>
<th>Probability</th>
<th>State Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete</td>
<td>A discrete random variable that can take on only a finite number of state values</td>
<td>Probabilities for each discrete state</td>
<td>Title of discrete states for each branch</td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>A continuous random variable that can take on an infinite number of state values over the specified range</td>
<td>Exceedance probabilities associated with state values</td>
<td>Range of state values</td>
<td></td>
</tr>
<tr>
<td>State Function</td>
<td>A deterministic relationship between state variables</td>
<td>1.0</td>
<td>User-specified relationship</td>
<td></td>
</tr>
<tr>
<td>Failure</td>
<td>The events of non-breach and the occurrence of one or more failure modes</td>
<td>System response probability (SRP) value</td>
<td>Title of failure mode</td>
<td></td>
</tr>
<tr>
<td>Exposure</td>
<td>Population exposure cases, e.g., summer and winter; or day and night.</td>
<td>Exposure factor as a time fraction</td>
<td>Title of exposure factor</td>
<td></td>
</tr>
<tr>
<td>Consequences</td>
<td>Life-loss or economic consequences</td>
<td>Not applicable</td>
<td>Consequence value</td>
<td></td>
</tr>
</tbody>
</table>
There are two types of collapsed nodes in DAMRAE: i) Copied Collapsed Node, and ii) Cloned Collapsed Node (Figures 2.7 and 2.8). When the entire succeeding sub tree structure connected to a node (“Host Node”) is identical to the succeeding sub tree structure of another node (“Donor Node”) located above in the event tree at the same
branch level, the sub tree structure and all user-defined input relationships can be copied from the Donor Node to the Host Node using one of the collapsed node options. If the Copied Collapsed Node option is used, the copied sub tree structure and inputs can be modified after coping with no effect on the Donor sub tree (see Figure 2.7). If the Cloned Collapsed Node is used, the cloned sub tree structure and inputs cannot be modified after cloning and they will remain always identical to the Donor sub tree (see Figure 2.8). In the DAMRAE event tree diagram, the cloned Host Node references the Donor Node, but to reduce the complexity of the diagram the cloned sub tree is not displayed except temporarily if the user clicks on the ‘+’ symbol on the Host node.

3.2. Event tree calculation

A simplified flowchart of the event tree computational logic of DAMRAE is depicted in Figure 2.9. The symbols used in the Figure 2.9 are as follows: a) LL = Loss of

![Figure 2.9](image-url)
Life (lives), b) ALL = Annualized Loss of Life (lives/year), c) EL = Economic Loss ($), d) AEL = Annualized Economic Loss ($/year), e) APF = Annual Probability of Failure (/year), f) = Range (Minimum and Maximum values) of Life Loss, and g) = Range (Minimum and Maximum values) of Economic Loss.

An example flood event tree shown in Figure 2.10 is used to illustrate the details of this computational logic. This example is very simple in comparison with some that DAMRAE has been applied to, which have included about 30 levels and a total of almost 200,000 rows [24], although there is no limit to these dimensions that can be defined in DAMRAE.

Level 1 in the example event tree in which the fan shape symbol is a continuous branch representing peak reservoir pool elevation vs. AEP relationship. Levels 2 and 3 are state function branches included to compute the peak overtopping depths and peak discharge values, respectively, from the peak reservoir pool elevation. Level 4 is a failure branch, which includes a non-breach branch and branches representing the three flood

![Figure 2.10. Example flood event tree](Image)
failure modes of embankment overtopping, spillway wall overtopping, and embankment toe erosion by re-circulating spillway flows. DAMRAE assigns a green color to all event tree branches except for failure branches and branches that are subsequent to these branches, which are assigned a red color. The downstream area is considered as a single consequence center and the event tree is extended to include the life-loss and economic consequences for this zone in Levels 5 and 6, respectively. The Levels 5 and 6 consequences branches following the spillway failure and toe erosion failure branches (host nodes) have been cloned using the overtopping failure consequence branches as the donor node\textsuperscript{3} since the same failure consequences are being assigned to all three failure modes. The user-assigned branch names and the program-assigned branch indices (shown within parentheses) are displayed adjacent to the branches in the event tree diagram shown in Figure 2.10. Using this example event tree, the steps of the computational logic are discussed below.

3.2.1. Connectivity matrix

The user-drawn event tree structure is first transformed into a matrix format, known as the connectivity matrix. The connectivity matrix represents a row-cell arrangement of the program-assigned event tree branch indices, arranged according to their connections with other branches in the event tree. The connectivity matrix for the example event tree with program assigned branch indices as $Br1$, $Br2$, $Br3$, etc. is shown in Figure 2.11.a.

The number of columns and number of rows in the connectivity matrix are defined by the horizontal extent (i.e., number of levels) and the vertical extent (as

\textsuperscript{3} The reference numbers displayed on the host and donor nodes (e.g., 5 in Figure 2.10) are to aid the visual identification of the donor node corresponding to a host node.
described in the next subsection) of the event tree, respectively. The vertical extent of the connectivity matrix account for the primary event tree structure shown in Figure 2.10 but without expanding that structure to show all computational branches that are defined by continuous branches to form the complete event tree for making event tree computations. This full structure is captured in the pedigree matrices that are defined in the next subsection.

3.2.2. Pedigree matrix

The connectivity matrix is expanded to generate the pedigree matrix, which includes additional rows, inserted to incorporate the number of intervals for the continuous branches present in the event tree. The full range of values for the continuous

---

**Figure 2.11.** Example of calculation matrices in DAMRAE

```
<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br1</td>
<td>Br2</td>
<td>Br3</td>
<td>Br4</td>
<td>Br5</td>
<td>Br6</td>
</tr>
<tr>
<td>Br1</td>
<td>Br2</td>
<td>Br3</td>
<td>Br4</td>
<td>Br5</td>
<td>Br6</td>
</tr>
<tr>
<td>Br1</td>
<td>Br2</td>
<td>Br3</td>
<td>Br4</td>
<td>Br5</td>
<td>Br6</td>
</tr>
<tr>
<td>Br1</td>
<td>Br2</td>
<td>Br3</td>
<td>Br4</td>
<td>Br5</td>
<td>Br6</td>
</tr>
<tr>
<td>Br1</td>
<td>Br2</td>
<td>Br3</td>
<td>Br4</td>
<td>Br5</td>
<td>Br6</td>
</tr>
</tbody>
</table>
```

b) Pedigree matrix for the example event tree shown in Figure 2.10 with ‘n’ intervals for the continuous branch in Level 1
variable of flood loading, which is represented by the continuous branch in Level 1 of the event tree, is partitioned into a number of intervals that is specified by the user. The number of intervals should be specified to provide adequate numerical precision in the event tree calculations and post processing [15]. If the range of peak reservoir pool elevations in the Level 1 branch is partitioned into \( n \) (an integer number) intervals, the connectivity matrix is expanded to include the \((n+1)\) intervals\(^4\) for this branch and thus, the resulting pedigree matrix shown in Figure 2.11.b is a \([4(n+1)\times 6]\) matrix of branch indices. The generated pedigree matrix is a complete representation of event tree paths, which uniquely identifies the pathways to all terminal nodes in the event tree. In addition to making the event tree calculation possible with all the different conditional probability relationship that can exist in an event tree, it also facilitates the collation of the contributions of different failure modes or loading ranges to the total risk.

3.2.3. Failure probability calculation

Only the event branches that precede the exposure and consequence branches are used to calculate the probability of failure. As mentioned earlier, each event branch in the event tree has branch attributes of a state value and a probability value. For the Level 1 branch, \( n \) interval values of peak reservoir pool elevation are the \( n \) state values and their corresponding annual probabilities of occurrence are the annual probability values representing the probability of peak reservoir pool elevations in each interval occurring. A representative state value equal to the mid-point of the interval is assigned to each interval. For each interval of peak reservoir pool elevation assigned in Level 1, the state function branch in Level 2 is used to calculate the peak overtopping depth by subtracting

\(^4\) An additional interval is added to include an interval corresponding to the exceedance of the highest value (or the last interval value).
the dam crest elevation from the representative peak reservoir pool elevation value that is assigned in Level 1. Since the state function branch is a single branch that does not divide as other branches do, it is assigned a probability of 1. The Level 3 branch is also a state function branch and therefore it is also assigned a probability of 1.0. A peak discharge corresponding to the representative value of the peak reservoir pool elevation is obtained by interpolation from a given reservoir stage-discharge relationship that is input by the user. The state values for each failure branch in Level 4 is the respective branch name (i.e., failure mode name assigned by the user) and the probability value is the conditional probability of occurrence of each failure mode that is represented by the respective SRP relationships input by the user. The SRP for the overtopping failure mode is conditioned on the peak reservoir pool elevation (Level 1) and the SRP for the spillway failure mode is conditioned on the peak reservoir overtopping depth (Level 2). The non-breach branch in Level 4 is assigned the branch name ‘Non-Breach’ by DAMRAE as its state value and its probability is calculated as 1- sum of the conditional probability values of the three failure branches in each interval of peak reservoir pool elevations that are assigned in Level 1.

The calculations for the total probability of failure for each failure mode or the total non-breach probability are based on the state value and probability matrices. These matrices have the same format as the pedigree matrix but with the last two columns of consequence branches excluded. The cells of these matrices are populated with the branch state and probability values corresponding to the respective branch indices in the pedigree matrix. Using these matrices, the end node probability (or, pathway probability), which is defined as the product of the probability of the initiating event and all
conditional probabilities along the pathway [25] is calculated as follows:

$$P_r = p_{(r,1)} \cdot p_{(r,2)} \cdot p_{(r,3)} \cdot p_{(r,4)}$$  \hspace{1cm} \ldots \text{Eq. 2.1}$$

where $P_r$ defines the pathway probability of failure for the $r^{th}$ row in the matrix. In the case when exposure factors are also multiplied in the pathway probability calculations, the resulted end node probabilities define the pathway probabilities of life loss.

Using the end node probabilities, the annual probability of failure $APF(FM_f)$ for each failure mode ($FM_f$) in the given example is calculated as follows:

$$APF(FM_f) = \sum_{r \in R_{FM_f}} P_r$$  \hspace{1cm} \ldots \text{Eq. 2.2}$$

where $f$ is the index of a failure mode (i.e., $f=1$ for ‘Overtop Fail’, $f=2$ for ‘Spillway Fail’, and $f=3$ for ‘Toe Erosion’) and $FM_f$ represents the corresponding failure mode of a failure mode index $f$. $p_{(i,j)}$ is the probability value in the $i^{th}$ row and $j^{th}$ column of the probability matrix, $R_{FM_f}$ represents an integer set of row-numbers that correspond to the failure mode $FM_f$, such that the state values $s_{(r,i)} = FM_f, \forall r \in R_{FM_f}$ in the state value matrix. In this example, Levels 2 and 3 are state function branches and therefore, $p_{(r,2)} = 1$ and $p_{(r,3)} = 1, \forall r \in R_{FM_f}$ is used in the calculation.

The event tree example in Figure 2.10 is a case of non-mutually exclusive failure events as the failure modes (i.e., overtopping, spillway failure, and toe erosion) can occur simultaneously at some pool elevations in the upstream reservoir. For such cases, the DAMRAE logic includes a common-cause adjustment (CCA) [9] to adjust the conditional system response probabilities of individual failure modes. The probability values corresponding to the failure modes are adjusted in the probability matrix before the total failure probabilities for each failure mode are calculated such that the sum of
their adjusted probabilities equals upper bound from the uni-model bounds theorem [26], which is based on DeMorgan’s Rule for combining probabilities of events under the assumption that the events are mutually independent. Specifically, a common cause adjusted conditional probability, \( p_{(i,j)}' \), is computed as follows:

\[
 p_{(r,4)}' = p_{(r,4)} \left( \frac{1 - \prod_{r=r-f+1}^{r-f+k} \left[ 1 - p_{(r',4)} \right]}{\sum_{r=r-f+1}^{r-f+k} \left[ p_{(r',4)} \right]} \right)
\]

…Eq. 2.3

where \( f \) is the index of the failure mode FM, \( k \) is the total number of failure modes (i.e., 3 in this example case), and \( P_r' \) represents the new end node probability for the \( r^{th} \) row. The total failure probability for failure mode \( FM_f \) is calculated as follows:

\[
 APF(FM_f) = \sum_{r \in RFM_f} p_{(r,1)} \times p_{(r,2)} \times p_{(r,3)} \times p_{(r,4)} = \sum_{r \in RFM_f} P_r'
\]

…Eq. 2.4

The CCA approach described here is applied in combination with “SRP Freezing.” The term “SRP Freezing” refers to the case in which the common-cause adjustments of SRPs (conditional probabilities of failure modes) for non-mutually exclusive flood-related failure modes [9] are held constant for all loading intervals above the first loading interval for which at least one SRP becomes 1.0, indicating that failure would certainly occur by that loading interval. This is illustrated in Figure 2.12.a where the values of SRPs of two failure modes, ‘Failure1’ and ‘Failure2’, increase until the water level reaches to a level at which the failure occurs by ‘Failure1’ (i.e., the SRP of ‘Failure1’ becomes equal to 1.0 implying that failure is certain to occur). Beyond this failure point SRPs of both the failure modes are fixed at their respective values at the water level where failure is considered to be certain to occur. SRP freezing is implemented to avoid unrealistic estimates of the probability of failure for individual
Figure 2.12. Illustrations of SRP freezing and consequences freezing
failure modes, such as attributing probability to a failure mode with a SRP threshold at a higher loading interval than the interval for which the SRP for another failure mode first becomes 1.0.

3.2.4. Incremental consequences calculation

The non-breach and failure consequences, incorporated in Level 5 and 6 of the event tree, are assigned as a function of peak discharge values (Level 3). DAMRAE places the interpolated values of consequences for each interval of the Level 1 branch in the consequence matrices for life-loss (LL) and economic consequences (EC), which have the same number of rows [i.e., \(4(n+1)\) in our example] as the pedigree matrix. A separate column is contained in each consequences matrix for each different consequence center, which are either different physical locations for which life-loss and economic consequences are input or they could represent different components of consequences, such as property damage and business interruption losses, for example. The components must be additive to obtain the total consequences. In the simplified example there is only one consequences center.

Similar to the “SRP Freezing” option, the DAMRAE computation also includes an option for “Failure Consequences Freezing.” The freezing of failure consequences holds the assigned values of failure consequences constant for all loading intervals above the first loading interval for which at least one SRP becomes 1.0, indicating that failure would certainly occur by that loading interval. This is illustrated in Figure 2.12.b where both the non-breach and failure consequences keep increasing until the water level reaches the level at which failure is considered to be certain to occur (i.e., where SRP
becomes 1.0 for at least one failure mode). For water levels above that certain failure point, failure consequences are kept constant at their values at the water level where failure is considered to be certain to occur, whereas non-breach consequences keep increasing with increases in the water level. The incremental consequences, which are calculated as the difference between the failure and non-breach consequences, are assigned a zero value for the higher water levels where non-breach consequences are greater than the failure consequences to avoid the negative incremental consequence values. This type of freezing is implemented to avoid unrealistic estimates of the failure consequences for individual failure modes, such as for the case in which failure certainly occurs (i.e., SRP = 1.0) on the rising limb of the flood hydrograph for which failure consequences would be less than if the failure did not occur until the hydrograph peak, for example. In this case, failure consequences would be frozen at the loading interval for which the first SRP becomes 1.0 because this represents the most severe level of failure consequences given that failure must occur by the that loading level and cannot occur at higher loading levels. To assign higher failure consequences at more severe loading intervals would give an overestimate of the total and incremental consequence attributable to dam failure. The freezing of failure consequences is applied to the life-loss and economic consequence matrices prior to calculating the total failure consequences for each failure mode.

The failure consequences are calculated as incremental consequences, which are defined as the difference between failure and non-breach consequences for flood-induced failure modes, although total consequences can be obtained by defining non-breach consequences as zero. The incremental life-loss (LL) and economic consequences (EC)
associated with each failure mode (FM) is calculated as follows:

\[
LL_j(\text{FM}_j) = \sum_{r \in R_{\text{FM}_j}} [l_{(r,1)} - l_{(r',1)}] = \sum_{r \in R_{\text{FM}_j}} [\Delta l]_{(r,1)} \quad \text{...Eq. 2.5}
\]

\[
EC_j(\text{FM}_j) = \sum_{r \in R_{\text{FM}_j}} [e_{(r,1)} - e_{(r',1)}] = \sum_{r \in R_{\text{FM}_j}} [\Delta e]_{(r,1)} \quad \text{...Eq. 2.6}
\]

where \(l_{(i,j)}\) and \(e_{(i,j)}\) are the life-loss and economic consequence values at the \(i^{th}\) row of the event tree and the \(j^{th}\) column (corresponding to a particular consequences center) of the life-loss and economic consequence matrices, respectively, \(r' = r - f\), is the row index of non-breach consequence corresponding to row \(r\), and \(\Delta l\) and \(\Delta e\) represent the incremental consequences.

Annualized (incremental) consequences are calculated for each row in the consequences matrices, corresponding to each terminal branch or unique event tree pathway. Total annualized (incremental) consequences (ALL and AEC) associated with each failure mode (FM) are calculated as follows:

\[
\text{ALL}(\text{FM}_j) = \sum_{r \in R_{\text{FM}_j}} \mathbb{P}_r' [l_{(r,1)} - l_{(r',1)}] = \sum_{r \in R_{\text{FM}_j}} \mathbb{P}_r' [\Delta l]_{(r,1)} \quad \text{...Eq. 2.7}
\]

\[
\text{AEC}(\text{FM}_j) = \sum_{r \in R_{\text{FM}_j}} \mathbb{P}_r' [e_{(r,1)} - e_{(r',1)}] = \sum_{r \in R_{\text{FM}_j}} \mathbb{P}_r' [\Delta e]_{(r,1)} \quad \text{...Eq. 2.8}
\]

where \(\mathbb{P}_r'\) is the end node probability for the \(r^{th}\) row after the common-cause adjustment (CCA).

The ranges of incremental consequences, i.e., the minimum and maximum incremental values of life-loss and economic consequences, for each failure mode (FM) are calculated as follows:
\[ R_{LL} = \{\min([\Delta l]_{(r,1)}), \max([\Delta l]_{(r,1)})\} \quad \ldots \text{Eq. 2.9} \]

\[ R_{EC} = \{\min([\Delta e]_{(r,1)}), \max([\Delta e]_{(r,1)})\} \quad \ldots \text{Eq. 2.10} \]

where \( R_{LL} \) and \( R_{EC} \), respectively, represents the range of incremental consequences for life-loss and economic consequences.

The event tree calculation step is performed one or more times depending on the selection of the calculation options: Base Run and Without CCA Sensitivity. The Base Run applies a common-cause adjustment [9] to non-mutually exclusive failure modes if this option is selected by the user. The Without Common-cause Adjustment Sensitivity calculation option generates the probability matrix without any adjustments in failure mode SRPs. This option is useful to assess the role of the common-cause adjustment as if a failure mode group is mutually exclusive failure modes instead of non-mutually exclusive failure modes.

3.3. Event tree results

The direct results of event tree calculation can be categorized as follows: i) Risk Estimates, which are the annual probability for failure and non-breach (APF), annualized incremental life-loss (ALL), and annualized economic consequences (AEC) and the ranges of incremental consequences (\( R_{LL} \) and \( R_{EC} \)) for each failure mode and as totals; and ii) Cumulative Plots, which are the plots of the cumulative values of selected risk estimates against the state values or probabilities of any user-selected branch level in the event tree. In particular, when these plots are made against the state values of a loading branch that are assigned to each calculation interval over the entire range of loading, they provide a useful visual tool to understand the contributions from individual failure modes to the overall risk over the complete range of loading. An example of a cumulative annual
probability of failure (for the three flood failure modes and their total) versus peak pool reservoir elevation plot is shown in Figure 2.13.

4. DAMRAE outputs

The risk estimates and cumulative plots for each event tree are classified as Level-I (Event Tree Level) outputs. The post-processing step of DAMRAE allows the user to do the following with the Level-I outputs: i) combine the risk estimates for different event trees (e.g. representing different loading types e.g., flood and earthquake) under each run case or safety state included in a DAMRAE project; ii) compare different run cases in terms of their risk reduction and cost effectiveness of risk reduction; and iii) compare each run case against USACE tolerable risk guidelines [14]. The results generated in the post-processing step are classified as Level-II (Project Level) outputs. These outputs are categorized into the seven types that are described in the Sections 4.1-4.7. They are represented schematically in Figure 2.14 where Level-I outputs for different

![Cumulative Plot](attachment:image.png)

**Figure 2.13.** Example of a cumulative risk estimate (annual failure probability) vs. loading range
event trees (e.g., flood, earthquake, etc.) are shown in a group in the left-hand side of the figure and Level-II outputs for the different event trees are shown in the right-hand side of the figure.

4.1. Annual probability of failure

This tabular output type includes the probability of failure (/year) for each failure mode and their percentage contribution to the totals across all failure modes. Also, percentage reduction in the failure probability for each failure mode as compared to the baseline state is displayed for risk reduction states. The probability of failure for each failure mode and their total are compared against the tolerable risk limit value of 1 in 10,000 (1x10⁻⁴) /year. Although this guideline applies only to the total probability of failure, values for each failure mode and the total that are greater than the tolerable risk
limit are highlighted in red and those values that are one order below the limit value are highlighted in yellow. All other values are highlighted in green.

4.2. Annualized incremental life-loss

Annualized incremental life loss (lives/year), percent contribution towards the total, range of incremental life loss (i.e., minimum and maximum incremental values of life loss), and a weighted mean ($\bar{N}$) value of incremental life loss (calculated as $\bar{N} = \text{ALL}/\text{APF}$) are tabulated for each failure mode and for the total. Also, the reduction in annualized incremental life-loss consequences as compared with the baseline case are tabulated for each failure mode and the total for the risk reduction states. Annualized incremental life loss values for the failure modes and their total are compared against the tolerable risk limit value of 0.001 ($1\times10^{-3}$) lives/year. The same color highlighting convention is used as described for Annual Probability of Failure in Section 4.1.

4.3. Annualized incremental economic consequences

Annualized incremental economic consequences ($$/year), percent contribution towards the total, the range of incremental economic consequences represented by minimum and maximum incremental values of economic consequences, and weighted mean ($\bar{S}$) value of incremental economic consequences (calculated as $\bar{S} = \text{AEC}/\text{APF}$), are tabulated for each failure mode and for the total. Also, the reductions in annualized incremental economic consequences as compared with the baseline case are tabulated for each failure mode and the total for the risk reduction states. There are no tolerable risk guidelines that apply to annualized incremental economic consequences and hence no color highlighting.
4.4. Incremental risk-reduction

This tabular output type includes the following:

a) (Adjusted) Equivalent Annual Implementation Cost for Risk-Reduction Measure ($/year), \(\text{ACC}_{\text{RRM}} = \text{ACC}_{\text{RRM}} + \text{OM}_{\text{RRM}} - \text{OM}_{\text{B}}\) (“Adjusted” refers to including the increase in O&M cost)

b) Annual Benefit of Risk-Reduction Measure ($/year), \(B_{\text{RRM}} = \text{EC}_{\text{B}} - \text{EC}_{\text{RRM}}\)

c) Total Economic Cost ($/year), \(C_{\text{RRM}} = \text{EC}_{\text{RRM}} + \text{ACC}_{\text{RRM}}\)

d) Benefit: Cost Ratio, \(B_{\text{CRRM}} = \frac{B_{\text{RRM}}}{C_{\text{RRM}}}\)

where \(\text{ACC}_{\text{RRM}}\) = Equivalent annual implementation cost for risk-reduction measure ($/year), \(\text{OM}_{\text{RRM}}\) = Annual O&M cost for risk-reduction measure ($/year), \(\text{OM}_{\text{B}}\) = Annual O&M cost for baseline ($/year), \(\text{EC}_{\text{B}}\) = Annualized incremental economic consequences for baseline ($/year), and \(\text{EC}_{\text{RRM}}\) = Annualized incremental economic consequences for risk-reduction measure ($/year).

In addition, the following measures of the cost effectiveness of life-loss risk, which are inputs to an ALARP evaluation:

a) Cost to Save a Statistical Life ($/Life), \(C_{\text{SSLRM}} = \frac{\text{ACC}_{\text{RRM}} - B_{\text{RRM}}}{\text{ALL}_{\text{B}} - \text{ALL}_{\text{RRM}}}\)

b) Disproportionality Ratio, \(R_{\text{RRM}} = \frac{C_{\text{SSLRM}}}{\text{WTP}}\)

where \(\text{ALL}_{\text{B}}\) = Annualized incremental life loss for baseline (lives/year), \(\text{ALL}_{\text{B}}\) = Annualized incremental live loss after implementation of the risk-reduction measure (lives/year), and \(\text{WTP}\) = Willingness to pay to prevent a statistical fatality ($). WTP is commonly referred as the “value-of-saving a-statistical-life” (VSL) by OMB, USDOT
and other federal agencies. USACE uses the USDOT value of VSL which is currently $6.2 million. ([http://ostpxweb.dot.gov/policy/reports.htm](http://ostpxweb.dot.gov/policy/reports.htm)).

### 4.5. Tolerable risk guidelines

Tabulations of the outcomes of evaluations against the following four USACE [14] tolerable risk guidelines are incorporated into DAMRAE:

a. **Total Annual Probability of Failure (APF):** APF > 1 in 10,000 (1x10^{-4})/year is considered as unacceptable, and is displayed as ‘No’ with red background. APF ≤ 1x10^{-4} is displayed as ‘Yes-ALARP?’ with a green background.

b. **Individual Risk:** The individual tolerable risk limit is set at 1 in 10,000 (1x10^{-4})/year. For the total APF ≤ 1x10^{-4}, individual risk is displayed as ‘Yes-ALARP?’ with a green background, while APF > 1 in 10,000 (1x10^{-4})/year is displayed as ‘Evaluated Externally’ with a yellow background.

c. **Probability Distribution of Potential Incremental Life Loss (F-N Chart):** Societal risk is evaluated based on the probability distribution of annualized life loss due to dam failure (F-N chart). If the probability distribution curve lies below (≤) the guideline curve, the societal risk evaluation outcome is displayed as ‘Yes-ALARP’ with a green background, and otherwise, as ‘No’ with a red background.

d. **Total Annualized Incremental Life Loss (ALL):** The tolerable risk limit for the total annualized life loss is set as 0.001 lives/year. ALL > 0.001 lives/year is displayed as ‘No’ with a red background, and otherwise, as ‘Yes-ALARP?’ with a green background.

In addition a partial evaluation of the ALARP justification is also displayed under
the same tab for the Benefit: Cost Ratio and Disproportionality Ratio. Other ALARP evaluation considerations require a qualitative evaluation and therefore must be performed externally to DAMRAE.

4.6. Non-breach risk:

Annualized non-breach risk estimates for probability, annualized life loss and annualized economic consequences for the range of non-breach inundation events considered in the risk analysis calculations are tabulated under this type. Also, the range of consequences represented by the minimum and maximum values of non-breach life loss (lives) and non-breach economic consequences ($\) are included under this tabulation. For risk reduction alternatives and stages, estimates of reductions (or increase) in non-breach benefits (both lives/year and $/year) are also included. There are no tolerable risk guidelines that apply to non-breach risk.

4.7. Residual risk

This tab includes the total failure incremental risk, total non-breach risk and total residual risk as the sum of incremental risk and non-breach risk for the life-loss and economic consequences.

4.8. Graphical outputs

As part of the risk evaluation against the USACE tolerable risk guidelines [14], F-N and $N$-charts (illustrated in Figures 2.1 and 2.3, respectively) are generated to evaluate the societal incremental life safety inundation risk. The F-N chart is a plot of $F$, the annual probability of exceedance (greater than or equal to) of potential life loss versus $N$, the incremental potential life loss. The $f-N$ chart displays $f$, the annual failure
probability against the $\bar{N}$, the average annual life loss. Also, an F-$S$ plot can be generated to assess the incremental economic inundation risk. The F-$S$ plot displays the annual probability of exceedance of economic consequences versus the incremental economic consequences.

Similar to the inundation risk F-N and F-$S$ plots, non-breach F-N and F-$S$ plots are generated to evaluate the non-breach inundation risk. For these plots, annual probability of non-breach event and the associated consequences (life loss and economic consequences) are used. There are no tolerable risk guidelines that apply to non-breach risk but the societal risk guidelines that apply to incremental failure risk are shown on the F-N plot (see Figure 2.3) for reference purposes only.

5. Summary of DAMRAE features

DAMRAE is developed to overcome the significant limitations of commercially available risk analysis tools, which are ill-suited for dam safety risk analysis applications as documented in Section 1. In some of the studies [10, 22], these limitations have been addressed through the use of spreadsheets, often including VBA macros to facilitate looping over the range of initiating (loading) events with variable step sizes, inputs of SRPs and consequence relationships, and post-processing for reporting and risk evaluation. However, the spreadsheet approach lacks generality and can require significant effort to apply to a specific dam or to modify the event tree structure to represent risk-reduction measures or for other purposes. DAMRAE event tree models can be readily applied to represent risk-reduction measures and provide the necessary input, output, and reporting features to eliminate the need of any external computational scripts. In addition interface options, such as add, delete, and relocate branches, accompanied
with advanced collapsed node copy and clone functionality provide easy and flexible event tree construction and modification features. The inputs for branches can be in the form of a numeric value, relational equation, or a tabular interpolation. The generated outputs include annualized risk estimates for each failure mode that is defined in the user-drawn event tree structure.

The overall structure of DAMRAE is designed to accommodate the iterative nature of dam safety risk analysis. An event tree model, once set up, can be copied to other run cases (i.e., safety states) or can be imported into any another DAMRAE project as desired. Thus, an analysis begun with the existing states of dam structure and consequence scenarios can easily be extended to analyze structural and non-structural RRM s by modifying the event tree structure and revising inputs for loading and SRPs, failure consequences, risk reduction cost inputs, and other inputs such as state functions representing the reservoir stage-discharge relationship. Within a DAMRAE project, the post-processing step enables a flexible tabulation of results combining functionality to obtain the contributions to the total dam failure risk from various combinations of failure modes, consequence centers, and exposure cases for a dam safety state. The DAMRAE interface includes a “drill-down” functionality for displaying the breakdown of tabular results by failure mode, exposure case or consequence centers. The probability-consequence pairs for each user-created combination are collected by the program to automatically generate the USACE tolerable risk guideline curves. The post-processing also facilitates the comparison of risk estimates with other safety states for the same dam following risk reduction, or when new information is obtained from investigations and analyses.
6. Concluding remarks

DAMRAE is a flexible software tool for conducting dam safety risk analysis using the event tree form of risk model. It is proposed as a solution to overcome the limitations of commercial riskwares or the use of spreadsheet models, which are commonly used in this field. DAMRAE offers an advanced comprehensive ETA tool without compromising the basic flexibility and user-friendliness embedded in most of the commercial riskwares for constructing and quantifying event trees. DAMRAE provides a canvas for the analyst to efficiently capture the art and science of dam safety risk analysis in a dam-specific event tree model, and a tool to produce precise risk estimates for the constructed model and assigned inputs. DAMRAE does not include any recommended event tree forms although work is on-going to provide guidance on forms for a range of dam safety applications. DAMRAE does not provide recommended input assignments since these must be estimated for each dam, and guidance is available for specific types of failure modes (e.g., USACE [27] and USBR [28]).

DAMRAE development is motivated by the surging acceptance of formal risk analysis in dam safety and the emerging requirements of portfolio risk assessment framework from the owners of large number of dams. The computational aspects of DAMRAE follow the theoretical advancements in the field. The object-oriented structure of DAMRAE components allows it to be compatible with a database environment. The original concept of DAMRAE has been extended to develop a database configured version of DAMRAE (referred to as DAMRAE-db) to serve as a computational core engine in a portfolio risk assessment and management system, for long dam applications [24] and to make calculations more rapidly.
DAMRAE has been used by the USACE, Tennessee Valley Authority, RAC Engineers & Economists and Utah State University to perform numerous risk analyses on major dams in the US and overseas. The event tree example included in this paper is only intended to provide the basic concepts of DAMRAE computations as the real scope of DAMRAE capabilities extends beyond the limits of this paper. A detailed example of a DAMRAE application for a dam safety risk assessment is presented in Chapter 3 of this dissertation. In addition, the prototype uncertainty analysis version, DAMRAE-U, is described in Chapter 4 and a detailed example is presented in Chapter 5 of this dissertation.

References


CHAPTER 3
DAMRAE APPLICATION FOR AN EXAMPLE DAM SAFETY RISK ASSESSMENT

ABSTRACT

The DAMRAE framework provides a convenient platform to structure the risk assessment of a dam in its existing condition, for risk reduction alternatives and at various stages of implementing a risk reduction plan. The computational logic within the framework quantifies the event tree form of the risk models, performs comparison against US Army Corps of Engineers (USACE) dam safety tolerable risk guidelines, and displays risk estimates in tabular and graphical forms for the dam in its exiting state and for other states representing risk reduction alternatives and stages that are included in a DAMRAE project. An example risk assessment is presented in this paper to demonstrate the application of DAMRAE functionalities. The example project includes a main dam and a saddle dam and event trees for flood and earthquake loading for the existing condition and five risk reduction alternatives implemented in a staged fashion. The paper details the structure and inputs of the flood and earthquake event tree models, describes the modifications for the risk reduction alternatives, and discusses the DAMRAE outputs and their evaluation against tolerable risk guidelines.

1. Introduction

Dam safety risk assessment can be used in an iterative manner to evaluate whether estimated risks have been reduced sufficiently. The risk analysis typically starts with the existing dam baseline case and then the estimated reduced risk is estimated for structural alternative risk reduction measures (e.g., upstream reservoir elevation, spillway...
capacity, number of functional gates etc.), and non-structural alternative risk reduction measures (RRMs) (e.g., increased warning time, enhanced evacuation planning etc.) combined into risk reduction plans that are formulated to address significant failure modes and factors that lead to high life loss. The staged implementation of RRM components of the overall risk reduction plan can be examined to identify and justify an implementation sequence. For the risk assessment of each stage (including the existing condition), all credible and significant failure modes are considered and the total estimated risk is evaluated against a tolerable risk guidelines (TRG) (e.g., ANCOLD [1] and USACE [2]). The flood and earthquake event tree models developed and quantified to include all credible and significant failure modes for the existing condition are modified and re-quantified for each risk reduction alternatives or stage to represent the changes associated with the structural or non-structural risk reduction measure. The dam failure risk for all failure modes that are included in the risk model is combined to estimate the total risk.

The architecture of the DAMRAE framework developed by the authors, including the underlying computational algorithm for the event tree analysis, the form of DAMRAE risk estimates, and unique contributions of the framework, is described in Chapter 1. In DAMRAE, event trees can be constructed by the user via a user interface using the types of event tree branches summarized in Table 3.1. Each event tree included in a DAMRAE project can be quantified to obtain the probability of failure and annualized breach and non-breach risk estimates and ranges of associated life-loss and economic consequences. The results for all the event trees included under a dam safety state can be combined to obtain the contributions to the total dam failure risk from each
Table 3.1. Types of event tree branches in DAMRAE [3]

<table>
<thead>
<tr>
<th>Branch Type</th>
<th>Description</th>
<th>Branch Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete</td>
<td>A discrete random variable that can take on only a finite number of state values</td>
<td>Probability: Probabilities for each discrete state</td>
</tr>
<tr>
<td>Continuous</td>
<td>A continuous random variable that can take on an infinite number of state values over the specified range</td>
<td>State Value: Title of discrete states for each branch</td>
</tr>
<tr>
<td>State Function</td>
<td>A deterministic relationship between state variables</td>
<td>Probability: 1.0</td>
</tr>
<tr>
<td>Failure</td>
<td>The events of non-breach and the occurrence of one or more failure modes</td>
<td>State Value: User-specified relationship</td>
</tr>
<tr>
<td>Exposure</td>
<td>Population exposure cases, e.g., summer and winter; or day and night.</td>
<td>Probability: System response probability (SRP) value</td>
</tr>
<tr>
<td>Consequences</td>
<td>Life-loss or economic consequences</td>
<td>Probability: Not applicable</td>
</tr>
</tbody>
</table>

 failure mode, consequence center, or exposure case. The probability-consequence pairs for each dam safety state are processed by DAMRAE to generate the USACE tolerable risk guideline charts. The post-processing step of DAMRAE also facilitates the evaluation of risk estimates against the USACE tolerable risk guidelines [2] and the comparison of risk estimates with other safety states for the same dam to examine the estimated effects of risk reduction measures, or the sensitivity of risk estimates to new information obtained from investigations and analyses or other changes in model inputs.

The significance of the estimated risks for each stage is evaluated using the following USACE tolerable risk “limit values” [2]:

1) An Annual Probability of Failure (APF) limit value of 1 in 10,000 /year as a
measure of the performance of the dam (see the horizontal limit line at 1 in 10,000/year on Figure 3.1)

2) An Individual Risk (IR) limit value of 1 in 10,000/year as a measure of life safety risk expressed as the probability of life loss for the identifiable person(s) most at risk.

3) A Societal Risk (SR) expressed as a limit of tolerability on a cumulative probability distribution (F-N Chart) of exceeding various magnitudes of life-loss as a measure of life-safety risk to a non-identifiable or random persons (see the slopping and vertical limit lines on Figure 3.2).

4) An Annualized Life Loss (ALL) of 0.001 lives/year as the average magnitude of life loss from the probability distribution of life loss in 3) as an average

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**Figure 3.1.** USACE APF and ALL tolerable risk guidelines ([f-N Chart] [2])

**Figure 3.2.** USACE societal risk guidelines (F-N Chart) [2]
measure of societal life safety risk (see the sloping limit line at 0.001 lives/year on Figure 3.1).

In the second part of the risk evaluation process, ALARP (as low as reasonably practical) criteria is evaluated. ALARP evaluation is both qualitative and quantitative in nature and it should take the following into account: the level of risk in relation to the tolerable risk limits; the disproportion between the sacrifice (money, time, trouble, and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved; the cost effectiveness of the risk reduction measure; compliance with essential USACE guidelines; and societal concerns as revealed by consultation with the community and other stakeholders.

The consideration of the cost effectiveness or “disproportionality” associated with the cost of achieving life safety risk reduction relative to the life safety benefit achieved is a quantitative aspect of an ALARP evaluation. Two factors – Disproportionality Ratio (R) and Cost-to-Save-a-Statistical-Life (CSSL) are estimated as quantitative measures to justify the implementation of a risk reduction measure to reduce the risk below the tolerable risk limit. CSSL is a measure of cost effectiveness estimated as a return (in term of the life-safety benefit) for the cost invested to achieve the life-safety risk reduction. Disproportionality Ratio is a measure of disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measure and the subsequent risk reduction achieved [1-3].

A hypothetical example of a dam safety risk assessment is used in this paper to demonstrate the computational features of DAMRAE. Section 2 of this paper describes the example dam, the dam safety issues, and the event tree models and their inputs used
in this example risk assessment. In Section 3 modifications made to event tree models are described to represent the risk reduction alternatives and stages. Risk assessment results are discussed in Section 4, and a summary and conclusions are included in Section 5.

2. Existing dam example risk assessment

The hypothetical example dam consists of a main embankment dam and a saddle embankment dam, both with the same crest elevation of 673 ft. msl. The main dam is evaluated for the flood and earthquake performance failure risk, whereas only the flood risk is considered for the saddle dam. The following seven types of flood and flood-internal failure modes are considered in the flood event tree:

a. Slope instability of the main dam (SI-M),
b) Overtopping of the main dam (OT-M),
c) Piping through the main dam embankment (PE-M),
d) Piping through the main dam foundation (PF-M),
e) Piping along the outlet works associated with the main dam embankment (PO-M),
f) Overtopping of the saddle dam (OT-S), and
g) Piping through the saddle dam embankment (PE-S).

The following two liquefaction-induced failure modes are considered in the earthquake event tree for the main dam:

a) Overtopping failure resulting from the vertical crest deformation (VD), and
b) Seepage erosion through cracks (SEC) failure resulting from disrupted filters and drains and transverse cracking developed by liquefaction-induced deformation (SEC).
The risk assessment is first performed for the initial stage (i.e., the existing condition baseline case) and for the various risk reduction measures (RRMs) as alternatives and as stages. A schematic of the DAMRAE runs for this hypothetical dam is shown in Figure 3.3. After the initial stage risk assessment, a stability berm and filter is implemented to saddle dam as Risk Reduction Stage 1 (RRS 1) to reduce the risk of piping failure under the flood loading and therefore with the flood event tree modified to represent this RRM. Following RRS 1, two alternatives are considered to further reduce the risk as ‘Risk Reduction Alternative 2.1’ (RRA 2.1) and ‘Risk Reduction Alternative 2.2’ (RRA 2.1). For the RRA 2.1, the repair of the main dam outlet works is considered to reduce the risk of the main dam embankment failure by piping along the outlet works whereas, a six-foot raise of the saddle dam to reduce the likelihood of overtopping failure.

**Figure 3.3.** Schematic of the DAMRAE runs for the existing condition and risk reduction alternatives and stages for the hypothetical dam
is considered under the RRA 2.2. Among these two competing alternatives, RRA 2.1 is selected for the implementation and it becomes the next stage of the risk assessment, (i.e., RRS 2) to be evaluated. To assess the possibility of further risk reduction following the ‘Risk Reduction Stage 2’, the three ‘Risk Reduction Alternatives 3.1, 3.2 and 3.3’ are considered, where these three alternatives are, respectively, spillway widening, raising the main and saddle dams, and raising the saddle dam only. Therefore RRA 3.2 includes the saddle dam raise that was evaluated under RRA 2.2.

2.1. Flood event tree

The Flood event tree for the flood and flood-internal induced failure modes is shown in Figure 3.4. Level 1 of the event tree is a continuous branch representing 500 intervals of annual exceedance probability (AEP) ranging from (1 in 1.01) to (1 in 1x10^8) for which event tree calculations are made in DAMRAE to analyses the entire range of flood loading. For each interval of AEP, the corresponding peak reservoir pool elevation (PRE) is interpolated from the peak reservoir elevation (PRE) flood frequency relationship (PRE vs. AEP) relationship shown in Figure 3.5 as the mid-point of each interval.

The Level 2 state function branch is included to calculate the peak discharge value corresponding to the mid-point peak reservoir pool elevation calculated for each interval are assigned in Level 1. The peak discharge values are interpolated from the user-input PRE vs. peak discharge relationship shown in Figure 3.6. This branch is required for the calculation of non-breach consequence (life-loss and economic consequences), which are defined as a function of peak discharge and used for the calculation of incremental failure consequences.
Figure 3.4. Flood event tree for the hypothetical dam

Levels 3 and 4 are state function branches representing the peak overtopping depth for the main and saddle dams, respectively. The overtopping depth is calculated by subtracting the respective dam crest elevation from each the mid-point peak reservoir pool elevation assigned in Level 1 of the event tree.
Level 5 is a failure branch group representing flood and flood-internal failure modes. The probabilities of the overtopping failure of the main and saddle dams are conditioned on their respective reservoir pool overtopping depths as calculated in Level 3 and 4, respectively, as shown in Figure 3.7 b and f. The SRP relationships shown in Figure 3.7 for the slope instability failure mode and the other piping failure modes are calculated as functions of the peak reservoir pool elevation that is assigned in Level 1. All seven failure modes included in Level 5 are considered to be non-mutually exclusive, and therefore, a common-cause adjustment option with SRP and consequence freezing [3] with respect to pool elevation is selected.

Level 6 includes the day and night exposure branches to represent the variations in the size and exposure conditions of the population at risk (PAR) over a 24-hour period. The day and night exposures are assigned exposure factors of 10/24 and 14/24, respectively, which are treated the same as branch probabilities in the event tree calculations.
a) Main dam slope instability SRP

b) Main dam overtopping SRP

c) Main dam piping through embankment SRP

d) Main dam piping through foundation SRP

e) Main dam embankment piping along outlet works SRP

f) Saddle dam overtopping SRP

g) Saddle dam piping SRP

**Figure 3.7.** SRP relationships for the main and saddle dams (Flood event tree Level 5 inputs)
Levels 7 and 8 of the event tree include the life-loss and economic consequence branches, respectively. Non-breach life-loss estimates are assigned as a function of peak discharge (Level 2), whereas different failure modes associated with the main and saddle dams are assigned as a function of peak reservoir pool elevation (Level 1). These various life-loss and economic consequence relationships are shown in Figure 3.8 and Figure 3.9, respectively.

2.2. Earthquake event tree

The earthquake event tree is shown in Figure 3.10. It begins with an earthquake loading or seismic hazard relationship represented by a continuous branch in Level 1.

This continuous branch represents 21 intervals of peak ground

\[ \text{Figure 3.8. Flood life-loss consequences (Flood event tree Level 7 inputs)} \]
accelerations (PGAs) ranging from 0.1g to 0.65g. The probability of each interval of PGA occurring is calculated as the difference of the annual exceedance probabilities (AEP) at each end of the interval, which are calculated from the PGA vs. AEP.

Figure 3.9. Flood economic consequences (Flood event tree Level 8 inputs)

Figure 3.10. Earthquake event tree for the hypothetical dam
relationship shown in Figure 3.11. A mid-point representative value of PGA is also calculated.

The Level 2 continuous branch represents 24 intervals of the range of reservoir stage between elevations 557 ft. msl. to 647 ft. msl. For each interval of reservoir stage (or pool elevation), the fraction of time that the interval of pool elevations occurs is obtained by taking the difference between the interpolated durations from the pool-duration relationship shown in Figure 3.12. A mid-point representative value of reservoir pool elevation is also calculated.

A state function branch is included in Level 3 of the event tree to obtain a best estimate the vertical crest settlement of the dam. For each assigned combination of a mid-point PGA value (Level 1) and a mid-point pool elevation value (Level 2), the best estimate of vertical crest deformation is interpolated from a two-way relationship of vertical deformation with PGA and pool elevation as shown in Figure 3.13. This relationship is based on estimates of vertical deformation obtained from applying the

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**Figure 3.11.** Earthquake loading (PGA-AEP) for the example risk scenario (Earthquake event tree Level I input)

**Figure 3.12.** Pool-duration relationships for the initial stage and two risk reduction alternatives (Earthquake event tree Level 2 input)
FLAC [4] model to the study dam for many combinations of PGA and pool elevation. In practice additional combinations would be considered for different ranges of earthquake magnitude (see Bowles et al. [5]) since this is an important consideration is estimating the response of an embankment dam and foundation to liquefaction. However, as a simplification, earthquake magnitude has not been included in this hypothetical example.

The estimated value of vertical deformation is used to obtain the conditional probability of overtopping failure in the failure branch in Level 4. Following the method described by Bowles et al. [5], the liquefaction-induced overtopping SRP is calculated based on constructing a judgmentally assigned triangular distribution about the best estimate of vertical deformation obtained in Level 3 to represent estimation uncertainty, and calculating the probability that the deformed crest elevation would fall lower than the pool elevation as schematically described in Figure 3.14. The inclusion of this consideration of uncertainty is important because of the extremely asymmetric nature of

![Figure 3.13](image1) ![Figure 3.14](image2)
the consequences or loss function. This method is assigned in DAMRAE using relational equations in a conditional statement (If-else) form of Equation 3.1.

\[
OT_{SRP} = \begin{cases} 
0, & c \leq a - 2b \\
1, & c \geq a - 0.5b \\
\frac{2}{3} \left( \frac{c-a+2b}{b} \right)^2, & c \leq a - b \ AND \ c > a - 2b \\
1 - \frac{4}{3} \left( \frac{a-0.5b-c}{b} \right)^2, & c > a - b \ AND \ c < a - 0.5b
\end{cases} \quad \text{...Eq 3.1}
\]

where, a, b, and c, respectively, represent the dam crest elevation, vertical deformation and pool elevation as shown in Figure 3.14.

If the pool elevation is not high enough to overtop the deformed crest of the dam to cause the overtopping failure in Level 4, the possibility of dam failure by seepage erosion through cracks (SEC) is represented in the failure branch in Level 5 of the event tree. The system response probability for a SEC failure is estimated using a two-way relationship with vertical deformation (Level 3) and pool elevation (Level 2) as shown in Figure 3.15. Unlike the overtopping failure which can be considered to initiate at the time of the earthquake, the initiation of the SEC failure mode takes place sometime after the earthquake occurrence [6]. This time delay in SEC failure initiation results in an increase in the warning time, which results in smaller estimates of life loss. The variability in this time delay is represented by a continuous branch included in Level 6 of the event tree. The continuous branch includes twenty intervals of time to SEC failure ranging from 30 minutes to 315 minutes. The associated probability of each time interval is estimated based on an exceedance probability relationship of the time to SEC failure as a function of pool elevation shown in Figure 3.16.

Level 7 exposure branches represent the day and night exposure cases, respectively, with exposure factors of 10/24 and 14/24, respectively. Levels 8 and 9
The life-loss consequences for the earthquake-induced overtopping failure are assigned as a function of pool elevation as illustrated in Figure 3.17, whereas the SEC failure life-loss in Figure 3.18 is conditioned on both the pool elevation and the time delay in SEC failure initiation as defined in Level 6. The economic consequences are assigned as a function of pool elevation as shown in Figure 3.19.

3. Risk reduction measures

The flood and earthquake event trees constructed for the existing dam baseline risk assessment were modified for the various risk reduction measures shown in Figure 3.3 as follows:

a) **Risk Reduction Stage (RRS) 1** – A new run-case was added following the ‘Initial Stage’ in the DAMRAE project hierarchy to contain the modified event trees for the case of implementing the stability berm and filter for the saddle dam. An equivalent annual implementation cost for this RRM was input as $697,048/year. The flood and earthquake event trees were copied
a) Day-time exposure

b) Night-time exposure

**Figure 3.17.** Earthquake overtopping failure life-loss

a) Day-time exposure

b) Night-time exposure

**Figure 3.18.** SEC failure life-loss

**Figure 3.19.** Failure economic consequences
from the initial stage and the saddle dam piping through embankment SRP relationship in Level 5 of the flood event tree was modified to represent the implementation of this RRM.

b) **Risk Reduction Alternatives (RRAs) 2.1 and 2.2** – Two alternative run-cases were added following RRS 1 in the DAMRAE project hierarchy to evaluate two options for the next risk reduction stage. Equivalent annual implementation costs were input as $348,524/year for both the alternatives. The flood and earthquake event trees were copied from RRS 1 for both of these alternative run-cases. For RRA 2.1, the SRP relationship for the main dam embankment piping along the outlet works in Level 5 of the flood event tree was modified to represent the repair of the main dam outlet works. For RRA 2.2, the flood event tree Level 4 relational equation was changed to represent the six-foot raise of the saddle dam.

c) **Risk Reduction Stage (RRS) 2** – Since RRA 2.1 was selected to be implemented as RRS 2 this new run-case was added following RRS 1 in the DAMRAE project hierarchy by copying the flood and earthquake event trees from RRA 2.1 without any modification and the same equivalent annual implementation cost of $348,524/year was input.

d) **Risk Reduction Alternatives (RRA) 3.1, 3.2 and 3.3** – Three alternative run-cases were added following RRS 2 to evaluate these options for the next stage of risk reduction. Equivalent annual implementation costs of $2,788,191/year, $3,485,239/year and $348,524/year, respectively, were input. The flood and earthquake event trees for each of these alternative run-cases were copied
from the RRS 2 and the modifications that are listed in Table 3.2 were made.

4. Results

DAMRAE was used to quantify the event trees for the existing dam baseline condition, risk reduction alternatives and risk reduction stages described in Sections 2 and 3. Some of the results obtained using DAMRAE are discussed in the following subsections.

4.1. Annual probability of failure (APF)

A comparison of the estimated annual probabilities of failure for the initial stage,

| Table 3.2. Changes in the event trees for risk reduction alternatives 3.1, 3.2, and 3.3 |
|-------------------------------|-------------------|-------------------|
| **Run-Case** | **Modifications** | **Earthquake Event Tree** |
| Risk Reduction Alternative 3.1 – Spillway widening | Level 1 PRE-AEP relationship modified as shown in Figure 3.5 to represent spillway widening | Level 2 Pool-Duration relationship modified as shown in Figure 3.12 to represent spillway widening |
| | Level 2 Peak Stage – Peak Discharge relationship modified as shown in Figure 3.6 to represent spillway widening | |
| Risk Reduction Alternative 3.2 – Raise main and saddle dams | Level 1 PRE-AEP relationship modified as shown in Figure 3.5 to represent raising main and saddle dams | Level 2 Pool-Duration relationship modified as shown in Figure 3.12 to represent raising main and saddle dams |
| | Level 2 Peak Discharge relationship modified as shown in Figure 3.6 to represent raising main and saddle dams | Level 4 Overtopping SRP function modified to include the new dam crest elevation (679 ft.) to represent raising main and saddle dams |
| | Dam crest elevations increased by 6 ft. in relational equations of Level 3 and Level 4 to represent raising main and saddle dams | |
| Risk Reduction Alternative 3.3 – Raise saddle dam | Relational equation of Level 4 is modified to include the new saddle dam crest elevation (679 ft.) | |
risk reduction alternatives, and risk reduction stages is presented in Figure 3.20. Total annual probabilities of failure representing combined contributions of all the failure modes included in the flood and earthquake event trees under each run case are plotted in

![Total annual probability of failure for different run cases](image)

### Figure 3.20. Annual probability of failure

**a)** Total annual probability of failure for different run cases

**b)** Percent contribution of various failure modes to the total annual probability of failure
Figure 3.20 a) and the percent contributions of each failure mode to the total APF are presented in Figure 3.20 b). The total APF for the initial stage is estimated as $4.20 \times 10^{-3}$/year, where the saddle dam piping failure has a major contribution of about 89%. After implementing the saddle dam berm and filter to address the piping failure mode in RRS 1, the total APF value is estimated to be reduced to $4.64 \times 10^{-4}$/year and the saddle dam piping failure contribution falls down to 0.82%.

For RRS 1, the largest contributions come from the main dam piping along the outlet works (about 59%) and the saddle dam overtopping (about 29%) failure modes. The options to reduce the likelihood of these failures modes are considered in RRA 2.1 (repair the main dam outlet works) and RRA 2.2 (raise saddle dam). RRA 2.1 has a greater impact on the estimated total APF and is selected as RRS 2. The estimated total APF for RRS 2 is estimated to be reduced to $1.92 \times 10^{-4}$/year, but this is higher than the USACE APF tolerable risk limit value of $1.0 \times 10^{-4}$ (i.e., 1 in 10,000)/year. Next RRA 3.1 (spillway widening), RRA 3.2 (raise main and saddle dams) and RRA 3.3 (raise saddle dam) are evaluated. The total APF value is estimated to be reduced below the tolerable risk limit guideline for RRA 3.1 and RRA 3.2, but not for RRA 3.3.

4.2. Annualized incremental life loss (ALL)

The totals of the estimated annualized incremental life loss for different run cases are displayed in Figure 3.21 a), and the percent contributions of the various failure modes to each total are shown in Figure 3.21 b).

After implementing the saddle dam berm and filter piping fix in RRS 1, the contribution of the saddle dam piping failure to the total ALL is estimated to be reduced from 66% to 0.19%, and the total ALL value, which is estimated as $1.68 \times 10^{-1}$ lives/year.
for the initial stage, is estimated to be reduced to $5.72 \times 10^{-2}$ lives/year.

RRA 2.1 (repair main dam outlet works), which is implemented as RRS 2, is estimated to give a greater reduction in the total ALL value than RRA 2.2 (raise saddle
The estimated total ALL value for RRS 2 is $1.49 \times 10^{-3}$ lives/year, which is higher than the tolerable risk limit value of $1.0 \times 10^{-3}$ (0.001) lives/year. RRAs 3.1 (spillway widening) and 3.2 (raise main and saddle dams) are estimated to reduce the total ALL but not quite below the ALL tolerable risk limit value; whereas RRA 3.3 (raise saddle dam), which showed a reduction in the total APF, is estimated to result in a slight increase in the total ALL value compared with RRS 2. This demonstrates an adverse effect of reducing the probability of the saddle dam safer because there is an increase in the probability of failure of the main dam, which has higher life-loss consequences compared with the saddle dam. RRA 3.1 or RRA 3.2 could be selected to be implemented as RRS 3 following RRS 2 in the DAMRAE project hierarchy and further risk reduction alternatives, perhaps non-structural in nature, could be evaluated.

4.3. USACE tolerable risk guidelines charts

F-N charts developed for different run cases are shown in Figure 3.22 for evaluation of the USACE societal risk limit guideline. Figure 3.22 a) shows the F-N curves for the initial stage and the two risk reduction stages, where only RRS 2 meets the USACE societal risk limit guideline. Similarly, Figure 3.22 b), which shows the F-N curves for RRS 2 and the three subsequent risk-reduction alternatives [RRA 3.1 (spillway widening), RRA 3.2 (raise main and saddle dams) and RRA 3.3 (raise saddle dam)], indicates that all four cases displayed in the figure meets the USACE societal risk limit guideline. The increase in life-safety risk for RRA 3.3 can be seen by comparison with RRS 2 in Figure 3.22 b).

Non-breach F-N charts developed to evaluate the non-breach inundation risk are shown in Figure 3.23. It is noted that showing the guidelines on these charts is only for
reference purposes. Non-breach F-N curves for the initial stage and the two risk reduction stages, shown in Figure 3.23 a), appear to be almost identical as there is only a slight difference in non-breach probabilities and the peak discharge values on which the non-breach consequences are dependent are similar for all the three cases. For the RRS 2 and the three subsequent risk reduction alternatives [RRA 3.1 (spillway widening), RRA 3.2 (raise main and saddle dams) and RRA 3.3 (raise saddle dam)], the non-breach F-N curves, shown in Figure 3.23 b), are more distinguishable from each other because the peak discharge relationship and the threshold of the discharge value where the failure occurs differs for each of these run cases. While RRA 3.2 lowers the total exceedance probability of non-breach life loss (i.e. at N = 1), by raising both the main and saddle dams, the range of non-breach life loss is expanded to a higher number of fatalities. This increase in fatalities can be attributed to increased storage capacities of both the dams.
Figure 3.24. Non-breach F-N charts

$f-N$ Charts are shown in Figure 3.24 for total $f-N$ pairs but not for individual failure modes due to space constraints in this paper. The total $f-N$ pairs for the initial and two risk reduction stages are presented in Figure 3.24 a) and show that the USACE APF and ALL tolerable risk limit guidelines are not met for all three run cases. The total $f-N$ pairs for RRS 2 and three subsequent risk reduction alternatives [RRA 3.1 (spillway widening), RRA 3.2 (raise main and saddle dams) and RRA 3.3 (raise saddle dam)] are presented in Figure 3.24 b) and show that RRA 3.1 and RRA 3.2 falls in a region where the tolerable APF limit guideline is met but the ALL limit guideline is not met, indicating that there may be justification for the further risk reduction.

4.4. Cost effectiveness, disproportionality and benefit:cost ratio evaluation

The quantitative measures of ALARP evaluation of Cost to Save a Statistical Life
(CSSL) and Disproportionality Ratio (R) are calculated by DAMRAE for each of the risk reduction stages and alternatives included in a project. Also, Benefit:Cost ratios (BCR) are calculated for each of the risk reduction stages and alternatives. Table 3.3 lists the estimated values for CSSL, R and BCR. It is to be noted that the CSSL and R values are displayed as N.A. (not applicable) if the computed BCR value is negative for the respective run cases.

Under the Tolerability of risk approach [2], risk reduction to the limit guidelines is normally considered to be required regardless of cost. Therefore, these parameters are normally considered only after the risk is reduced to the point where all the tolerable risk limit guidelines are met, which is not achieved for ALL in this hypothetical example project. If the values of CSSL and R for RRS 1 and RRA 2.1 (RRS 2) were obtained for

Figure 3.24. $f\bar{N}$ Charts
cases where all limit guidelines were already met, these values are small enough to indicate a strong case for proceeding with further risk reduction, whereas the large values obtained for RRA 3.1 and RRA 3.2 indicate a very poor case for proceeding with risk reduction. Again it is emphasized that these cost effectiveness and disproportionality measures would not normally be consider for any of these cases since the limit guidelines are not already met.

5. Concluding remarks

The hypothetical example dam safety risk assessment presented in this paper demonstrates the DAMRAE functionalities. The example illustrates flood and earthquake event trees for various failure modes for two dams forming the same reservoir considering a full range of loading. Non-mutually exclusive failure modes are handled through the calculation options available in DAMRAE for common-cause adjustment and SRP and consequences freezing. The earthquake risk model presented here does not explicitly include the liquefaction and instability events in the event tree structure as the liquefaction and stability analyses are combined within the FLAC [4] model that was
used to estimate the vertical crest deformation relationship used in Level 3 of the earthquake event tree.

Following the assessment of the existing dam baseline condition, various risk reduction measures are evaluated by adding new run cases in the DAMRAE project hierarchy. Due to the space constraints, only a few example outputs of DAMRAE are presented in this paper. However, DAMRAE generates detailed outputs for each of the event trees under various run cases, which are combined and compared to evaluate the risk reduction measures.

The efficiency and flexibility with which dam safety risk assessment can be performed using the DAMRAE software is in contrast to the use of spreadsheets or commercial software that is developed for primarily for business applications and not well suited for the needs of dam safety risk assessment as discussed in Chapter 1.

This particular hypothetical example highlights the following observations:

a) If the failure of main and saddle dams are considered in the risk assessment as competing with each other (i.e., non-mutually exclusive events), any attempt to reduce the risk for one of these dams and not the other could result in a higher risk for the other dam.

b) Another form of the first observation is that for the non-mutually exclusive failure modes in an event tree, any risk reduction measure implemented to address a particular failure mode reduces the probability for that failure mode but redistributes the decreased amount of probability to other failure modes. Therefore, a risk reduction measure that reduces the total APF and the APF of
a particular failure mode could increase the APF of another failure mode and hence, could increase the annualized consequences for the other failure mode.

c) The flood failure and non-breach inundation cases are complementary events. Efforts to reduce the failure probability increase the non-breach inundation probability, with a resulting effect on the probability of non-breach inundation consequences that should be carefully assessed.

References


ABSTRACT

Based on a generalized event tree algorithm, a deterministic event tree based risk model referred to as DAMRAE was developed for dam safety risk assessment. With the objective of incorporating an uncertainty analysis functionality in DAMRAE, we review various aspects and requirements of uncertainty analysis in the context of dam safety risk assessment, and extend the DAMRAE framework to develop a generic risk and uncertainty analysis tool, DAMRAE-U, for dam safety risk assessment. DAMRAE-U is structured to represent knowledge uncertainty for the event tree variables and natural variability associated with flood and earthquake loading. It also provides for separating the effects of uncertainty in the existing condition of the dam system on which the event tree model is dependent and representing this source of uncertainty in a logic tree. In this paper, we review the background for uncertainty analysis in dam safety risk assessment and present the details of the DAMRAE-U computational framework.

1. INTRODUCTION

Probabilistic risk assessment of a dam system is commonly based on the event tree form of risk model. A generalized computational framework, known as DAMRAE, was developed by the authors to support the deterministic form of event tree calculations. The word ‘deterministic’ is used in the sense that the branch probabilities and state values assigned to different branches in the event tree are either
fixed values or non-stochastic relationships. The natural variability (aleatory uncertainty) in the outcomes of random events (state variables), such as flood inflow to a reservoir, seismic ground acceleration, spillway gate reliability, the likelihood and extent of spillway plugging with debris, population exposure scenarios, and the timing of warning and evacuation, can be represented by branches emanating from a node on the event tree. However, the presence of knowledge (epistemic) uncertainty associated with probabilities associated with the various branches is omitted in the deterministic approach. Sometimes reasonable best estimate values, as judged by subject matter experts, are used but in other cases it may be appropriate to use somewhat conservative values in a deterministic form of event tree analysis when significant uncertainty is recognized, especially at a screening level. Sensitivity analysis may be useful in the situation where only determinism analysis is being used to explore the effects of the range of uncertainty and its effect on decision making.

The deterministic event tree analysis in DAMRAE generates the risk estimates in various forms including annual risk estimates (probability of dam failure and expected values of life-loss and economic consequences) and graphical displays such as charts for evaluating USACE tolerable risk guidelines charts: F-N charts\(^5\) displaying exceedance frequency (\(\geq\)) – incremental life-loss estimates; F-$ charts displaying exceedance frequency (\(\geq\)) – incremental life-loss estimates; F-$ charts displaying exceedance frequency (\(\geq\)) – incremental life-loss estimates; F-$ charts displaying exceedance frequency (\(\geq\)) – incremental life-loss estimates; F-$ charts displaying exceedance frequency (\(\geq\)).

\(^5\) The F-N chart, which is an annual probability of exceedance of life loss (F) versus the incremental life loss (N) plot, is commonly known in the literature\(^{(1,2)}\) as the “risk curve”. For a particular life-loss level (say n) on the abscissa, the ordinate corresponds to the frequency with which the life-loss level n or greater (\(\geq\)) is estimated to occur; although the literature is not entirely consistent and sometimes the ordinate represents the frequency that the life-loss level n is estimated to be exceeded (\(>\)). We have adopted the more conservative \(\geq\) convention in our work. In the deterministic form of event tree analysis, the natural variability included in the event tree model defines the extent of the curve on both the axes.
frequency (≥) economic consequences; and \( f-\bar{N} \) charts displaying annual probability of failure vs. an estimate of life loss as a weighted average over failure modes and exposure scenarios.

In case of a risk analysis of risk reduction options, additional decision variables such as Risk Reduction Benefits, Risk Reduction Cost, Benefit:Cost Ratio, Cost to Save a Statistical Life (CSSL), and Disproportionality Ratio (R) are also calculated as described in Chapter 2.

The Office of Management and Budget \((^3)\) has emphasized the important of properly accounting for uncertainties in conducting risk analyses to justify federal government decisions and expenditures. Referring to the six levels of analytical sophistication in risk analysis that were suggested by Paté-Cornell \(^2\), the “deterministic” DAMRAE framework is classified as a Level 4 analysis. Our objective in this paper is to extend the DAMRAE computational framework to a Level 5 analysis which includes explicit probabilistic characterization of knowledge (epistemic) uncertainties associated with various branch inputs, such as loading and system response probabilities and consequences. In Section 2 we explore the conjunction between dam safety and risk and uncertainty analysis, and provide an overview of uncertainty analysis. In Section 3, a classification structure to identify the uncertain variables in dam safety risk analysis is proposed. In Sections 4, the generic extended theoretical framework is described. The framework is referred to as DAMRAE-U, to efficiently characterize, propagate, and display the outcomes of uncertainty analysis based on event tree modeling. The paper closes with a summary and conclusions section. The Chapter 5 contains an example application of DAMRAE-U to a hypothetical dam.
2. DAM SAFETY AND RISK AND UNCERTAINTY ANALYSIS

Risk and uncertainty are ubiquitous terms in a variety of fields spanning from psychology to the space shuttle, and therefore, unsurprisingly, many definitions of these terms and views about their relationship appear in the literature. However, in the context of engineering applications, a common notion is to accept risk and uncertainty as dependent terms. In a quantitative sense, risk is defined as a triplet set of scenario, likelihood, and consequence \( R = (s, p, c) \), and uncertainty is inevitably involved in the assessment of all three elements.

Uncertainty analysis is viewed as a means of quantifying or estimating the degree of confidence in risk analysis outputs based on characterizing the principal sources of uncertainty in the analysis inputs. An appropriate treatment of uncertainty in risk quantification is also considered to be important to support decision making that is informed by the results of risk analysis. The same conjunction between risk and uncertainty applies to the dam safety field; although there are very few practical examples of the use of formal uncertainty analysis in dam safety risk assessment that can be found in the literature.

The risk associated with dam failure is quantified by developing event tree models for the significant risk scenarios. For dam safety, these scenarios are typically defined following the general source-pathway-receptor approach as proposed by Rowe and adapted for dam safety by Bowles et al. Sources include external (e.g. flood or earthquakes) or internal initiating events (e.g. internal erosion) that can threaten the safety of a particular dam. Pathways include the response of the particular reservoir-dam-foundation system to external and internal initiating events, the outcomes of those
responses, including normal operation or dam failure, and the routing of non-breach and failure floods downstream of the dam to the location of receptors or via other non-physical pathways such as those applying to financial or reputation consequences of dam failure for the dam owner. Exposure factors that represent whether or not receptors will be present to be exposed to the non-breach or failure conditions are commonly included in the pathways. Receptors include the people, physical objects and other entities or systems that can be affected by the failure of a dam, where the consequences of dam failure are typically considered to be incremental in the sense of the increase in the magnitude of consequences over those that would occur without dam failure (e.g. flood damages due to normal operation of a spillway that may release large flows through an urban area).

An event tree is a graphical model, which can be represented in a general symbolic form as $\mathbb{E}[s, p(s), c(s)]$, where $s = [s_1, s_2, s_3, ...]$, $p(s) = [p_1, p_2, p_3, ...]$ and $c(s) = [c_1, c_2, c_3, ...]$ are vectors of state variables that are represented by event tree branches, probabilities of the state variables taking on various values, and the consequence values associated with each vector of state values, respectively. The conditional probabilities and consequence values that are represented by event tree branches are generally functions of state values for preceding branches in the event tree.

Uncertainty is intrinsic to all three types of inputs ($s, p$ and $c$) in an event tree model. In engineering contexts, uncertainty is often broadly classified into two categories as Aleatory (natural variability) or Epistemic (knowledge) uncertainty. (4) Aleatory uncertainty arises from the inherently random character of a variable in the real physical world, whereas knowledge uncertainty derives from the lack or absence of adequate
knowledge to assess the underlying phenomena associated with the variable. In addition, knowledge uncertainty is often increased by deliberate choices of model simplification, constraints on available sampling (observations), and various errors associated with measurements and modeling. As mentioned before, aleatory uncertainty in loading variables in dam safety risk analysis is commonly modeled as an initiating event in the event tree structure, but the representation of knowledge uncertainty is much less commonly included. Some researchers support the probabilistic approach as the most logical and sufficient methodology for addressing the knowledge uncertainty \(^{6, 12-15}\), while others propose alternate approaches, such as fuzzy set theory, evidence theory, possibility theory, probability bounds, interval analysis, and various combinations of such theories.\(^{16-20}\) However, the probabilistic approach to characterizing epistemic uncertainties offers the most intuitive and practical approach for application in the dam safety field.

In addition to the above, another source of uncertainty that can affect dam safety is policy uncertainty. This is defined by NAP \(^{21}\) as “uncertainty with respect to a course of action means that a plan is not determined or is undecided.” Examples of this type of uncertainty can include decisions that will be made about factors that affect population growth that will affect the size of the population at risk and hence the magnitude of dam failure consequences. We do not address policy uncertainty in this paper, except to suggest that an effective way to consider it is through scenario modeling in which alternatives policy outcomes are considered and their effect on dam-safety decisions are evaluated.

Considering the input uncertainties, the event tree representation can be modified
as \( \Xi[s, p(s), c(s)|K, V] \), where \( K \) and \( V \) represent the knowledge uncertainties and natural variability, respectively. In the deterministic DAMRAE version, \( K \) is not explicitly considered in DAMRAE calculations and single state values, \( K = k \), are considered as representative values to obtain point values of the risk estimates. The basic risk estimates obtained from an event tree quantification are probabilities of dam failure \( (P_f = [P_{f_1}, P_{f_2}, P_{f_3}, \ldots]) \) and corresponding annualized incremental failure consequences (life loss or economic consequence) \( (C_f = [C_{f_1}, C_{f_2}, C_{f_3}, \ldots]) \) for the potential failure modes \( f_1, f_2, f_3, \ldots \) included in the event tree. A general formulation to calculate the annual probability of failure and annualized consequences for a particular failure mode \( (f_i) \) can be given as follows:

\[
P_{f_i} = \sum_v \left[ \prod_{l=1}^{L} (p^l|s^l, s^{l-1}, \ldots, s^1) \right] = \sum_v \mathbb{P}^L \quad \ldots 4.1
\]

\[
C_{f_i} = \sum_v \mathbb{P}^L [c(s) - c^n(s)] \quad \ldots 4.2
\]

where \( p^l \) is the probability assigned to a branch at level ‘\( l \)’ in the event tree \( (p^l \in p) \), \( c \) is the failure consequence value per event \( (c \in c) \), \( c^n \) is the non-breach consequence value for the respective event, and the summation over ‘\( V \)’ takes place over the natural variability range of the end node probabilities \( (\mathbb{P}^L) \) included in the event tree. The aleatory range represents an inclusive set of all the possible combinations of the random states of the state variables that are represented by the branches in the event tree model. The pairs of \( \{\mathbb{P}^L, c\} \) for each state \( v \in V \) are collected to generate the risk curve.

Under the probabilistic approach, the knowledge uncertainty of a state variable is characterized using a probability distribution rather than a point value as is the case for
the deterministic approach. These distributions are estimated on the basis of the available empirical information combined with expert opinion and judgment. The assigned distributions are propagated through the event tree model to determine the distributions of the risk estimates. The uncertainty propagation step is performed using a stochastic simulation method such as Monte Carlo. The Monte Carlo simulation (MCS) approach is commonly used as an efficient approach for such a purpose\(^{(19, 22)}\) and we develop our generic computational framework based on the same approach. The outcome distributions of the risk estimates can be presented as a cumulative distribution function (CDF) or as a complimentary cumulative distribution function (CCDF), which is more suitable for the decision making for dam safety.

3. ANALYSIS CLASSIFICATION STRUCTURE

Dam safety risk analysis is an integrated procedure which logically synthesizes the engineering performance aspects of a dam-reservoir system and its surroundings to obtain quantitative risk estimates over the full range of credible and significant external and internal hazards. This analysis is useful for evaluating existing risks and for justifying and prioritizing technical and monetary resources for risk reduction and improved risk management in the context in which the dam is owned and operated. In Figure 4.1 we propose an uncertainty analysis classification structure comprising initial uncertainty, risk estimation uncertainty and decision justification uncertainty.

3.1. Initial Uncertainty

The evaluation of future performance of a dam system is conditioned upon the state or condition of the dam system at the present time and the characteristics (such as
The frequency and severity) of a peril that could unexpectedly occur in a future time. The uncertainty associated with these two conditions is designated as Initial Uncertainty.

Important aspects of the uncertainty about the existing condition of a dam system can be included in an uncertainty analysis using a Logic Tree that precedes the event tree. Thus the logic tree represents the initial uncertain states on which the system response relationships represented in the event tree structure are dependent.\(^{(23)}\) The logic tree branches can represent different uncertain properties or flaws associated with, for example, the embankment fill material (e.g., erosion, seepage, saturation, burrows or root holes, etc.), foundation material (e.g., compaction, seepage, etc.), dam structure or its appurtenances (e.g., cracks, spalling and pop-outs, condition of valve or gates, spillway plugging, etc.), and the relevant maintenance, operation and performance history. The initial characterization of such properties and flaws is subject to uncertainty due to the

**Figure 4.1.** Analysis classification structure for dam safety risk assessment
variations in geology, soil and hydraulic properties, and various technical and analytical limitations involved in their assessment. An uncertainty variable included as a logic tree branch could be aleatory (e.g., moisture content of the embankment material, blanket thickness, SPT (Standard Penetration Test)\(^{(24)}\) blow counts for the foundation material, etc.) or epistemic (e.g., extent of cracking at the structure-foundation interface, seepage location and condition, etc.), or a combination of aleatory and epistemic. Uncertainties can be specified using a deterministic sensitivity analysis approach (e.g., flaw-no flaw, degrees of flaw) or characterized using a probability distribution.

The flood and earthquake initiating events are commonly characterized in the event tree model using a cumulative probability distribution of annual exceedance probability (AEP) vs. peak reservoir elevations (PRE) or peak ground accelerations (PGA). The distribution encompasses the aleatory uncertainty, i.e., the entire range of inflow flood events or possible earthquake events. Separate distributions can be developed for different flood generating mechanisms (e.g. snow melt or convective storms) and for different earthquake magnitude ranges. These distributions are developed within the realm of technical and scientific procedures and their associated limitations, which include knowledge uncertainty such as measurement errors, model selection error, parameter selection error, data uncertainty, and operational uncertainty.\(^{(25-28)}\) To account for the knowledge uncertainty, probability distributions for PRE or PGA can include confidence intervals as illustrated in Figure 4.2 a and b, respectively.

3.2. Risk Estimation Uncertainty

The fundamental steps within the risk estimation level are as follows: a) Estimation of the chance of failure of a dam system in future performance due to various
existing conditions within the dam system (e.g. defects) or externally imposed loads that exceed the dam system capacity, and b) Estimation of the downstream and other consequences (e.g., property damage, monetary loss, life loss, loss of services, etc.) of dam failure.

The estimation of dam system failure probability is based on the system response or fragility curves. In simple scenarios, a system response relationship, developed for a specific failure mode, such as overtopping or internal erosion, directly relates the conditional probability of the dam system failure to the initiating event. However often, in complicated scenarios, system response probabilities (SRPs) are function of various intermediate state variables. Some examples of the state variables, which are frequently used in the event tree models, are vertical and horizontal deformation of the dam crest in response to an earthquake; and percent spillway plugging and debris blockage, number of

**Figure 4.2.** Example knowledge uncertainty distributions on Flood (PRE-AEP) and Earthquake (PGA-AEP) loadings
operating spillway gates, overtopping depth, and peak discharge for floods.

After defining the existing condition of the dam system and the initiating event, the event tree model is continued with adjoining the branches to represent the relevant state variables that characterize each significant failure modes. The epistemic uncertainty associated with SRPs for each state variable, such as percentage spillway plugging or number of functional spillway gates, can be structured in the event tree model itself using multiple branches, or alternatively, discrete probability distributions could be assigned for these variables. Similar to the AEP curves of the initiating event, SRP relationship curves with uncertainty bounds are input to the event tree model.

The event tree model is further extended, after the failure level, to structure the consequence assessment level of the analysis. The consequence part of the event tree (also, referred to as consequence sub-tree (23)) includes branches to represent the exposure cases for characterizing the temporal variation in the presence of people or other objects or entities for a dam failure or no-failure scenario, and b) the consequence estimates for failure mode-exposure scenarios. The exposure cases are considered as model domain parameters, and are included in the event tree model as multiple discrete branches to represent the seasonal (e.g., winter and summer), diurnal (e.g., day and night), hourly, or any other possible exposure cases. The selections of consequence types and consequence areas (or impact zones) are also model domain parameters, but they are not treated as uncertain parameters. Their selection is site-specific and depends on the requirements for

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6 Morgan and Henrion (29) define the model domain parameters as “Model domain parameters specify the domain or scope of the system being modeled, generally by specifying the range and increments for index variables”. In case of dam risk assessment, exposure cases controls the temporal detail of the downstream consequences and therefore, are considered as model domain parameters.
decision making. The consequence values, which are assigned to the consequence branches in the event tree, come from an external flood inundation model of the downstream area. The flood inundation modeling has its own inherent uncertainties arising from uncertainties in breach formation time and geometry, topographic representation, hydraulic parameters and modeling techniques, and geospatial operations. These uncertainties are included in the event tree model, as part of the uncertainties in the estimates of consequence using suitable probability distributions that are assigned to the consequence branches.

3.3. Decision Justification Uncertainty

For the base (or existing) case risk analysis, the outputs obtained from the risk estimation level are used as decision variables. The basic decision that is to be made is whether or not the dam is adequately safe in its existing condition and with its existing operational and risk management regime. This decision should not be the automatic result of applying decision criteria to the evaluation of estimates obtained from a risk analysis. However, decision guidelines, including tolerable risk guidelines (TRG) for judging the significance of life-safety risk can play an important role in informing the risk evaluation and subsequent decision-making process. From a technical perspective, the outcome of the dam safety risk assessment process is to recommend and make a case for or justification for a decision.

Tolerable risk guidelines for dam safety have been developed by various organizations, including the Australian Committee of Large Dams, Bureau of Reclamation and US Army Corps of Engineers. Typically, in countries with a common law legal system, these guidelines follow a two-part evaluation process as
established by the UK Health and Safety Executive (HSE). The first part compares total estimated risk for all failure modes against the tolerable risk limits for Individual Risk (IR) expressed as a probability of life loss for the identifiable person(s) most at risk and for Societal Risk (SR) expressed as a limit of tolerability line on an F-N chart. Variations of TRG used for dam safety also consider tolerable risk limits for Annual Probability of Failure (APF) as a measure of the performance of the dam and Annualized Life Loss (ALL) as the expected value or average annual magnitude of life loss from the probability distribution of life loss for Societal Risk in the F-N chart.

The second part of the risk evaluation process is a determination of whether risks have been reduced to be as low as reasonably practicable (ALARP). This evaluation is both qualitative and quantitative in nature and typically, it should take the following into account: (36) the level of risk in relation to the tolerable risk limits; the disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk-reduction measures and the subsequent risk reduction achieved; the cost-effectiveness of the risk-reduction measures; compliance established good dam safety practice; and societal concerns as revealed by consultation with the community and other stakeholders. To conduct an ALARP evaluation requires that practical options for reducing the risk through structural and non-structural means are identified and evaluated.

The consideration of the cost effectiveness or “disproportionality” associated with the cost of achieving life-safety risk reduction relative to the life-safety benefit achieved is a quantitative aspect of an ALARP evaluation. This introduces the consideration of cost, but only to justify further incremental risk reduction below the tolerable risk limits, and not to justify achieving those limits in the first place. Hence, there is normally no
consideration of a “balancing” of the economic impacts of operating restrictions and the reductions in life-safety risk in meeting the tolerable risk limits.

Therefore in case of a risk analysis of risk reduction options, additional decision variables such as Risk Reduction Benefit, Risk Reduction Cost, Benefit:Cost Ratio, Cost to Save a Statistical Life (CSSL), and Disproportionality Ratio (R) are considered. The calculation of these variables utilizes the annual risk estimates, and other quantities, such as project life, cost of risk reduction, incurred operation and maintenance cost, discount rate, and willingness to pay (WTP) for life-safety risk reduction,\(^7\) as inputs. The project life is a model domain parameter as it defines the life span of a dam over which the monetary expenses and accrued benefits are estimated, and hence, is not considered as an uncertain quantity. Other input quantities (different costs, discount rate, and WTP) are value parameters\(^8\) to the analysis. In dam safety risk analysis, these values are used for a comparison of different risk reduction alternatives and therefore, their approximate or projected values are usually assigned by the risk analyst. Moreover, if required, sensitivity analysis could be performed to explore the sensitivity of these value parameters.

The variable classification proposed in Figure 4.1 and described above is intended to aid the investigation and identification process of critical uncertain variables that are involved in various steps of the risk analysis. In the framework that we propose in this paper the initial, risk estimation and decision justification uncertainties are not treated as three disjoint steps but rather as an integrated approach to an uncertainty analysis for a

\(^7\) Often referred to as value for saving a life (VSL) (e.g., USDOT \(^{34}\))

\(^8\) “Value parameters represent aspects of the preferences of the decision makers or the people they represent.” – Morgan and Henrion.\(^{29}\)
4. DAMRAE-U COMPUTATIONAL FRAMEWORK

In the deterministic computational framework of DAMRAE, which is shown schematically in the top part of Figure 4.3, single point estimates, $X_1 = x_1, X_2 = x_2, ... (X_1, X_2, ..., \epsilon X^e)$ of state variables such as flood or earthquake loading, system response relationships and consequences, along with other fixed inputs ($d^e$) (e.g., dam crest elevation), are processed through the event tree model $\mathcal{E}(X^e, d^e)$ to obtain the point estimates of the annual probability of failure (APF), annualized life loss (ALL), annualized economic consequences (AEC), maximum and minimum values of life loss ($R_{LL}$) and economic consequences ($R_{EC}$). Also, single traces in the F-N chart are generated to compare against the tolerable societal risk limit guidelines. (33)

In DAMRAE-U, this deterministic computational framework is enclosed within a generalized Monte Carlo simulation framework. DAMRAE input features are extended to allow definition of parametric or empirical forms of probability distributions for the uncertain variables and to assign the correlation among those variables. The computational framework of DAMRAE-U is framed to provide alternatives forms of uncertainty analysis simulation as described in the following two subsections and represented schematically in parts a) – b) of Figure 4.3.
4.1. Event Tree Simulation

Parametric (e.g., Uniform, Normal, Triangular, etc.) or other user-specified or empirical forms of probability distributions \((D_1, D_2, D_3, \ldots)\) are assigned by the user to characterize the uncertain variables in the event tree. Using those distributions, correlated samples of the uncertain variables are generated using the Latin Hypercube sampling technique. Each set of the correlated samples is iteratively propagated through the event tree model to generate risk estimates and an F-N curve corresponding to each sample. The samples of the risk estimates are collected and further processed to generate the percentile curves as CDFs. The percentile curves for the F-N risk curve are obtained by collecting the samples of exceedance frequency \(F\) for a predefined set (bins) of life-loss...
4.2 Logic Tree – Event Tree Simulation

Risk assessment of a dam system is basically an assessment of its future performance. This assessment is conditioned upon the existing state of the dam system and uncertainty about what that state is, such as uncertainty about the existence of a flaw (e.g., hydraulic fractures in the embankment due to cross valley arching $^{(36)}$) which could initiate internal erosion. To incorporate uncertainty about such existing conditions in the analysis, the Logic Tree can be used in front of the event tree. The logic tree structure can be used to represent the uncertain existing states on which the system response relationships represented in the event tree structure are dependent. $^{(23, 37)}$

The concept of logic tree used here is a widely recognized tool to quantify and incorporate knowledge uncertainty in the field of probabilistic seismic hazard analysis (PSHA).$^{(38)}$ Different sources of knowledge uncertainty (e.g., alternative models or alternative parameter values) which lead to different sets of inputs for the hazard analysis model are included in different levels of the logic tree where each uncertainty source could either take a form of discrete branches with weights (or confidence of the analyst) assigned to each branch or it could be represented using a continuous distribution. Similar application of logic trees can be used for the dam safety risk analysis where the existing state uncertainty can be represented in the logic tree. Logic trees and event trees can also be used to separate knowledge uncertainty and natural variability (e.g., Bowles et al. $^{(8)}$) or to make other types of distinctions but in this paper we limit ourselves using the logic tree to representing uncertainty in the existing state of the dam system.

Each logic tree branch in DAMRAE-U either represents an uncertain variable
(X^t \in X^t) or an uncertain fixed quantity (d^t \in d^t). All reasonably possible combinations of the values for the logic tree variables (X^t), included in different levels of the logic tree model (L[X^t, d^t]), form the possible existing system states (e = e_j, j = 1, 2, 3, ... ) for the event tree model [\mathcal{E}(X^e, d^e)]. An uncertain variable (X^t \in X^t), included in a logic tree model L[X^t, d^t] to represent a particular current state, could exhibit natural variability (e.g., moisture content of the embankment material, blanket thickness, etc.) or knowledge uncertainty (e.g., extent of cracking at the structure-foundation interface, seepage location and condition, etc.), or a combination of both. Based on the method used to specify the inherent uncertainty in the logic tree variables, the following three types of simulation options are provided in DAMRAE-U.

4.2.1. Sensitivity Analysis

Uncertainties in the logic tree or event tree variables can be represented by bounding values (e.g., flaw-no flaw, reasonable minimum and maximum extent of a flaw) using a deterministic sensitivity analysis approach in which the deterministic event tree model is run with each of the bounding values one at a time or with combinations of bounding values for more than one variable. Sensitivity analysis can be used as a preparatory step in preparing for an uncertainty analysis to provide insights to help guide the process of selecting which variables to treat as uncertain variables and which are appropriately considered as deterministic variables. Where there is little sensitivity for all key decision variables to changing a variable across the entire range of uncertainty represented by bounding values, then that variable can be treated as a deterministic variable. By minimizing the number of variables that are treated as uncertain variables the computational time needed to complete uncertainty analyses can be kept to a
4.2.2. Aggregated Uncertainty Analysis (Type I)

The uncertainty associated with the logic tree variables \( X^l \) defines the knowledge uncertainty about the existing states, whereas the uncertainty associated with the event tree variables \( X^e \) represents other sources of knowledge uncertainty in the event tree model. Also natural variability is included in the event tree as explained in Section 1.0. Parametric or empirical probability distributions, \( D_1^l, D_2^l, \ldots \) and \( D_1^e, D_2^e, D_3^e, \ldots \), can be assigned to characterize the significant uncertain variables associated with the logic tree and event tree variables, respectively. A schematic of Type I simulation is shown in Figure 4.3.b. In this type of simulation, both the existing condition and other sources of knowledge uncertainties are treated in a single phase of a Monte Carlo simulation. For each iteration of a Monte Carlo simulation, a set of \( X^l \) values is sampled from the \( D_1^l, D_2^l, \ldots \) distributions in the logic tree and correspondingly, a set of \( X^e \) values is sampled from the \( D_1^e, D_2^e, D_3^e, \ldots \) distributions in the event tree. Using these sampled values for the uncertain variables, event tree outcomes are quantified. A large number of iterations are usually performed to obtain the desired level of numerical precision in the outcomes. Although the event tree outcomes of each iteration correspond to a particular existing condition state, their distinguishable identity is lost in the collective population obtained from the simulation. Therefore, each percentile curve, generated by processing the risk estimates from all iterations, represents an aggregated form of knowledge and existing condition uncertainties. The horizontal extent of the percentile curve represents the combination of the existing condition uncertainty and the other sources of knowledge uncertainty as illustrated by the thick line in Figure 4.4.
4.2.3. Disaggregated Uncertainty Analysis (Type II)

Type II simulation provides the capability of separating the existing condition uncertainty represented in a logic tree from the knowledge uncertainty represented in an event tree. A schematic of this simulation is shown in Figure 4.3.c. Similar to Type I simulation, this simulation also includes both the logic tree $L[\mathbf{x}^l, \mathbf{d}^l]$ and event tree $\mathcal{E}(\mathbf{x}^e, \mathbf{d}^e)$ models, but the respective knowledge uncertainties in these models are treated in separate nested layers of a two-phase Monte Carlo simulation. In the outer layer, a set of values for the $\mathbf{x}^l$ variables in the logic tree is sampled, and correspondingly, a population of set of values for the $\mathbf{x}^e$ variables in the event tree is sampled in the inner loop. The $\mathbf{x}^e$ values sampled in the inner loop characterizes the full knowledge uncertainty for each of the uncertain variables included in the event tree corresponding to or conditioned on the existing condition state sampled in the outer loop. Even though the $\mathbf{x}^l$ and $\mathbf{x}^e$ variables are sampled in two different loops, any correlation between them can be specified and preserved. Multiple iterations of the outer loop are performed, and for each iteration, the inner layer simulation outputs a set of the risk

![Figure 4.4. Percentile curves in DAMRAE-U](image-url)

Figure 4.4. Percentile curves in DAMRAE-U
estimates, which in turn gives a separate percentile curve for each of the outer loop risk estimate as illustrated by a single dashed curve in Figure 4.4. Thus, the collective outputs of the two-layer simulation are family of percentile curves for the risk estimates as shown in Figure 4.4. Each percentile curve in the family represents the other knowledge uncertainty conditioned on the sampled values of logic tree variables in the outer loop; whereas the spread of the family of curves represents the existing condition uncertainty for the logic tree variables.

5. CONCLUDING REMARKS

The objectives of uncertainty analysis in dam safety risk assessment are to quantify: a) the confidence levels in the risk estimates, and b) the degrees of confidence with which tolerable risk and other guidelines are met. The deterministic version of DAMRAE is extended in DAMRAE-U to accommodate these objectives. Functionality to incorporate natural variability and knowledge uncertainty of the variables used in an event tree risk model is included in DAMRAE-U. Additionally, uncertainty about the existing conditions on which the event tree model is dependent can be represented in a separate logic tree form of model. An event tree model, when coupled with a logic tree model, can be analyzed for the following three options: a) Sensitivity analysis for the existing condition estimates to identify their effects on risk estimates as a preliminary step in uncertainty analysis; b) Aggregated uncertainty analysis to characterize the combined effect of the existing condition uncertainty and the knowledge uncertainty in the event tree model; and c) Disaggregated uncertainty analysis to separate the existing condition uncertainty in the logic tree and other knowledge uncertainty in the event tree,
and to identify the effects of the knowledge uncertainty for each of the possible existing condition states.

REFERENCES


CHAPTER 5

DAMRAE-U APPLICATION FOR AN EXAMPLE DAM SAFETY RISK ASSESSMENT WITH UNCERTAINTY ANALYSIS

ABSTRACT

DAMRAE-U is a tool for performing the event tree based dam safety risk assessment with uncertainty analysis. It allows the users to efficiently characterize, propagate, and display the outcomes of uncertainty analysis in the risk assessment. DAMRAE-U is structured to analyze the natural variability and knowledge uncertainty of the event tree variables, as well as the effects of uncertainty in the existing condition of the dam system on which the event tree model is dependent. The paper presents an hypothetical example application to illustrate the inputs and outputs of DAMRAE-U, and the implementation of tolerable risk evaluation incorporating uncertainty in risk estimates.

1. INTRODUCTION

The computational framework of DAMRAE(1-3) supports the deterministic form of event tree analysis where the branch probabilities and state values (branch inputs) assigned to different branches in the event tree are either fixed values or deterministic relationships (see also Chapter 2). This deterministic logic of DAMRAE is enclosed within a generalized Monte Carlo simulation framework to develop the uncertainty analysis version of DAMRAE, known as DAMRAE-U. DAMRAE input features are extended to allow the definitions of parametric or empirical forms of probability distributions for the uncertain variables and to assign the correlations among those
variables. The computational framework of DAMRAE-U uses two types of component models in the uncertainty analysis simulation: a) Event Tree Model, and b) Logic Tree Model. The event tree form of risk model in DAMRAE-U is structured using six types of event tree branches, which are defined in Table 5.1, and associated uncertain variables, which are characterized using the parametric (e.g., Uniform, Triangular, Normal, etc.) or other forms of user-specified or empirical probability distributions. In the logic tree – event tree form of model, a logic tree precedes the event tree. The logic tree can be used to represent the existing state of the dam system on which the event tree model is dependent. The knowledge uncertainty about the existing state is represented in the logic tree, whereas the natural variability and other sources of knowledge uncertainty are represented in the event tree. This form of representation allows the following three types of simulation options in DAMRAE-U-

a) **Sensitivity Analysis**, where bounding values of uncertain variables (e.g.,

<table>
<thead>
<tr>
<th>Branch Type</th>
<th>Description</th>
<th>Branch Input</th>
<th>Probability</th>
<th>State Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete</td>
<td>A discrete random variable that can take on only a finite number of state values</td>
<td>Probability for each discrete state, Exceedance probabilities associated with state values</td>
<td>Title of discrete states for each branch</td>
<td>Range of state values</td>
</tr>
<tr>
<td>Continuous</td>
<td>A continuous random variable that can take on an infinite number of state values over the specified range</td>
<td>System response probability (SRP) value, Exposure factor as a time fraction</td>
<td>User-specified relationship</td>
<td>Title of failure mode</td>
</tr>
<tr>
<td>State Function</td>
<td>A deterministic relationship between state variables</td>
<td>1.0</td>
<td>User-specified relationship</td>
<td>Title of exposure factor</td>
</tr>
<tr>
<td>Failure</td>
<td>The events of non-breach and the occurrence of one or more failure modes</td>
<td>System response probability (SRP) value, Title of failure mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposure</td>
<td>Population exposure cases, e.g., summer and winter; or day and night.</td>
<td>Exposure factor as a time fraction, Title of exposure factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consequences</td>
<td>Life-loss or economic consequences</td>
<td>Not applicable</td>
<td>Consequence value</td>
<td></td>
</tr>
</tbody>
</table>
flaw-no flaw, reasonable minimum-maximum extent of a flaw) are analyses to explore the sensitivity of risk estimates.

b) **Aggregated Uncertainty Analysis (Type I)**, where the existing condition knowledge uncertainties represented in the logic tree and the other knowledge uncertainties and variabilities represented in the event tree are collectively analyzed to obtain uncertainty distributions each type of risk estimate that aggregate all modeled sources of knowledge uncertainty and variability in the logic and event trees.

c) **Disaggregated Uncertainty Analysis (Type II)**, this is a two-layer simulation where the existing condition uncertainty is represented in the logic tree separately from the other knowledge uncertainties, which are represented in the event tree. For each type of risk estimate (e.g. probability of failure, annualized life loss, benefit:cost ratio, cost per statistical life saved), a family of uncertainty distributions is output, where each distribution incorporates the variability and event tree knowledge uncertainty conditioned on a sampled state of existing condition knowledge uncertainty, which is represented in the logic tree. The spread across the family of uncertainty distributions represents the disaggregated effect of the range of existing condition uncertainty.

An example risk assessment to illustrate the computational framework of DAMRAE-U is presented in this paper. The details of the logic tree and event tree models and their inputs are included in Section 2. The risk and uncertainty estimates obtained from DAMRAE-U, the implementation of the tolerable risk evaluation including uncertainty, and the additional insights gained by explicitly considering
uncertainty in the risk assessment are discussed in Section 3. The paper closes with a summary and conclusions in Section 4.

2. EXAMPLE RISK MODEL

The hypothetical example is for a project that comprises a main embankment dam and a saddle embanked dam. The example risk model, as shown in Figure 5.1, comprises a single-level logic tree and a twelve-level event tree. The event tree part of the model includes the following four flood and flood-internal failure modes in the failure branch in Level 10: a) overtopping of the main dam, b) overtopping of the saddle dam, c) piping through the abutment, and d) piping through the embankment. The uncertainty associated with the threshold elevations at which the piping failure modes would be expected to initiate is represented in the logic tree, whereas the other knowledge uncertainties (associated with the peak inflow flood frequency relationship, system response probabilities (SRPs) for the piping failure modes, and the consequences) and the natural variability in inflows and gate reliability are included in the event tree model. The different branches and their inputs are described in the following sections.

2.1. Logic Tree

An uncertain variable $L_{var}(1)$ is included under the logic tree branch to define the uncertainty in the threshold peak pool reservoir elevation for the piping failure modes. A parametric triangular distribution with 691.39 m as the best estimate is assigned to the logic tree variable. The upper and lower uncertainty bounds on the triangular distribution
Figure 5.1. Example flood risk model
are judgmentally assigned as 1m above and below the best estimate. Graphically, \( L_{\text{var}}(1) \) represents the horizontal triangular distributions (shown in Figure 5.2 and Figure 5.3) which are used to characterize the system response probabilities (SRPs) for the piping through the abutment and piping through the embankment failure modes.

### 2.2. Event Tree

A state function branch is included in Level 1 of the event tree to represent the number of spillway gates that open on demand. This variability is represented using a discrete probability distribution of \( r \) out of 5 total gates opening on demand assigned to this branch. This distribution is listed in Table 5.2 and represents the independent failure of each separate gate and a common cause failure of all five gates.

Level 2 is a state function branch that represents the Peak Inflow – Annual Exceedance Probability (AEP) relationship. The AEP scale is transformed to z-variate to represent a normal probability distribution plot (Figure 5.4). The knowledge uncertainty

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**Figure 5.2.** Piping through the Abutment SRP  
**Figure 5.3.** Piping through the Embankment SRP
associated with this relationship is defined using triangular distributions with the 50th percentile or mode (best estimate), 5th and 95th percentile values for given AEP values as shown in Figure 5.4. Using the assigned relationship as an input to this branch, a set of z-variate values corresponding to a given set of peak inflows, which are used to define the peak reservoir stages, is interpolated as output of this branch.

Level 3 is a continuous branch representing 40 intervals of annual exceedance

Table 5.2. Spillway gate reliability

<table>
<thead>
<tr>
<th>Number of Gates Failing to Open at a Time (r)</th>
<th>Gates Fail to Open Case ID (GID)</th>
<th>Total Probability of Failure to Open r Gates at a</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0.894882</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.091314</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.003727</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.000076</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.000001</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.010000</td>
</tr>
</tbody>
</table>

Figure 5.4. Peak inflow - AEP relationship

Figure 5.5. Peak inflow - peak pool elevation relationship for different spillway gates fail to open cases (GIDs)
probability (AEP), ranging from (1 in 1.2) to (1 in 1.2x10^7). This spread of AEP values covers the range of uncertainty in the flood loading. The AEP intervals are internally calculated in DAMRAE-U to cover this range with one additional exceedance interval for AEP < 1 in 1.2x10^7. The state value output is simply the corresponding z-variate transformed value of the AEP.

The Peak Stage is calculated using the state function branch in Level 4 and represents the peak elevation that the reservoir can attain for a given level of peak inflow and a given number of spillway gates available. A peak inflow value is interpolated to obtain the peak reservoir elevation (PRE) using the relationships between peak inflow and peak stage shown in Figure 5.5) for each number of spillway gates failing to open. For computational convenience of propagating the interval z-variate values in Level 3, this relationship is assigned in terms of the z-variate (corresponding to peak inflows as calculated in Level 2) and peak stage.

Peak inflow is calculated using the Level 5 state function branch (Inflow) corresponding to the mid-point of a z-variate interval assigned in the Level 3 continuous branch. This calculation utilizes the z-variate versus peak inflow relationship that is obtained in Level 2.

Peak outflow is calculated using the Level 6 state function branch (Outflow) corresponding to the peak inflow value calculated in Level 5. This calculation is based on the approximate Peak Inflow-Peak Outflow relationships shown in Figure 5.6 the six spillway gate availability cases specified in Level 1. The case when all gates are available is represented in Figure 5.6 a by a one-to-one sloping line assuming that the peak outflow is equal to the peak inflow. The other cases shown in Figures 5.6.b to f are represented by
a) 0 of 5 gates fail to open  b) 1 of 5 gates fail to open  c) 2 of 5 gates fail to open

d) 3 of 5 gates fail to open  e) 4 of 5 gates fail to open  f) 5 of 5 gates fail to open

Figure 5.6. Approximate no-failure peak inflow – peak outflow relationships

a one-to-one sloping line drawn up to the point where the peak inflow reaches the discharge capacity of the available gates. Beyond that, peak outflow remains at the same level until the peak inflow reaches the dam crest elevation and then again, the relationship follows the one-to-one sloping line. These relationships assume that there are no other discharge facilities that are available. Peak outflow is needed for the calculation of no-failure life loss and economic consequences, which are defined as a function of peak outflow and are used for the calculation of incremental failure consequences.

Level 7 is a state function branch (Overtop Depth) in which the peak overtopping depth is calculated by subtracting the dam crest elevation from the peak reservoir pool elevation assigned in Level 4.

Levels 8 and 9 are state function branches included to define two uncertainty
variables $\text{Svar}(2)$ and $\text{Svar}(3)$, respectively, for uncertainty in the SRPs for the two piping failure modes. Parametric triangular distributions are assigned to these variables as shown in Figures 5.2 and 5.3 with vertical triangular distributions. The logic tree variable $\text{Lvar}(1)$ and state variable $\text{Svar}(2)$ are used to characterize the SRP relationship for the piping through the abutment failure, and similarly, $\text{Lvar}(1)$ and $\text{Svar}(3)$ variables are used to characterize the SRP relationship for the piping through the embankment failure.

Level 10 is a group of failure branches representing the flood failure modes. The conditional probability of occurrence of a failure mode is represented by its system response probability. The main and saddle dams overtopping SRP relationships, which are conditioned on peak reservoir overtopping depth (Level 7), are assigned as shown in Figures 5.7.a and 5.7.b, respectively. SRPs for the piping failure modes, which are dependent on peak reservoir elevation $\text{PRE}$ (Level 4), are assigned in the form of the conditional statements presented below in Eq. 5.1 and 5.2. These equations are used to represent the SRP estimates obtained based on the USACE Internal Erosion toolbox $^{(4)}$ and are adjusted using expert elicitation. The steep parts of the relationships correspond to the threshold peak reservoir elevation at which each failure mode is expected to

![Main Dam Overtopping SRP](image1)

![Saddle Dam Overtopping SRP](image2)

Figure 5.7. Overtopping system response probabilities
initiate, which is shown as a very small but non-zero value of the SRPs because semi-log interpolation is used for these relationships. Each of these equations is a mathematical representation of the SRP relationship that is sampled from the uncertainty distribution defined using the logic tree variable $L_{\text{var}(1)}$ and state variables $S_{\text{var}(2)}$ and $S_{\text{var}(3)}$. Examples of the sampled relationship for piping through the abutment and piping through the embankment failure modes are shown in Figures 5.2 and 5.3, respectively.

$$\text{SRP}(\text{Piping}_{\text{Abutment}}) = \text{IF}(\text{PRE} \leq L_{\text{var}(1)}, 1 \times 10^{-10}, 10^{\text{MIN}(p_1,p_2,0)})$$

…Eq. 5.1

$$\text{SRP}(\text{Piping}_{\text{Embarkment}}) = \text{IF}(\text{PRE} \leq L_{\text{var}(1)} + 1, 1 \times 10^{-10}, 10^{\text{MIN}(p_3,p_4,0)})$$

…Eq. 5.2

where

$$p_1 = 8.94 \ast (\text{PRE} - L_{\text{var}(1)}) + \text{LOG}_{10}(1 \times 10^{-10})$$

$$p_2 = 0.14 \ast (\text{PRE} - 695) + S_{\text{var}(2)}$$

$$p_3 = 7.55 \ast (\text{PRE} - (L_{\text{var}(1)} + 1)) + \text{LOG}_{10}(1 \times 10^{-10})$$

$$p_4 = 0.60 \ast (\text{PRE} - 695) + S_{\text{var}(3)}$$

The variable "PRE" used in Eq. 5.1 and 5.2 is the peak pool reservoir elevation calculated in Level 4, $L_{\text{var}(1)}$ is a logic tree variable as defined in Section 3.1, and $S_{\text{var}(2)}$ and $S_{\text{var}(3)}$ are state variables.

Levels 11 and 12 of the event tree contain the life-loss and economic consequences branches, respectively. No exposure branches were included in this simplified example. Different parametric triangular distributions are assigned to characterize the uncertainty in the life-loss and economic consequences estimates associated with no-failure and different failure modes as shown in Figures 5.8 and 5.9.
2.3. Correlations

The uncertain variables $L_{var}(1)$, $S_{var}(2)$ and $S_{var}(3)$ are assumed to be mutually independent and therefore, no correlation is assigned for these variables. The uncertainty distributions assigned to form a synthetic realization of the Peak Inflow –AEP relationship used in Level 2 are specified as perfectly correlated with each other and hence sampled values of the uncertainty distributions for these relationships will correspond to line of equal percentiles as illustrated by the dashed lines drawn on these distributions. Similarly, the uncertainty distributions assigned to form the life-loss and economic consequences in Level 11 and 12 are also specified as perfectly correlated for

![Image](image-url)
each particular relationship.

2.4. Risk Reduction Measure

Installation of a full depth vertical cutoff wall into the foundation and into the abutment is considered as a risk reduction measure to reduce the risk of piping failure. The parameters of the state variables $S_{var}(2)$ and $S_{var}(3)$ are reduced by a factor of 100 to reflect the decrease in piping SRPs as a result of the risk reduction measure. The similar uncertainty analysis simulations, as those were used for the base condition analysis, were performed to generate the risk estimates for the risk reduction measure. The risk estimates for the base condition and risk reduction measure are further compared
to generate the risk reduction estimates. In order to eliminate differences in synthetic sampling errors between the two uncertainty simulations the same seed number was used for both the base condition and risk reduction cases. (5)

3. UNCERTAINTY ANALYSIS RESULTS

DAMRAE-U is used to perform the uncertainty analyses for the risk model shown in Figure 5.1 and described in Section 2. For the Type I aggregated uncertainty analysis, where the effects of the knowledge uncertainties associated with the piping thresholds in the logic tree and other knowledge uncertainties in the event tree are combined, a thousand Monte Carlo simulations were used to generate the uncertainty distributions of the risk estimates and the various decision or risk evaluation variables (e.g., Benefit:Cost ratio, cost to save a statistical life, etc.) for the risk reduction measure.

In the Type II disaggregated uncertainty analysis the knowledge uncertainties are treated in two separate loops as described in Section 1. The outer loop for the logic tree model, which represents the piping threshold uncertainty, was iterated hundred times, and for each iteration of the outer loop, the inner loop containing the event tree with additional knowledge uncertainties represented in addition to natural variability, was iterated hundred times to collectively generate the families of probability distributions of the risk estimates and the decision justification variables. Thus for each iteration of the outer loop, the inner loop risk estimate are conditioned on the outer loop sampled values of the piping threshold. Some uncertainty analyses results obtained for these simulations are discussed and compared in the following subsections.
3.1. Probability of Failure

The estimated uncertainty distributions for the total annual probability of failure (APF) for Type I and Type II simulations are shown in Figures 5.10 and 5.11, respectively. Figure 5.10 indicates a confidence level of about 98% that the dam in its base condition meets the USACE APF tolerable risk limit of 1 in 10,000/year. This confidence level increases to close to 100% for the risk reduction measure.

For Type II simulation, families of uncertainty distributions for the estimated APF for the base condition and risk reduction measure are shown in the top graphs of Figures 5.11 a) and b), respectively. The bottom graphs in these figures are conditional distributions of uncertainty in the total APF the piping threshold uncertainty for the 95th percentile level of knowledge uncertainty in the event tree estimates. For the base condition, the lower percentiles on the top graph representing event tree knowledge uncertainty indicate 100% confidence in meeting the APF TRG limit value of 1 in 10,000/year since the entire family of distributions is below the limit value. This confidence level decreases for the higher percentiles on the top graph. For example, for the 95th percentile the confidence level lowers to 98%. For the risk reduction case, a

![Figure 5.10. Uncertainty distributions of total probability of failure estimates from Type I simulation.](image-url)
100% confidence in meeting the USACE APF TRG limit is indicated for all the percentile levels of knowledge uncertainty in the event tree.

### 3.2. Annualized Incremental Life Loss

The estimated uncertainty distributions for total annualized incremental life loss (ALL) for the Type I and Type II simulations are shown in Figures 5.12 and 5.13, respectively. The USACE ALL TRG limit value is defined as 0.001 lives/year. The Type I simulation shows a 0% confidence in meeting the tolerable risk limit (or, in other words, 100% confidence in failing to meet the tolerable risk limit) for the base condition. This confidence level increases to about 80% for the risk reduction measure. For the Type II simulation, again 0% confidence is indicated for all the percentiles of knowledge uncertainty in the event tree as displayed in the top graph of Figure 5.13 a. For the risk reduction measure (Figure 5.13 b), 100% confidence is displayed for the lower percentiles (below 75th percentile) of peak inflow uncertainty whereas the confidence
level switches to 0% for the higher percentiles, such as for the 95th percentile shown in Figure 5.13 b.

3.3. USACE Societal Risk Guidelines (F-N Chart)

The F-N charts developed for the base condition and risk reduction measure using the Type I simulation are shown in Figures 5.14 a) and b), respectively. These charts
display the F-N curves for the 5th, 50th (median), and 95th percentiles of knowledge uncertainty included in the logic and event trees. For the base condition, only the 5th percentile F-N curve appears to meet the tolerability limit, whereas all three percentile F-N curves meet the societal risk guidelines limit for the risk reduction measure case.

Similar F-N charts can be developed for the Type II simulation also, where each percentile of uncertainty in peak inflow will consist of multiple F-N curves conditioned on selected percentiles of the uncertainty in the piping threshold.

The information portrayed via the F-N curves for the Type II simulation can alternatively be represented in the plot shown in Figure 5.15 as the confidence of meeting the societal risk limit guideline based on the knowledge uncertainty in the piping thresholds for different percentiles of knowledge uncertainty included in the event tree. The horizontal axis of the plot represents the percentile levels of knowledge uncertainty.

Figure 5.14. F-N chart for selected percentiles of knowledge uncertainty from the Type I simulation
in the event tree and the vertical axis represents the confidence levels (%) as empirical frequencies of meeting the societal risk limit guidelines for multiple F-N curves corresponding to percentile levels on the horizontal axis. The confidence-percentile plot shown in Figure 5.15 shows a 100% confidence in failing to meet the societal risk guidelines limit for the base condition for all percentiles exceeding about the 10\textsuperscript{th} percentile, whereas the for risk reduction measure 100% confidence in meeting the guidelines is indicated for almost all the percentile levels except those exceeding about the 95\textsuperscript{th} percentile.

3.4. USACE APF and ALL Tolerable Risk Limit Guidelines ($f$-$\bar{N}$ Chart)

The $f$-$\bar{N}$ pairs obtained from the Type I simulation are plotted on the $f$-$\bar{N}$ chart\textsuperscript{9} as shown in Figures 5.16 a) and b) for the base condition and risk reduction measure, respectively. The $f$-$\bar{N}$ chart is divided into the following three regions shown with

\textsuperscript{9}$f$-$\bar{N}$ chart displays annual probability of failure vs. the average magnitude of life loss from the probability distribution of life loss as a weighted average over failure modes and exposure scenarios.
shading, based on the USACE TRG limit values for APF and ALL: i) $\text{APF} \geq 1$ in 10,000/year, ii) $\text{APF} < 1$ in 10,000/year and $\text{ALL} \geq 0.001$ lives/year, and iii) $\text{APF} < 1$ in 10,000/year and $\text{ALL} < 0.001$ lives/year. The confidence levels displayed as percentages in each region are calculated as percentage of simulations with $f\bar{N}$ pairs lying in each of these three regions. A higher confidence is shown that the risk of dam failure is in the lower risk APF-ALL regions ii) and iii) for the risk reduction measure (Figures 5.16 b) compared with the base condition (Figure 5.16 a).

For the Type II simulation, this information for the three APF-ALL regions is displayed as confidence levels corresponding to different percentile levels of the knowledge uncertainty in the piping initiation elevation represented in the logic tree model. The confidence-percentile curve shown in Figure 5.17 a) for the base condition
indicates more than 94% confidence that the risk lies in the APF-ALL region ii) for all percentile levels of the piping threshold uncertainty but very little confidence that it lies in the lowest APF-ALL risk region iii). For the risk reduction measure, the confidence of the reduced level of risk lying in the APF-ALL region ii) is between 20% to 22%, and for lying in the lowest risk APF-ALL region iii) it is more than 78%.

**Figure 5.17.** Percentile distributions of confidence of \( f - \bar{N} \) pairs lying in the three APF-ALL regions from Type II simulation
3.5. Economic Evaluation and Decision Justification

The estimated uncertainty distributions for cost to save a statistical life (CSSL) and benefit:cost ratio are shown in Figures 5.18 and 5.19, respectively. CSSL is a measure of cost effectiveness of reducing life safety risks that is one of several considerations in evaluating the ALARP (as low as reasonably practical) principle for a risk reduction measure.\(^{(6-8)}\) Based on the magnitude of the CSSL value, following four illustrative ALARP justification ratings: “Very Strong,” “Strong,” “Moderate,” and “Poor” are assigned as shown in Figure 5.18 a) (Bowles\(^{(6)}\)). For the Type I simulation the risk reduction measure a more than a 93% confidence level of a “Poor” ALARP justification rating is estimated with CSSL > $205M as indicated in Figure 5.18 a). For the Type II simulation there is estimated to be a 100% confidence of “Poor” ALARP justification rating for the example 95\(^{th}\) percentile of knowledge uncertainty in the event tree as shown in Figure 5.18 b). Such a high confidence of a “Poor” ALARP rating would

**Figure 5.18 a).** Distributions of cost to save a statistical life and ALARP justification ratings for risk reduction measures from Type I simulation

**Figure 5.18 b).** Uncertainty distributions for cost to save a statistical life from Type II simulation
indicate poor justification for proceeding with the risk reduction measure if all TRG limits were already met prior to the implementation of this measure. However this is not the case and so this evaluation would not normally enter into the decision process. It is shown here to only demonstrate this type of output from DAMRAE-U.

The uncertainty distribution of benefit:cost ratio as obtained from the Type I simulation shown in Figure 5.19.a indicates a value of 0.0007 for the 95th percentile of natural variability and knowledge uncertainties. For the Type II simulation, benefit:cost ratios vary from 0.0004 to 0.001 for the selected 95th percentile of natural variability and knowledge uncertainty in the event tree shown in Figure 5.19.b.

Under the ALARP evaluation, the disproportionality ratio \( R \) is used as a quantitative measure to justify the implementation of a risk reduction measure to reduce the risk below the tolerable risk limit values. (6-8) The criterion of disproportionality ratio can be applied in relation to the individual risk (IR), which is expressed as a probability.

\[ \text{Figure 5.19 a). Uncertainty distributions of benefit:cost ratio from Type I simulation.} \]

\[ \text{Figure 5.19 b). Uncertainty distributions of benefit:cost ratio from Type II simulation.} \]
of life-loss for an individual person. For simplicity in this paper we have conservatively estimated IR as the total annual probability of failure (APF). The ALARP justification ratings for this criterion (shown in Figure 5.20) are based on updated USACE guidance. Based on these ratings, the risk reduction measure, as estimated for the Type I simulation, has a 98.5% confidence level of poor justification (Figure 5.20). For Type II simulation, this information is represented as confidence levels in ALARP justification ratings for different percentile levels of the uncertainty included in the logic tree model. Figure 5.21 shows more than 94% confidence of poor justification for the risk reduction measure for all the percentile levels of the logic tree uncertainty.

4. SUMMARY and CONCLUSIONS

The deterministic version of DAMRAE is extended to include uncertainty analysis. In addition to handling the uncertainty in the event tree variables, DAMRAE-U introduces logic trees to address the knowledge uncertainty of the existing state of a dam system on which the event tree model is dependent. Alternatively logic trees can be used

![Figure 5.20 a). Disproportionality ratios vs. Individual Risk for the risk reduction measure with percent confidence of ALARP guidance ratings for Type I simulation](image1)

![Figure 5.20 b). Disproportionality ratios vs. Individual Risk for the risk reduction measure for Type I simulation with expanded vertical axis](image2)
A logic tree-event tree form of risk model is presented to demonstrate the DAMRAE-U concepts. For the hypothetical dam, a single logic tree branch is included in the model, but in general, logic trees are not limited to just one branch as illustrated in the example. The number of branch levels in a logic tree depends on the number of sources of knowledge uncertainty that are planned to be included in the analysis, and the number of branches in a branch level depends on whether a set of discrete branches or a continuous distribution is used to represent the range of uncertainty.

The example risk model is demonstrated for both the aggregated Type I and disaggregated Type II uncertainty analyses. The aggregated uncertainty analysis lumps all sources of knowledge uncertainty that are included in the event tree risk model and those associated with the logic tree (existing condition knowledge uncertainty in the example in this paper) to provide estimates of the uncertainty in the risk estimates. In
contrast, the disaggregated uncertainty analysis separates the contributions to overall knowledge uncertainty in risk estimates into those associated with the event tree risk model and those associated with the logic tree. Separating these contributions to uncertainty in the output risk estimates can be useful for evaluating the degree to which reducing the existing state uncertainty would increase the confidence in risk estimates.

The results of the two types of simulations are presented in specific formats. Cumulative probability distributions are generated to show knowledge uncertainty as confidence levels on the risk analysis outputs, such as annualized risk estimates and cost-effectiveness of risk reduction alternatives. The risk evaluation outcomes are presented in terms of the estimated confidence with which tolerable risk and other guidelines are met.

REFERENCES


CHAPTER 6
SUMMARY AND FUTURE WORK

DAMRAE is proposed as a solution to overcome the limitations of commercial software and other alternative approaches (e.g., spreadsheet models) that are commonly used in the field of dam safety risk analysis. To develop the generalized framework of DAMRAE, that is readily adaptable for a computational processing, several refinements to traditional risk analysis modeling terminology are made. The concepts of Connectivity and Pedigree matrices are introduced to quantify the user-drawn event tree structures with proper accounting of interdependencies among the event tree branches. A generic calculation of Common-Cause Adjustment (CCA) for the non-mutually exclusive failure modes is implemented along with introducing the new concepts of SRP and consequence freezing. Several new output presentation formats such as cumulative risk estimate vs. initiating variable plots to analyze the increase of an incremental (annualized) risk estimate as a function of initiating variable are introduced. An additional consideration is given to the non-breach risk estimates in the risk modeling and new output formats such as non-breach F-N and F-$ charts are included as standard risk analysis outputs. The key features of DAMRAE can be summarized as follows:

a) DAMRAE includes a user-friendly graphical interface for the event tree development and input assignment. Common interface options, such as add, delete, and relocate branches, accompanied with advanced collapsed node functionality provide easy and flexible event tree construction features.

b) Types of branches defined in DAMRAE to draw the event tree structure covers all the possible events that are commonly used in the event tree modeling. Range of
continuous variable (e.g., flood loading) can be handled using a continuous branch type. Nested continuous variables, such as PGA-AEP loading and stage-duration relationships for the earthquake event tree, can be included using multiple continuous branches.

c) Event tree quantification is performed by DAMRAE to generate the risk estimates in various forms including annual risk estimates (probability of dam failure and expected values of life-loss and economic consequences) and graphical displays such as charts for evaluating USACE tolerable risk guidelines.

d) For the risk reduction analysis, the existing risk analysis can be reiterated by adding new run-cases to a DAMRAE project. For the new run-cases, existing event tree models can be copied and modified to represent the specifications pertaining to the proposed risk reduction measure.

e) In case of a risk analysis of risk reduction options, additional decision variables such as Risk Reduction Benefits, Risk Reduction Cost, Benefit:Cost Ratio, Adjusted Cost per Statistical Live Saved (ACSLS), and Disproportionality Ratio (R) are also calculated.

DAMRAE supports the deterministic form of event tree analysis where the branch probabilities and state values (branch inputs) assigned to different branches are either fixed values or deterministic relationships. DAMRAE framework is extended in DAMRAE-U to incorporate the uncertainty analysis for the event tree models. In DAMRAE-U, Monte Carlo simulation based generic uncertainty propagation logic is implemented with the consideration of correlations among uncertain variables. This computational logic includes a new functionality of uncertainty separation for the logic
tree and event tree form of risk models. Uncertainty about the existing state, on which the event tree model is conditioned, can be defined in a separate logic tree model appended before the event tree structure. A logic tree –event tree form of model can be simulated to analyze the combined effect of the existing state uncertainty, and knowledge uncertainty and natural variability in the event tree model. In the case where the separation of existing state uncertainty and event tree knowledge uncertainty is required, disaggregated uncertainty analysis option can be selected.

The computation logic also enables the simulations of risk reduction measures and provides estimates of uncertainty distributions for the risk and risk reduction estimates. When uncertainty analyses are conducted the evaluation against tolerable risk limit guidelines is changed from a relatively straightforward assessment as to whether risk estimates are above or below limit guidelines to an assessment of the degree of confidence that the estimated risk is above or below a limit guideline. DAMRAE-U automatically performs such assessment and attributes degrees of confidence with which tolerable risk and other guidelines are met.

DAMRAE is continuously widening its user group and hence, there will be always scope of improving the interface features and functionality as per the requirements of the users. At the core calculation level, computational processing can be enhanced with parallel processing and other advance techniques in computer programming. From theoretical and conceptual design point of view, following are some of the features which could be included to further improve the role of DAMRAE in dam safety risk analysis -

a) Intervention sensitivity option for event trees can be included to assess the
degrees to which the probabilities of successful interventions reduce the failure risk estimates.

b) Database aspects of the program can be enhanced to support the uncertainty analysis functionality with increased data storage capacity and parallel simulations for risk reduction measures.

c) Capability for performing sensitivity and scenario analysis can be developed for the uncertainty analysis version to identify the significant uncertain variables.

d) Batch simulation functionality with proper accounting of correlations among different dam or levee segments can be included to support applications for long dams or levees that requires multiple applications of DAMRAE to dam or levee segments.

e) Facility for importing standard templates of dam safety risk models and adapting them for application to a specific dam can be included.
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