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Generalized Event Tree Algorithm and Software for Dam Safety Risk Analysis

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GENERALIZED EVENT TREE ALGORITHM AND SOFTWARE FOR DAM SAFETY RISK ANALYSIS

by

Anurag Srivastava

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

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2008

ABSTRACT

Generalized Event Tree Algorithm and Software for Dam Safety Risk Analysis

by

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Utah State University, 2008

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Event tree analysis is a most commonly used method in dam safety risk analysis modeling. Available software tools for performing event tree analyses lack the flexibility to efficiently address many important factors in dam safety risk analysis. As a result of these practical limitations, spreadsheets have been used, sometimes including Visual Basic macros, to perform these analyses. However, this approach lacks generality and can require significant effort to apply to a specific dam or to modify the event tree structure. In response to these limitations, here a generalized event tree analysis tool, DAMRAE (DAM safety Risk Analysis Engine), has been developed. It includes a graphical interface for developing and populating an event tree, and a tool for calculating and post-processing an event tree risk model for dam safety risk assessment in a highly flexible manner. This thesis describes the underlying theoretical and computational logic employed in the current version of DAMRAE, and provides a detailed example of the calculations in the current version of DAMRAE for an application to a US Army Corps of Engineers (USACE) dam. The thesis closes with some conclusions about the capabilities of DAMRAE and a summary of plans for its further development.

(134 pages)

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Anurag Srivastava

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CHAPTER I

INTRODUCTION

Dam Safety Risk Analysis

Dams are considered as an essential infrastructure in a country. They are essential because they contribute in economic, environmental, and social development. Some of their benefits are recreation, flood control, water supply, hydroelectric power, waste management, river navigation, and wildlife habitat. But, history is the evidence that dams have also been a potential source of catastrophes in the world. Their possible failure poses great risks to social life and valuable property. Therefore, the safety of a dam structure is critical to realizing the benefits of dams and to the people and property surrounding the structure. Generally agencies, lawmakers, public and many others are concerned about dam safety but it is a legal and moral responsibility of the dam owner to ensure the safe operation of a dam.

Of the total 76,926 dams listed in the US national inventory (based on the 1998-1999 data), private business, citizens, and state and local governments own a large majority. To spread the awareness of dam safety, to improve the state of the practice in dam safety management, and to educate individual dam owners many organizations [e.g. Association of State Dam Safety Officials (ASDSO), National Performance of Dam Programs, US Society on Dams (USSD), etc.] are working in the field of dam safety. Also, researchers are consistently attempting to enhance the engineering aspect of dam safety approach. The traditional dam safety approach uses the periodic examinations and project specific modifications to dams. But, in 1979, after the failure of Teton Dam, the

Federal Guidelines for Dam Safety introduced the risk-based analysis as an additional tool to combine with the benefits of the time-tested traditional approach to dam safety. The implementation of risk-based analysis serves as a dam safety tool to improve the effectiveness and efficiency of dam safety efforts. Risk-based analysis is becoming more widely used as method to supplement traditional approaches to dam safety decision-making.

The overall risk-based analysis includes risk analysis as an essential step for providing inputs to decision making. Risk analysis can provide insights into the performance of the dam system and its safety issues. In the present state of the practice, the risk analysis step is performed to identify the potential failure modes, to make quantitative estimates of the probabilities of each failure mode and their associated consequences, and also, to address the uncertainty issues inherent in the dam structural behavior and the consequences of failure.

Application of ETA in Dam Safety Risk Analysis

Event trees can be used to obtain quantitative estimates of the probability of dam failure and its associated consequences. This can be done for an existing dam or for various risk reduction measures. Event trees can also serve as qualitative or diagrammatic representations of failure modes, their associated outcomes (system effects), and their consequences for various types of initiating events.

The series of events, represented by an event tree, begins with an initiating event and continue with the events that can lead to the outcomes of normal operation or various modes of dam failure (i.e. an uncontrolled release of the reservoir contents). Partial failure and specified non-failure damage states (incidents) may also be defined as outcomes of interest. No-failure outcomes are of interest for flood events if the incremental consequences due to dam failure are to be calculated.

The initiating event may be external to the dam-foundation-abutments-reservoir-spillway system (referred to as the “dam system” hereafter), such as the loading associated with a flood or an earthquake. Alternatively, the initiating event can be internal to the dam system, such as the development of a sink hole in an embankment dam. The series of events represented by the event tree describe the various responses of the dam system to the initiating event. A divergent event tree structure is formed by branching at each chance node where there is more than one possible result from the precursor event.

For dam safety risk assessment, event trees often include a representation of various exposure scenarios that affect the estimated magnitude of consequences, especially for life loss. In addition, human interventions, such as emergency measures to lower a reservoir following discovery of a sink hole, or to repair a jammed spillway gate during a flood, can also be incorporated into event trees.

In dam safety risk assessment, it is important that the results obtained from ETA can be used to perform risk evaluations against tolerable risk guidelines, such as those of ANCOLD (2003).

Available ETA Software Tools

Event Tree Analysis comprises the following four phases: (a) initial conception, (b) construction, (c) quantification, and (d) post-processing and report generation. In any field, initial conception is always a matter of the analyst's experience and knowledge but the other three phases of ETA are amenable to a generalized systematic approach. Thus, a number of commercially and government-funded computerised tools have been developed to streamline the process of drafting, quantifying and reporting in ETA. All these software tools have the functionalities to fulfill some of the requirements of a particular application in a particular field but none provides a complete solution to the issues an analyst is required to handle while performing a dam safety risk assessment. For example, various software tools are available for business risk analysis applications but all of these are ill-suited for use in dam safety risk assessment. Saphire is a very sophisticated software package developed by the US Department of Energy's Idaho National Engineering and Environmental Laboratory (INEEL) for the nuclear industry. Some other examples of this type of software are DATA (TreeAge Software), DecisionPro (Vanguard Software Cooperation), DPL (ADA Decision System) and Precision Tree (Palisade Cooperation).

Although most of these software tools could be applied to dam safety risk assessment, they generally lack the flexibility to deal with initiating events such as floods and earthquakes for which it is desirable to use variable computational step sizes to achieve numerical precision in ETA calculations. They also lack the capability to readily assign system response probabilities (SRPs) and consequences to event tree branches considering the interdependencies among the variables in the event tree. In some software tools output is available only as expected values or annualized estimates of risk with poor flexibility to obtain breakdowns of total risk estimates. In addition, there is often no straightforward way to track and obtain probability-consequence pairs with their associated state values so that they can be presented in graphical and tabular forms, including F-N charts. Most software tools provide user-friendly ways to construct graphical representations of event tree diagrams, although they do not contain all the options needed for dams safety applications, such as common-cause adjustment for non-mutually exclusive failure modes (Bowles, Anderson, and Chauhan, 2001) and handing continuous events such as flood and earthquake initiating events. It is typically tedious to construct the full event tree and is sometimes awkward to modify. In addition, the full event tree diagram can be difficult to readily understand.

Some software tools provide the option of developing the risk model as an influence diagram, which can be converted to an event tree by the software. However, no unique inverse transformation is available from event trees to influence diagrams.

In dam safety risk assessment practice these significant limitations have been addressed through the use of spreadsheets, sometimes including Visual Basic macros to facilitate looping over the range of initiating events with variable step sizes, input of SRP and consequences relationships, and post processing for reporting and risk evaluation (e.g. Chauhan and Bowles, 2001; Hill et al., 2003). @Risk and Crystal Ball have been linked to these spreadsheet models to perform uncertainty analysis (e.g. Chauhan and Bowles, 2003). However, the spreadsheet approach lacks generality and can require significant effort to apply to a specific dam or to modify the event tree structure.

Objectives of Research

The objective of this thesis is to develop a general computational routine for developing event trees applied to the dam safety risk analysis and performing the associated computations and some aspects of post processing such as applying some tolerable risk guidelines. This objective is addressed from the following perspectives: (a) specific computational requirements of event tree analysis (b) solution to all analysis requirements, and (c) ease of event tree analysis. As mentioned above, several proprietary software packages exist, and these are particularly suited for various business risk analysis applications but none is in itself well suited to performing dam safety risk analysis. So the other facet of this thesis objective includes presenting the computational routine in a flexible user-friendly graphics-based software format, which can be easily used for any dam safety risk analysis. To facilitate the applicability of the tool, the following design objectives were established for the tool:

a) Stand-alone GUI based software,
b) Interactive event tree construction,
c) Graphical display of event trees on screen,
d) Capability to add or remove of any event tree branch at any time,
e) Immediate update on the screen as changes are mode,
f) Capability to perform calculations for different forms of input methods,
g) Capability to plot input data tables,
h) No restriction on the size of event tree or the number of downstream impact centers,
i) Capability to perform dam risk evaluation specific calculations on probabilities and consequences,
j) Capability to store the event tree structure and all calculated values for future modification or completion,

k) Interactive display of failure probabilities and consequences, and

l) Capability to perform post processing

With above-listed functionalities and a generalized computational algorithm, efforts to fulfill the thesis objective have been focused on developing a general independent dam safety event tree modeling tool. To ensure the validity of the computational logics and also, to demonstrate the capabilities of the developed software, an important part of this thesis has been to compare the results with those from a completed and verified dam risk analysis model.

Organization of the Thesis

This thesis describes the development process and functionalities of an independent software tool, DAMRAE (***DAM*** safety ***R***isk ***A***nalysis ***E***ngine), developed for performing dam safety risk analysis using event tree analyses and some aspects of risk evaluation. This report is organized into six chapters as follows. Chapter I begins with the past and the present state-of-the-art in dam safety techniques and proceeds with discussing the importance and requirements of event tree analysis, as the most prevalent method in risk analysis. Chapter II presents a literature review of the construction and computational algorithm for event tree analysis and includes some discussion of the existing software tools for performing event tree calculations. Chapter III provides the definitions and descriptions of the terminology used as a basis for the generalized software development. To present the computational efforts and programming steps employed in DAMRAE, a detailed description of computational logic has been included in Chapter IV. For demonstrating the major capabilities and potential application of

DAMRAE, an example application to Success Dam is included in Chapter V based on a completed risk assessment by Bowles et al. (2004). Chapter VI summarizes the research conclusions and lists some topics for future research. Finally, an appendix has been attached containing a user manual guide for using the DAMRAE software.

CHAPTER II

LITERATURE REVIEW

Introduction

The risk-based dam safety management process is an enhanced system safety approach that incorporates the following four fundamental steps: (a) risk analysis, (b) risk evaluation, (c) risk assessment, and (d) risk control (Bowles et al., 1999; Hartford and Baecher, 2004). These four well-defined steps are implemented in sequence to support better decision-making by contributing to a greater insight into risks including their consequences. The first three steps deal with identifying the threats that can potentially affect a given dam and assessing the resulting risk. The last step involves taking actions to reduce either the likelihood or consequences dimensions of the risk of the dam failure or strengthening management actions in support of dam safety risk management.

The principal methods, most commonly used to analyze the risk of dam failure, as adapted from the Canadian Standards Association’s (1991) Risk Analysis Requirements and Guidelines, are as follows: (1) failure modes and effect analysis (FMEA), and associated methods, (2) fault tree analysis (FTA), and (3) event tree analysis (ETA).

Failure modes and effects analysis (FMEA)

FMEA is a logic diagram based inductive methodology used to identify potential failure modes, determine their effect on the safe operation of the dam, and identify actions to mitigate the failures (Hartford and Baecher, 2004). In the analysis process, a dam system is broken down into its individual elements and the failure modes of each element are identified and analyzed. FMEA is used during the design stage of a dam and is continued throughout the life of the dam. An example of FMEA used to illustrate the relationship between failure mode, failure cause and failure effect is shown in Figure 1.

Fault tree analysis (FTA)

Hartford and Baecher (2004) define FTA as a quantitative or qualitative technique to deductively identify the conditions and factors that can contribute to a specified undesired event. FTA can also be defined as "a top-down approach to failure analysis starting with an undesirable called a top event, such as a failure or malfunction and then determining all the ways it can happen" (Hartford and Baecher, 2004). An example of a fault tree for the failure of an emergency spillway generator to start is illustrated in Figure 2.

Event tree analysis (ETA)

ETA is a commonly-used approach for understanding, analyzing and communicating dam safety risk and for supporting decision making (Bowles and McClelland, 2000; Hartford and Baecher, 2004). According to Turney and Pitblado (1996), ETA is a process which beings with an initiating event and depicts the possible sequences of events, which can lead to an accident. In dam safety applications, ETA can also be extended to the representation of possible series of event that link the occurrence of a dam failure (or accident) or even normal operations especially in the case of flood operation, to the realization of consequences (Bowles and McClelland, 2000).

Given the occurrence of an initiating event, ETA also serves as a logical method to quantify the consequences resulting from a given initiating event. ETA requires a mix of both inductive and deductive logics to construct the dam failure event tree and to calculate the total risk posed by the dam failure (Bowles and McClelland, 2000).

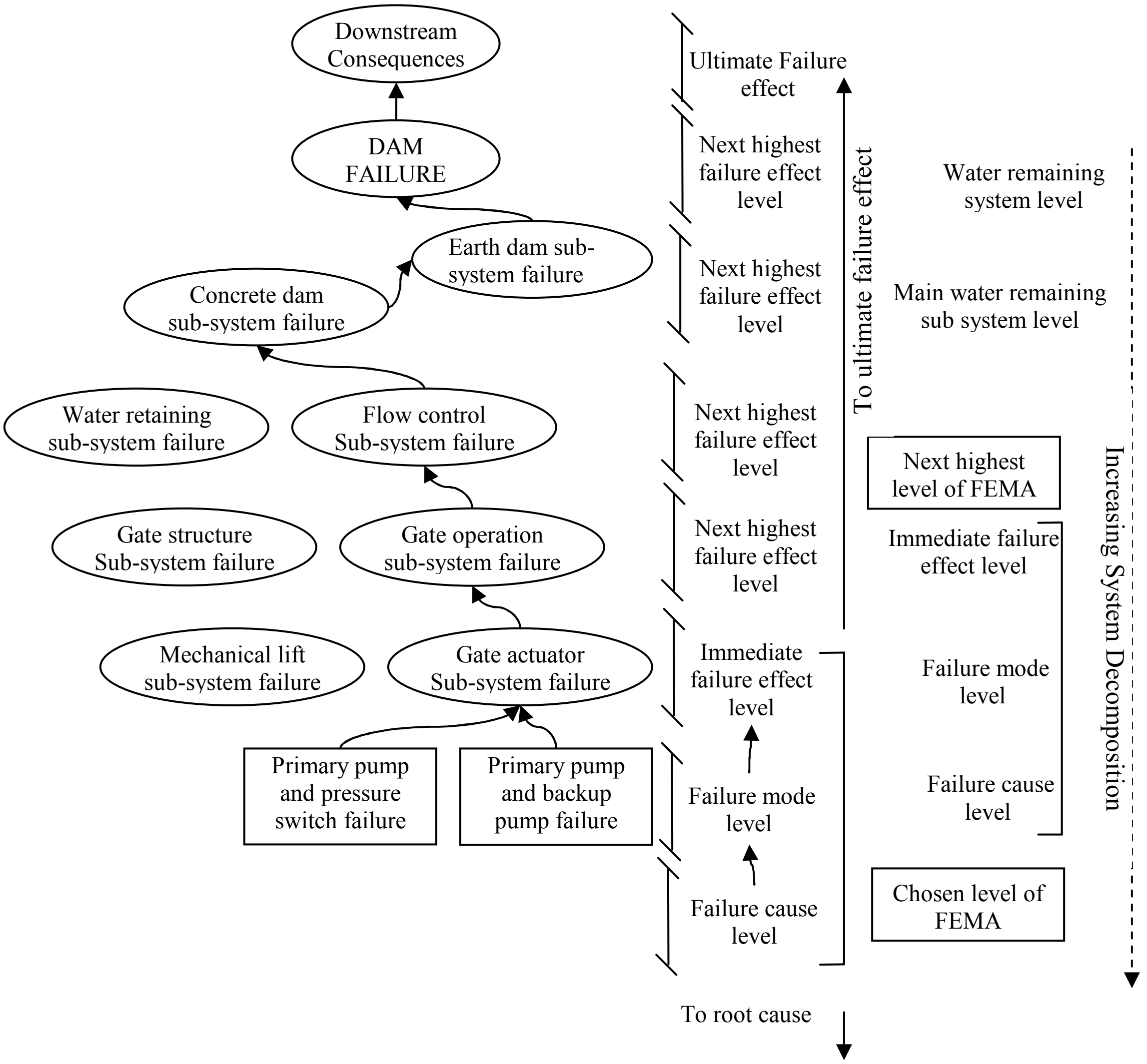

Figure 1. Hierarchical nature of FMEA (Hartford and Baecher, 2004).

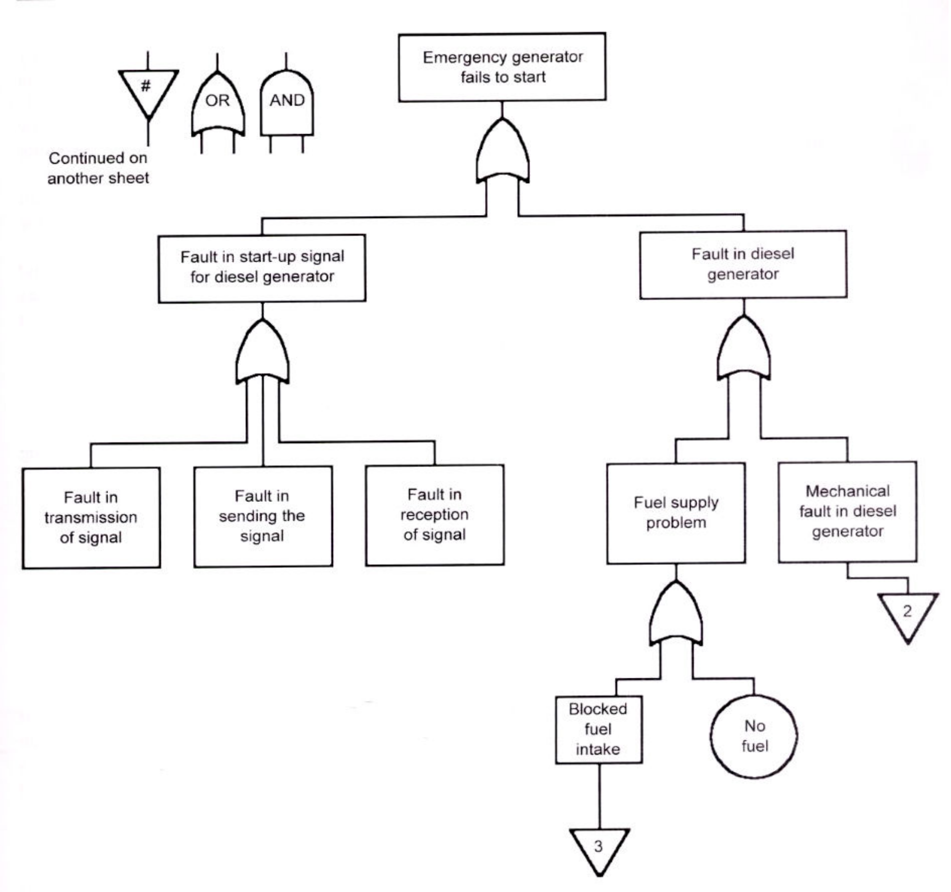

Figure 2. Fault tree for failure of an emergency spillway generator to start (Hartford and Baecher, 2004).

Event Tree

The essential component of an Event Tree Analysis is the event tree. An event tree is a visual representation of all the events which can occur in a system, with a precise mathematical representation associated with it. According to Bedford and Cooke (2001), event tree is a basic modeling technique which provides an effective method of dissecting the operation of an arbitrary system or process into critical events which can then be assigned probabilities of success or failure. In the context of the dam safety risk assessment, Bowles and McClelland (2000) describe an event tree as a series of events, which begins with an initiating event and continues with a series of events that can lead to the outcomes of normal operation or various types of dam failure (Figure 3). For dam safety risk assessment, the series of events represented by an event tree describe the various responses of the dam system to the initiating event, which are triggered in a cascading fashion and failure, partial failure, and no-failure states are generally defined as desired outcomes in the event tree. Event trees are also extended to include various exposure scenarios that affect the estimated magnitude of consequences, especially life loss and different human interventions, such as emergency measures to lower a reservoir, or to remove a jammed spillway gate, during a flood (Bowles and McClelland, 2000).

Quantification of the event tree diagram helps in predicting the frequency of each of the outcomes. The outcome event consequences, usually expressed in terms of fatalities, are then combined with the frequency of occurrence to produce an F-N curve to help assess the acceptability of the response to hazards (Andrews and Dunnett, 2000).

The Event Tree method was first used by the US Nuclear Regulatory Commission in 1960 to perform risk assessments for nuclear power plants (Rasmussen, 1975). After that, event tree analysis was used to study system risk in various contexts arising in both the public and private sectors. A survey by Sherali, Desai, and Glickman (2006) shows that these studies include steam generator tube ruptures (Zhang and Yan, 1999), water resources planning (Beim and Hobbs, 1997), fusion-fission hybrid reactor failures (Yang and Qiu, 1993), electrical accident counter-measure system for mines (Collins and Cooley, 1983), failure of temporary structures (Hadipriono, Lim, and Wong, 1986), reliability analysis of high voltage transmission systems (Ohba et al., 1984), and emergency response in the event of chemical hazard or spills (Raman, 2004; Zhang et al., 2004) .

The use of event trees in dam safety issues came into the picture in 1979, after the failure of Teton dam, when a committee of Federal agency representatives appointed by the President developed the Federal Guidelines for Dam Safety to promote prudent and

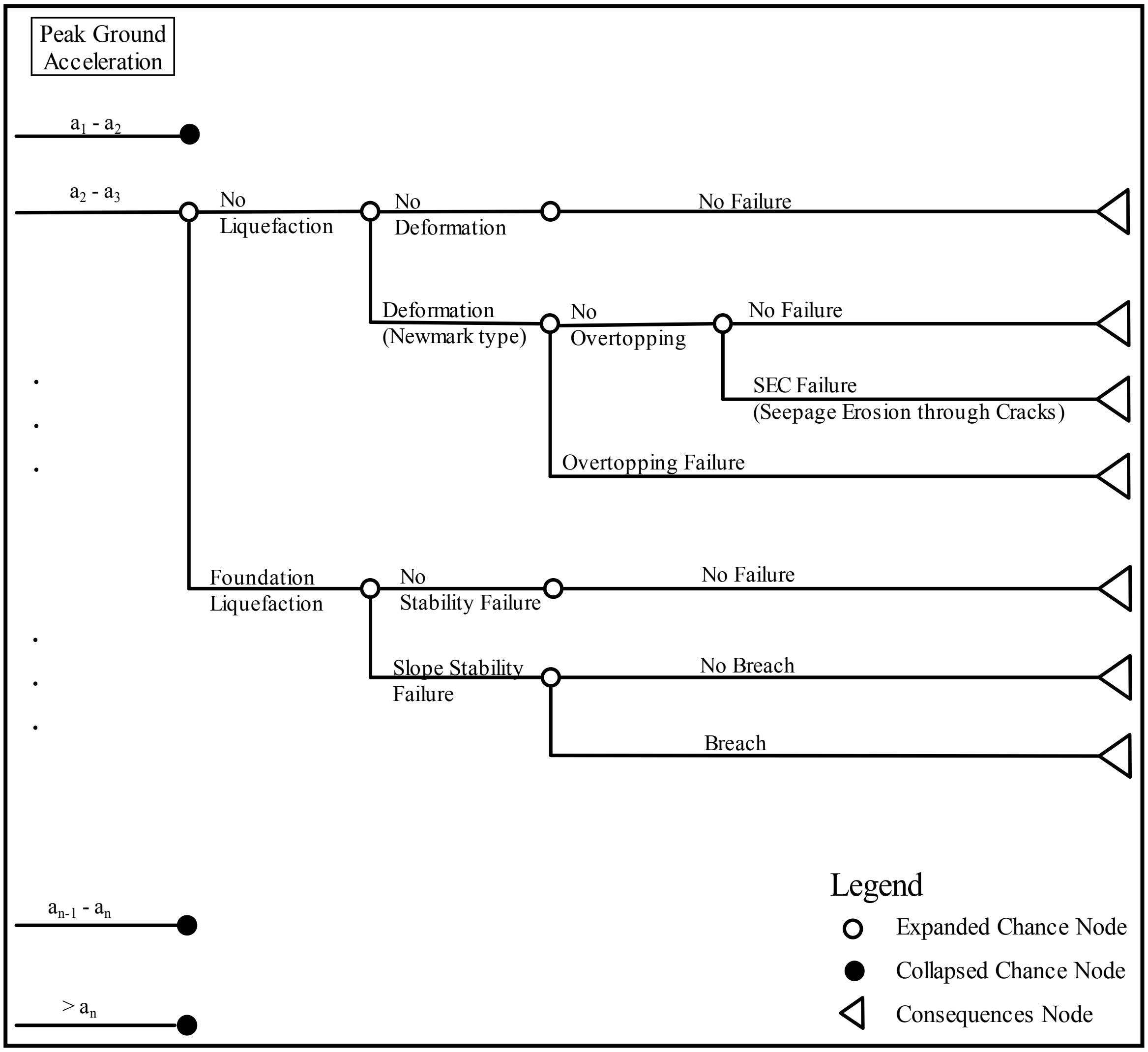

Figure 3. Generic earthquake event tree for PRA of Fort Worth District Dams (Bowles et al., 2006).

reasonable dam safety practices among Federal agencies. At present, event trees have become a prevalent method used in risk-based system safety analysis in many industries and businesses. The basic three attributes that make an event tree a valuable tool in risk analysis are as follows: (1) it is graphic; (2) it provides qualitative insight to a system: and (3) it can be used to quantitatively to estimate a system's reliability (Hartford and Baecher, 2004).

Event tree structure

Paté-Cornell (1984) refers an event tree as a graph without loops. The risk analysis literature for power plants, aircrafts and other mechanical equipment suggests that the events within the event tree are usually limited to binary outcomes (McCormick, 1981; Levenson, 1995). These kinds of event trees are known as Bernoulli event tree and they use binary branching to illustrate that either that the system succeeds or fails at each system logic branching node. Since in dam safety cases events may have many possible discrete outcomes or even have continuous outcomes, event trees are not necessarily binary (Hartford and Baecher, 2004).

An event tree serves as a model of the physical dam system in which each node represents an identifiable behavior of the dam or its physical components and each event should be something that happens in space or time (Hartford and Baecher, 2004). An event tree begins with a single initiating branch on the left hand side and progress toward more detailed events to the right hand side. Starting with an initiating event branch (e.g. a severe flood, an earthquake or other natural or human caused hazards), each node is divided at various nodes to generate all possible subsequent events. Each node is an origin of possible subsequent events and each branch is a possible event that is a logical consequence of the one before it, and a necessary precursor of the one that follows. As the number of events increases, the structure fans outs like the branches of a tree until each event tree chain comes to a terminal branch. Terminal branches are the system outcome or system effect of an initiating event which leads to adverse consequences or failure of the system completely or partially. The tree may be extended to represent the economic damages and life-loss consequences associated with the terminal branches.

Since the first event tree applications in the 1960s many studies have been done using event trees related to the fields of nuclear industry, chemical processing, offshore oil and gas production, and transportation. In the past, various authors have investigated the role of event trees in dam failure risk assessment but recently, Bowles and McClelland (2000), and Hartford and Baecher (2004) have presented detailed descriptions of the event tree structures in context of the dam risk safety management. As adapted from their literature, a brief description of the terminology used in event tree structures has been presented as follows (Figure 4):

Initiating event. Initiating events are the first level branches in an event tree that precede the subsequent chain of the events leading to failure. Initiating events can be external to the dam system (e.g. flood, earthquakes and upstream dam failure) or they can be internal to the dam system (e.g. piping and slope instability).

Branch. A branch graphically links the sequence of one system state to the subsequent system state. In its simplest form, a branch represents a real physical event but in advance analyses, a branch can also be used to represent the process whereby the system transitions from one state to another. In case of discrete nature of the event (i.e.

the number of states of an event is finite), branch is designated by a line segment but in case of continuous nature of the event (i.e. the number of possible states of an event is infinite), branch is displayed as a fan originating from the node (Figure 5).

Chance node. Chance node is a branching point at which a new random variable (event) is introduced in the event tree (Pate-Cornell, 1984). It represents transitions from one system state to one or more new states.

Terminal point. Terminal point is a unique end-state of one of the events associated with the last level of branches in an event tree. Alternatively, the terminal point could be associated with the consequences of the final system state.

Branch probability. Branch probability is the likelihood of the occurrence of an event (branch), conditional on the occurrence of the preceding events (branches).

Pathway. Pathway is a chain of events in an event tree beginning from an initiating event to an event of interest. Pathway probability is the joint probability of occurrence of an intersection of events belonging to the chain of events.

Critical pathway. Critical pathway is a pathway that leads to system failure or some other outcome of interest.

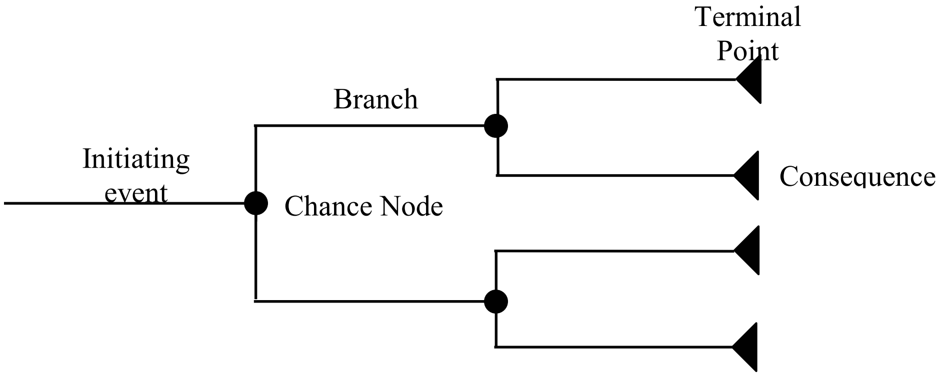

Figure 4. Event tree terminology (Hartford and Baecher, 2004).

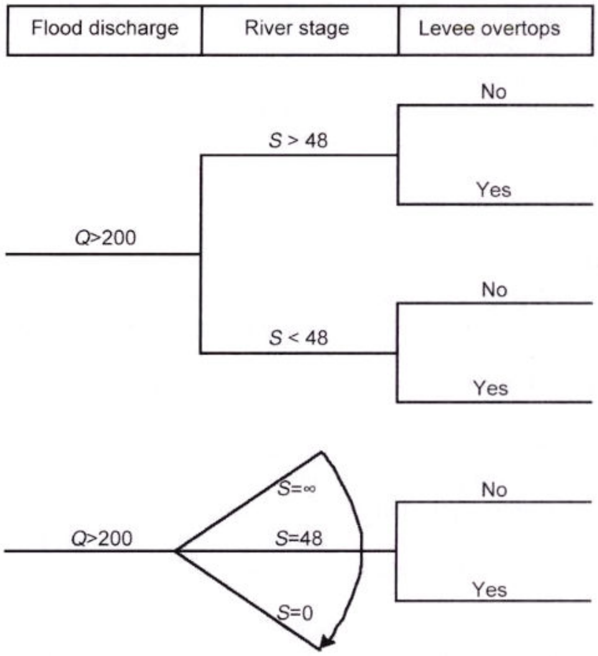

Figure 5. An example levee overtopping event tree: top showing dichotomous representation of river stage branches; bottom showing continuous representation of river stages (Hartford and Baecher, 2004).

Failure mode. Failure mode is a characterization of the way that can cause the failure of the sub-system or system. It includes all critical pathways of same type of events at each level of branches that results in a common failure outcome.

Consequences. Consequences are the impacts in the downstream, as well as other, areas resulting from failure of the dam or its appurtenances. Generally, economic and life-loss consequences are of most interest in the dam safety risk analysis.

Event tree construction

There is no unique event tree for a dam subjected to a particular initiating event (Baird, 1989). The construction of an event tree for a dam safety risk assessment depends on the scope and objectives of risk assessment and the nature and functional characteristics of the dam. Based on what the event tree is required to represent (physical system, joint probabilities of events; or system information, knowledge, and beliefs), different rules and considerations can be applied for an event tree construction, but as an event tree is logic based graphical statement of a system, it should be logically consistent and mathematically valid (Hartford and Baecher, 2004). Figure 6 depicts the general steps applied to an event tree construction process but a detailed study on the rules and logic and mathematical considerations employed in dam-safety related event tree construction is discussed in Bowles and McClelland (2000), and Hartford and Baecher (2004) literatures.

Probability and consequences assignment

The quantitative aspect of an event tree analysis comprises the inclusion of numerical probabilities and consequences values into the event tree. As per the defined definition, risk is a combination of probabilities and consequences. So, in order to assess the risk represented in an event tree, it is essential to quantify the probabilities of a set of undesired events and the consequences should those events occur.

Probability assignment for different initiating events such as extreme floods or earthquakes is done by using an appropriate statistical model and typically includes some reliance on subjective expert judgments. These are usually expressed as annual exceedance probabilities (AEP). Probability values for the system response branches (events) which are usually expressed as system response probabilities (SRPs) are conditional on all preceding events in the tree leading to the node from which they emanate, and their sum over all the branches emerging from the same node equals one. Various approaches for obtaining SRPs have been summarized by Fell et al. (2000).

Loss of life and economic losses are typically quantified as consequences values in an event tree analysis for dam safety. These values are based on the available data, models and experience. Based on the locations of impact areas or some other criteria, consequences values are aggregated into "consequence centers" (Bowles and McClelland, 2000). To calculate the "incremental consequences" i.e. the difference between failure and no-failure consequences, it is required to enter both failure and no-failure values into the event tree analysis.

The mathematics of event trees

The basic mathematical concept of event trees is reasonably straightforward and has not changed since its conception in the 1960's when this approach was successfully used in the WASH 1400 study (Andrews and Dunnett, 2000). After drawing the structure and assigning the probabilities and consequences values to an event tree, a simple multiplication of branch probabilities along any pathway yields the probability associated with that terminal node. The probability associated with a terminal node times the consequences value is often calculated as an estimate of the annualized risk associated with that terminal node. This seemingly simple mathematical multiplication becomes a cumbersome calculation when the event tree size is large or when the event tree has to be re-quantified several times. To quantify an event tree in an efficient and accurate manner several theories have been proposed by different authors.

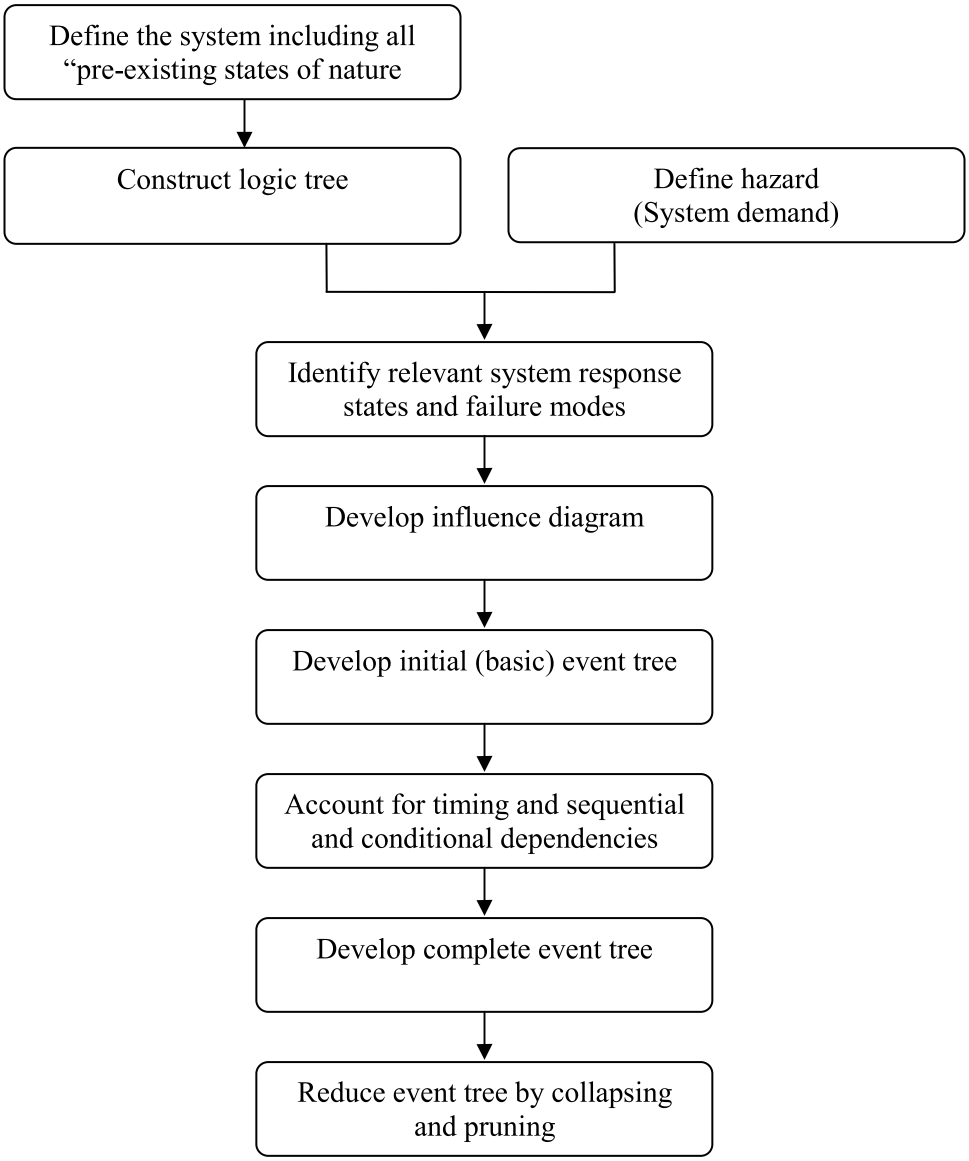

Figure 6. Steps in constructing an event tree (Hartford and Baecher, 2004).

To highlight the inherent conceptual and computational aspect of event tree analysis, Kaplan (1982) formulated the theory of replicating an event tree using transition matrices. Matrix theory formalism by Kaplan (1982) was a significant contribution in building up the basis for structuring event tree analysis as an automated computer program. Considering the nature of large event tree calculations, Takaragi et al. (1983)

proposed a theory for estimating an upper-bounding approximation of failure probabilities. This theory was based on eliminating a few basic events from the event tree using minimum cut/prime implicant sets. For transforming the event tree structure and the associated branch probabilities into a computer programming compatible numerical form input, Unwin (1984) suggested a compact numerical representation method for event trees. To strengthen the concept of automated computer assisted event tree construction and evaluation technique, Papazoglou (1998) developed a mathematical representation method for event trees based on basic concepts of set theory and probability theory. Papazoglou (1998) defined the event tree as a graphical representation of the outcome space of an event base where each path of the event tree corresponds to an element of the outcome space. The concept of outcome space enables the generation of the event tree in its reduced form to facilitate the formal quantification of the event tree. Some other authors such as, Andrews and Dunnett (2000) and Xu and Dugan (2004) discussed the relationship of event trees and fault trees while Kenarangui (1991), Patra, Soman, and Misra (1995), Huang, Chen, and Wang (2001), Dumitrescu, Ulmeanu, and Munteanu (2002), and Jin, Yan, and Zhou (2003), addressed the uncertainty issues involved in an event tree analysis using the fuzzy set-based approach. Apart from these system-specific or generic event tree construction and evaluation oriented literatures, Bowles and McClelland (2000), and Hartford and Baecher (2004) reported the basic mathematical concepts for event tree analysis applied specifically to the dam safety risk assessment. As adapted from their literature a brief description of basic event tree calculations can be summarized as follows:

Pathway probability. Pathway probability is the product of the probability of the initiating event and all conditional probabilities along the pathway. If the event tree branches along a given pathway are serially identified as A, B, C … M, N, beginning with the initiating event, A, then their joint probability is given as follows:

$$P_{N/A,B,C,...,M}(n/a,b,c,...,m)P_{M/A,B,C,...}(m/a,b,c,...) \ \ldots \\ P_{C/A,B}(c/a,b)P_{B/A}(b/a)P_{A}(a)$$

The units of pathway probability are same as those of the initiating events. Typically for dam safety event tree analyses “per year” units are used.

Probability of failure. Joint probabilities of all mutually exclusive and collectively exhaustive pathways, which lead to an identical terminal outcome is summed together to calculate the total probability of that terminal outcome occurring given the initiating event. The total probability of failure for a particular initiating event can be calculated by summing the pathway probabilities of all the critical (failure) pathways. Alternatively, only those critical pathways that involve a particular system response (e.g. spillway gate failure) could be summed to calculate the failure probability associated with that system response and initiating event.

Common-cause adjustment (CCA). Common-cause failures (CCF) are failures that can occur simultaneously at a single dam section or multiple dam sections due to a single, shared cause. In case of CCF, failure modes (events) emanating from a common chance node are not mutually exclusive which contrasts the typical condition of event tree calculation. To adjust the event tree calculation for the non-mutually exclusive events, Hill et al. (2003) proposed the theory of common-cause adjustment (CCA).

Common-cause adjustment can be performed using one of the two approaches (Uni-model bounds theorem and physical dominance) described in their literature.

Annualized incremental consequences. Annualized incremental consequences are calculated as the expected value of consequences by summing the incremental consequences (ΔC_i) times the pathway probability (p_i) over the n pathways of interest, as follows:

$$\sum_{i=1}^{i=n} p_i \Delta C_i$$

The units of annualized incremental consequences are typically \$/year for economic losses and lives/year for life loss.

Post processing. Post processing is performed, (a) to interpret the evaluated event tree results in terms of prescribed guidelines by different dam safety associated agencies, and (b) to arrange the results in a presentable manner which is easily adaptable for making decisions. There can be several possible ways for post-processing calculations and graphical displays that can be developed from an event tree analysis but most common and simple methods can be categorized as follows:

a) Annualized Risk Measures – Separate estimate of probability of dam failure, incremental risk cost and annualized incremental life loss can be generated based on the types of initiating events, types of failure modes, or, some other pattern of interest such as parts of the overall range of initiating events.

b) Range of Incremental Consequences – The range of incremental economical damages can be represented by the minimum and maximum incremental damages over the failure pathways and the range of incremental life loss can be represented by the minimum and maximum incremental life loss over the failure pathways.

c) Societal Risk Measures – can be represented by cumulative frequency (F) versus life-loss severity (N) chart which is usually referred as F-N plot. In F-N plot, F-N pair values are obtained by sorting f (pathway probabilities)-N pairs in descending order of life-loss severity and then cumulating f values in order corresponding from largest to smallest N values.

Proprietary Software Tools for ETA

Due to the concern of public's safety, several industries are required to ensure the very high reliability of their safety and control systems. Generally, safety systems used in various industries involve large numbers of components, much redundancy, and have very small failure probabilities (Koren, Rothbart, and Putney 1984). With the enhanced knowledge of event tree structures for most of these systems and also, in desire to assess the best estimate of failure probability and associated consequences, the use of much detailed and complex event tree analyses has become prevalent. According to Koren, Rothbart, and Putney (1984), in the past, event trees were small and often, quantitative results were not needed but at present, these trees are very large and quantitative results are more useful. In order to simplify the process of drafting, quantifying and reporting the result of event tree analyses, Koren, Rothbart, and Putney (1984) developed an event tree modeling software written in BASIC computer language. This tool was a graphics based user-friendly program but it was developed to run on the IBM Personal Computers only.

In 1989, Idaho National Laboratory (INL) released a modified version of its basic software, IRRAS, with the capability to draw, edit, and analyze graphical event trees. The current SAPHIRE software is an advanced version of IRRAS software, which was originally developed for the U.S. Nuclear Regulatory Commission (NRC) activities. In 1992, EC (Event Consequence) Tree software was developed by members of the Advanced Technology Group of SAIC in New York to facilitate the rapid generation of event trees for application to event based risk analyses, specifically for use in short turnaround assessments to estimate the risk and reliability of space flight missions. This software was a product for the specific use in NASA's Integrated Modeling and Simulation Program and it was developed using Microsoft Excel and Visual Basic (Sen et al., 2006). The ever-growing interest in ETA-based risk management procedures has always spurred the software analyst to come up with more delicate and more user-friendly software to ease the tedious task of algebraic manipulation employed in event tree analysis. Also, Webb (1997) states, "The whole subject of risk analysis and management within the context of engineering projects has grown in significance over the last few years. This trend has not escaped the attention of the software developers who have produced a range of packages, but each tends to be confined to a particular aspect of the problem."

Some of the more commonly used ETA software tools, as named by Bowles and McClelland (2000), are DATA, DecisionPro, DPL, Precision Tree, and Saphire. These software packages provide very nice user-friendly ways for the graphical representation of any event tree diagram but Bowles and McClelland (2000) observation shows that all of these software packages lack the flexibility to handle the computational variation used in a specific dam safety event tree from other general event trees. Based on their experience on risk assessment for several dam cases, Bowles and McClelland (2000) found that the use of Microsoft Excel with Visual Basic macro is most efficient to facilitate looping over the range of initiating events with variable step sizes, input from SRP and consequences protocols, post processing, and uncertainty analysis employed in dam safety risk assessment.

CHAPTER III

THEORETICAL DEVELOPMENT OF DAMRAE

Introduction

This chapter summarizes some theoretical concepts for DAMRAE in the following subsections: branch attributes; branch identifiers; calculation of state, branch probability, exposure and consequences values; types of branches; and collapsed nodes. We have made some refinements to traditional ETA terminology to develop a generalized event tree algorithm that is readily adaptable for a computational processing in dam safety risk analysis.

Branch Attributes

The following three types of Branch Attributes are important properties of branches or events in the quantification of an event tree:

1. State Value. This is also referred to the 'State' of a branch. It can be defined as a condition (e.g. "liquefaction occurs" or "liquefaction does not occur" to an extent sufficient to be of interest in a potential failure mode), a point value (e.g. $500m in economic losses), or a range of values (e.g. peak reservoir pool elevations associated with extreme flood events between 645 m and 647 m) that are used to describe a situation or variable of interest in a risk analysis (Hartford and Baecher, 2004). The state value can be assigned by the user or it can be calculated as a function of other preceding (i.e. located to the left in the event tree) state variables, as described in the next subsection.

2. Branch Probability. The likelihood that a branch has a particular state value. A branch probability can be a user-specified value or it can be calculated as a function of the state values of the branch or other preceding branches. Thus, it is typically a conditional probability, often referred to as a system response probability (SRP), unless the branch is in the first level of branching representing an initiating event, in which case it is typically a maximum annual event probability. The conditional branch probabilities across all branches in a group, which emanate from a chance node, must sum to 1.0.

3. Exposure Weight: The fraction of the time that the exposure case occurs, where an exposure case is a time period over which the size of the PAR that is exposed to the dam failure hazard varies or the PAR is exposed in different ways such as differences in the effectiveness of warning systems at day or at night. For example, if life-loss is estimated in four six-hour intervals to represent variations in the magnitude and exposure conditions of the PAR over a 24-hour period, then each of the four Exposure Branches would be assigned an equal weight value of 0.25, which is treated the same as a probability in the event tree calculations.

4. Consequence Value. It shows the impacts in the downstream and other areas resulting from failure of the dam or its appurtenances (Hartford and Baecher, 2004). Generally, economic and life-loss consequences are of most interest in the dam safety risk analysis. Values can be assigned by the user or they can be calculated as a function of other preceding state variables. Life-loss consequence values are also influenced by the exposure state(s), such as time of day, weekday/weekend and season of the year. In the case of flood initiating events, no-failure consequences can be considered on no-failure branches so that incremental consequences can be calculated.

Branch Identifiers

The following three types of identifiers are used in DAMRAE to assign a unique identity to each branch. These unique identifiers are used in the computational algorithm, plotting and reporting wherever it is required to access the input data or calculated values associated with a branch.

1. Branch Variable Name: This is a brief description of the event that is represented by a branch. It is input by the user and used in reporting but it is not used by the DAMRAE computational algorithm.

2. Branch Variable Code: This code is used by the DAMRAE computational algorithm and by the user when defining functional and probabilistic dependencies to calculate state values, probabilities and consequences for a branch as a function of the state values or probabilities of the branch or other branches. This code is input by the user and should be chosen so that the event that it represents can be readily interpreted from the code.

3. Branch Level Number: This number is assigned by DAMRAE and represents the position of a branch from left to right in the event tree with the initiating branch being Level 1.

Calculation of State, Branch Probability, Exposure, and Consequences Values

The user can select from the following three methods to calculate the state, branch probability, exposure, and consequence values associated with each branch in DAMRAE:

1. User-specified Input: A specific numerical value input by the user is assigned to the state probability or consequence; or it can be an alpha-numeric value in the case of state or exposure values (e.g. “liquefaction occurs” or “liquefaction does not occur”; “day” or “night”).

2. Tabular Interpolation: The numerical value is interpolated from a table of dependent and independent values input by the user. Tabular interpolation can be a one-way interpolation (i.e. one dependent variable and one independent variable) or it can be two-way interpolation (i.e. one dependent variable and two independent variables). Based on the relationship between the dependent and independent variables, the interpolation method can be linear, logarithmic or semi-logarithmic. Interpolation can also be done between a dependent variable and z-variate of the independent variable.

3. Relational Equation. Functional relationships input by the user can be used to calculate the values from an algebraic equation that is a function of the state value of the branch or preceding branches. Equations can be imbedded in tables.

Types of Branches

To facilitate the event tree calculations in DAMRAE, the following seven types of branches or branch groups have been defined, each with unique properties in the DAMRAE algorithm:

1. Discrete Branch Group: Represents a discrete random variable that can take on only a finite number of state values, where each value is represented by a branch. Thus, the number of branches is selected to match the number of discrete values that the variable can take on. Each discrete branch is assigned a user-specified state value and the

probability that the value will occur. The state value and probability are calculated by one of the three methods described in the previous subsection.

2. Continuous Branch Group: Represents a continuous random variable that can take on an infinite number of state values in an interval defined by user-specified lower and upper values. Continuous branches can be used to represent flood (e.g. peak reservoir pool elevation) or earthquake [e.g. peak ground acceleration (PGA)] loading variables, for example. DAMRAE divides the interval over which the continuous random variable is defined into a user-specified number discrete computational branches, which can be varied to achieve numerical precision in the resulting risk estimates. Each of these computational branches is assigned a calculated interval of state values and the probability that this interval of state values will occur. The state value and probability are calculated by any of the three methods described in the previous subsection.

3. State Function Branch: Represents a deterministic variable, which therefore has a probability of 1 of occurring conditioned on the preceding branches, but which is included in the event tree so that its state value can be used to calculate the probabilities or state values in succeeding branches to its right. State functions can be used to represent deterministic relationships between variables in the event tree such as: stage-discharge; stage-duration; and vertical and horizontal deformations as a function of earthquake magnitude, PGA, and reservoir pool elevation (Bowles et al., 2006).

4. Failure Branch Group: Represents no failure and one or more failure modes. These branches are characterised by their state values, which are the failure mode names assigned to each branch and the SRPs that each failure mode will occur conditioned on one or more preceding branch(es). By defining failure modes in one or

more failure branch group(s), DAMRAE allows the user to readily develop reports displaying the estimated risk associated with each failure mode or with groups of failure modes defined by the user as illustrated in the application at the end of this paper.

5. Exposure Branch Group: Represents different exposure cases (e.g. summer and winter; or day and night). This type of branch is characterised by the state value, which is the branch name that is assigned to the branch and an exposure weight, which is the fraction of the time that the exposure case occurs. For example, if life loss is estimated in four six-hour intervals to represent variations in the size and exposure conditions of the PAR over a 24-hour period, then the Exposure Branch Group would comprise four branches with equal weights of 0.25.

6. Intervention Branch Group: Represents human interventions, such as emergency measures to lower a reservoir when signs of piping, instability or a sink hole are observed, or to repair a jammed spillway gate during a flood event. The two discrete intervention branches represent the events of successful intervention and unsuccessful intervention. The branches are labeled by their Branch Variable Names (i.e. “Successful intervention” and “Unsuccessful intervention”) and the probability of each occurring is calculated using one of the three methods in the previous subsection. By defining one or more Intervention Branch Groups, the user can readily perform sensitivity analysis to explore the degree of dependency on successful intervention.

7. Consequences Branch Group: Represents the economic or the life-loss consequences for various types of initiating events, failure modes, exposure conditions or other preceding event combinations. Consequence branches are characterized by the branch variable code.

The discrete, failure and exposure types of branch groups must have at least two branches connected to a single preceding node. The number of branches for the intervention branch group is also currently limited to two. The state function type of branch group always has only one branch. The consequences type of branch group is shown in the event tree diagram as having only one branch to keep the event tree compact and readily understandable (see discussion in the next subsection on “Collapsed Nodes”), but in reality it has as many computational branches as the user defines to achieve numerical precision.

Collapsed Nodes

Event trees can become very large if they are fully developed for all state values at all levels of the event tree. Although a full development is necessary to complete the event tree calculations, the full tree can be difficult to understand[1] and tedious to construct. In fact, the latter limitation of event trees is one of the drivers behind the development of DAMRAE. To assist in understanding of the event tree structure and to reduce the effort required to construct the event tree diagram, DAMRAE includes a collapsed nodes feature. Collapsed nodes (referred to as “Host Nodes”) take on the sub tree structure and the input relationships of another node (referred to as the “Donor Node”). There are two types of collapsed nodes used in DAMRAE as described below:

1. Copied Collapsed Node: When the entire succeeding sub tree branch structure connected to a node (chance or deterministic) is identical to or similar to the succeeding sub tree structure of another node located above in the same branch level

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[1] To paraphrase a popular expression, "It is difficult to see the tree for the branches.”

(referred to as the “Donor Node”), the sub tree structure and all user-defined input relationships for state variables, probabilities, exposure weights and consequences can be copied from the Donor Node to the other node (referred to as the “Host Node”). This saves time and effort in constructing the Copied sub tree. At the time of copying, references in input relationships in the Donor sub tree to branches on its left are modified in the Copied sub tree to refer to the corresponding branches to the left of the Host Node. Following copying, the structure and the calculation relationships in the Copied sub tree can be changed by the user with no effect on the Donor sub tree. The DAMRAE event tree diagram shows a copy of the Donor Node’s succeeding branch structure appended to the Host Node.

2. Cloned Collapsed Node: When the entire succeeding event sub tree branch structure connected to a node and all user-defined input relationships are identical to the succeeding sub tree structure of another node located above in the same branch level (“Donor Node”), the sub tree structure and all user-defined input relationships can be associated with the other node (“Host Node”) in addition to the Donor Node. This saves time and effort in constructing the Cloned sub tree. Like copying, at the time of cloning references in input relationships in the Donor sub tree to branches on its left are modified in the Copied sub tree to refer to the corresponding branches to the left of the Host Node. Following cloning, the structure, and the calculation relationships in the Cloned sub tree cannot be changed because they will continue to be identical to those in the Donor sub tree. Also, if the Donor sub tree structure or its input relationships are changed by the user, the same changes will be associated with the Cloned sub tree. In the DAMRAE event tree diagram, the Host Node references the Donor Node, but the Cloned sub tree is

not displayed to reduce the complexity of the diagram. However, the event tree diagram contains a hidden image of the Donor sub tree structure and refers to the user-specified input relationships in the Donor sub tree.

CHAPTER IV

COMPUTATIONAL METHODOLGY OF DAMRAE

Introduction

DAMRAE has been developed as independent software using the VB.NET environment and some dynamic-link library (*dll*) files for performing the graphical and database functions. Intermediate calculation files and output data are stored in MS Access and using .xml files. The event tree structure and input data are stored in an MS Access file but all output matrices (pedigree, branch code, etc.) are stored in .xml files. The major capabilities included in the prototype version of the model are as follows:

1. Event tree construction, which is conducted graphically and includes flexible options to update the event tree by, for example, inserting or deleting branches. The event tree and other inputs are stored in a database. The event tree can comprise discrete, continuous and other types of branches described in the previous chapter.

2. Input of probability, consequences and state variable relationships, which can be in the form of assigned numerical values, equations or tables for interpolation. In the latter two cases, values can be calculated or interpolated for a particular branch as a function of the state value in that branch or state variables that are located to the left of the variable to be calculated in the event tree.

3. Event tree calculations, which are structured based on the event tree graphic that is built on the screen. This involves generating the pedigree matrix to track pathways, that is every level of branching, that is passed through to reach an end node. In addition to making the probability calculation possible with all the different conditional

probability relationships that can exist, the pedigree is stored in the database to facilitate obtaining information about the contributions of different factors to the overall risk during post processing. The pedigree and the branch connectivity concepts are the keys to implementing this flexible approach to event tree modeling for dam safety risk analysis.

4. Basic risk calculations, which commence with the assignment of state variable values, probabilities and consequences to branches in the event tree and continue with the calculation of branch probabilities, annualized life loss and annualized economic loss (risk cost). In addition, although "probability-consequences pairs" are also stored in the data base for post processing. Probability calculations are structured in a general form that includes the common-cause adjustment for non-mutually exclusive failure events following the approach developed by Bowles, Anderson, and Chauhan (2001).

5. Post processing of the basic risk calculations, which results includes tabular and graphical outputs with flexibility in formatting based on the event tree structure and user needs.

Event Tree Algorithm

The DAMRAE computational process can be subdivided into the following four major steps:

1. Draw the Event Tree Diagram and assign the inputs to branches;
2. Calculate branch state values and branch probabilities for all branches;
3. Calculate branch and annualized consequences for all branches; and
4. Post process to generate summary tables and plots.

The four steps must be performed in sequence. Each step is described using examples in the following subsections.

Figure 7 is a flowchart for the first and second steps of the computational process. It begins with the construction of the event tree diagram in the DAMRAE interface and continues with the user assigning the necessary branch attributes and identifiers, which are described in the subsection on Step 1, below. The user can opt to input tabular relationships by importing text files (e.g. SRP data tables). This flowchart ends at the bottom of Figure 7 with branch probabilities being calculated for all branches in the entire event tree, including all intervals of continuous branches and all branches associated with copied collapsed nodes and hidden branches for cloned collapsed nodes. These are passed to Step 3 in the flowchart shown in Figure 8 as indicated by the symbol ‘E’ in Figures 7 and 8. In addition, branch inputs, a Pedigree (explained in the next subsection for Step 1), a Branch Code and a State Value for all branches, contained in separate matrices (labeled as ‘A’ ‘B’, ‘C’ and ‘D’, respectively) are passed to Step 3 in the flowchart shown in Figure 8.

Figure 8 is a flowchart for Steps 3 and 4 of the computational process in which the branch consequences are calculated and the primary results are post-processed.

Step 1. Event tree diagram and inputs

The event tree structure is drawn by the user on the DAMRAE interface screen. Simultaneously, relationships for branch identifiers and relationships for calculating state, branch probability, exposure and consequences values are input by the user. There are flexible options to update the event tree by, for example, inserting or deleting branches.

The user-generated event tree diagram and input relationships are stored in a database for computational processing.

Event tree calculations are dynamically structured in the DAMRAE computational algorithm to match the form of the event tree diagram built by the user on the screen. To communicate the structure of the event tree diagram to the DAMRAE computational algorithm, connectivity and pedigree matrices are generated by DAMRAE. The connectivity matrix is a row-cell display of the program-assigned branch labels arranged according to their connections with other nodes. These branch labels are assigned to match the identity of the branch that is located immediately to its left in event tree.

The pedigree matrix uniquely identifies the pathways to all terminal nodes in the event tree. In addition to making the probability calculation possible with all the different conditional probability relationships that can exist, the pedigree matrix is stored in the database to facilitate obtaining information about the contributions of different failure modes or loading ranges to the total risk during post processing.

The pedigree and the branch connectivity concepts are the keys to implementing the flexible approach to event tree modeling for dam safety risk analysis in DAMRAE. The connectivity and pedigree matrices are explained below through an example event tree shown in Figure 9.

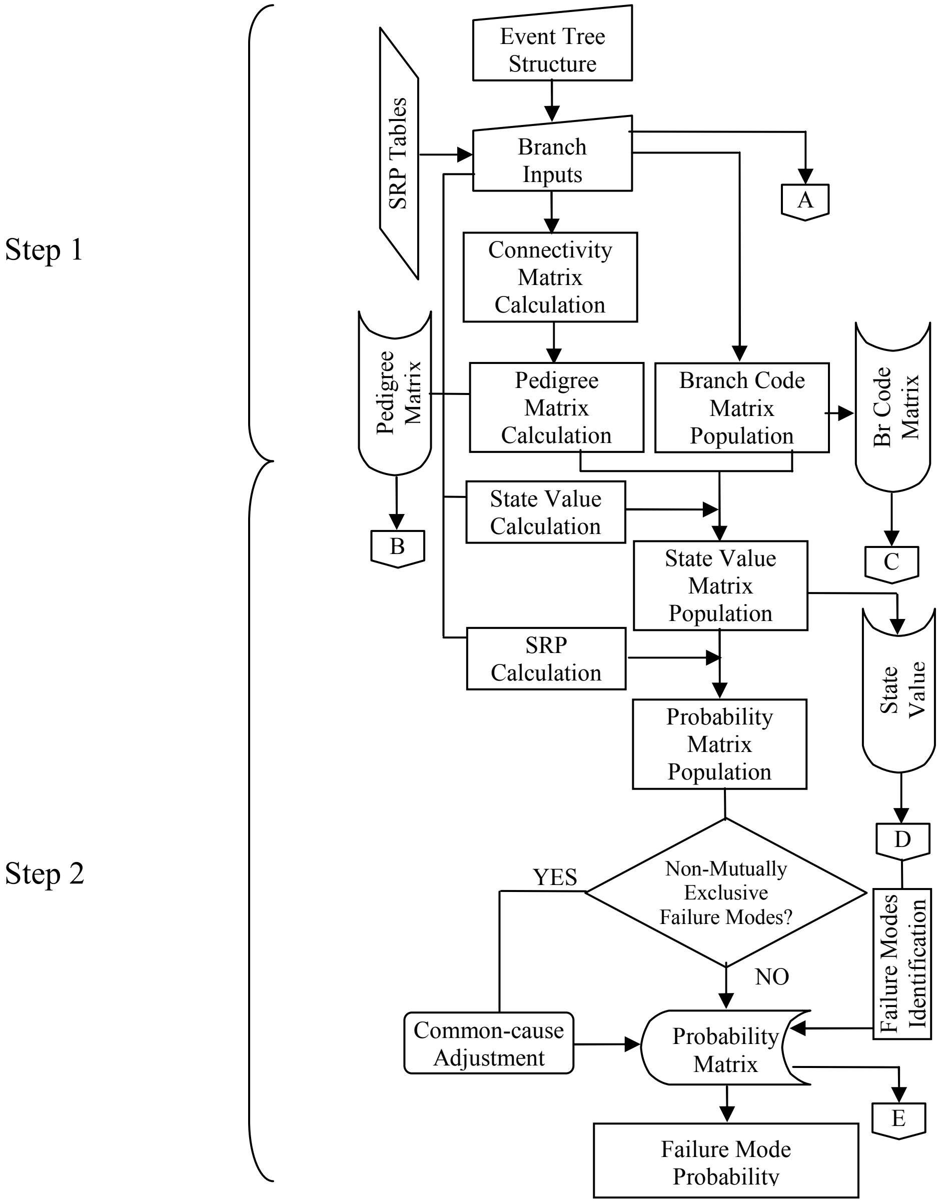

Figure 7. Steps 1 and 2: event tree, input relationships and branch probability calculation flowchart.

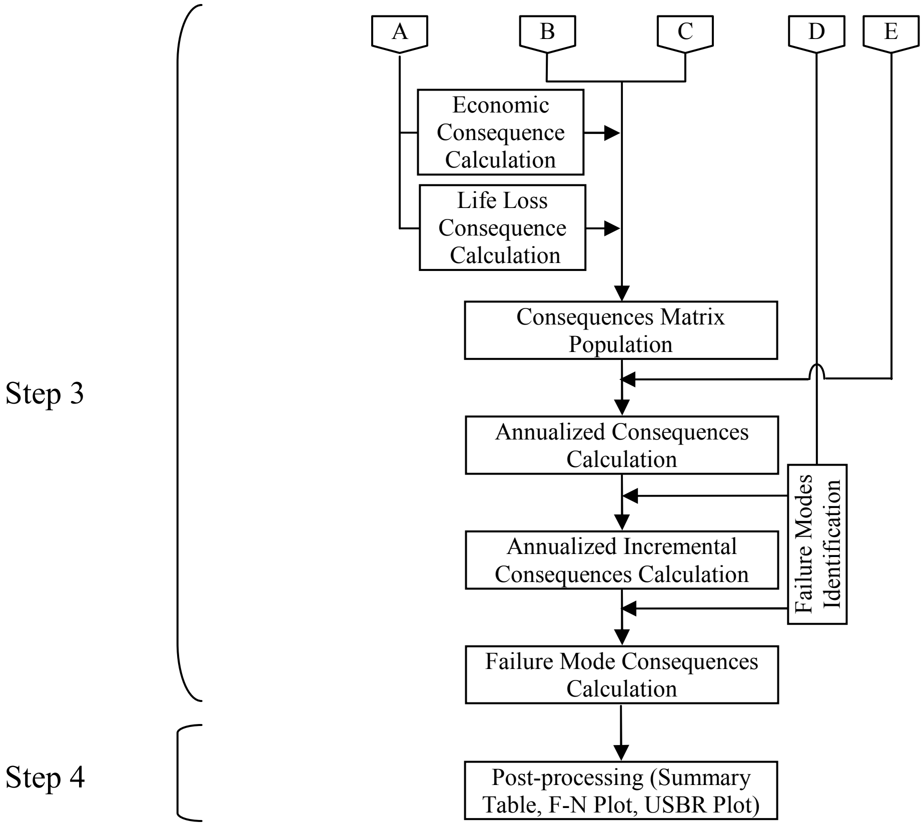

Figure 8. Steps 3 and 4: branch consequences calculation and post-processing flowchart.

Figure 9 shows an event tree with the initiating branch as a single discrete branch in the first branch level. The second level of the event tree is a group of two discrete branches. The first branch in this group leads to a continuous branch, which contains a total of *i* loading intervals. The second branch leads to a state function branch in the third level of the event tree structure, with a “dummy” discrete branch (treated automatically by DAMRAE as a state function branch with no defined state value and a conditional probability of 1.0) connecting it at the second level. In the fourth level of the event tree, two failure branches are connected to all the loading intervals of the continuous branch, although DAMRAE only shows these connected to the first branch in the continuous branch group because the other (*i*-1) branches are collapsed; which is indicated in this diagram by the solid black circle for the Host Node and an open circle for the Donor Node. A state function branch at the fourth level is connected with the third level state function branch at the bottom of the event tree in Figure 9. All branches emanating from a node are numbered within each group starting at the top of the event tree diagram in Figure 9. These are referred to as branch index numbers. They represent the order of a branch within each group of branches. For a continuous branch group, the branch index numbers depend on the number of loading computational intervals or branches that the user has specified to be used in the DAMRAE event tree computations. For the example, in Figure 9, the continuous branch group has three computational branches (i.e. $i = 3$), and these branches are assigned the branch index numbers 1, 2, and 3.

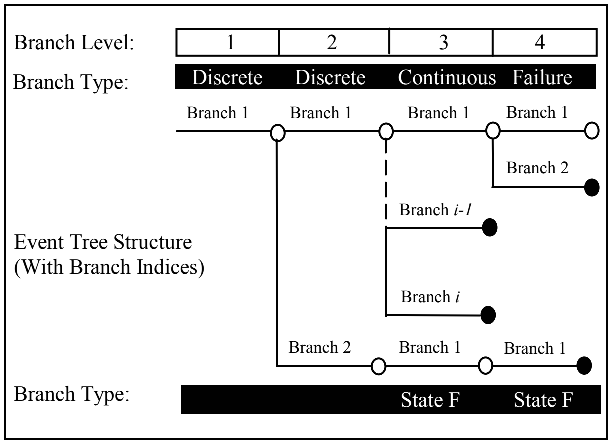

Figure 9.An example event tree structure.

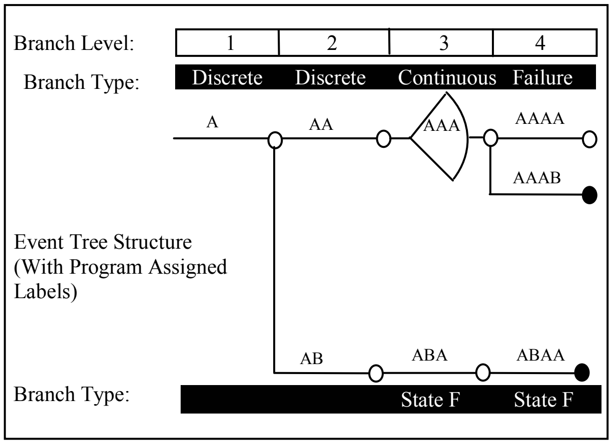

Figure 10.DAMRAE-assigned branch labels for the example event tree shown in Figure 9.

The example event tree structure from Figure 9 is shown in Figure 10 in the form that it would have on the DAMRAE interface. The DAMRAE representation in Figure 10 is similar to the representation in Figure 9, except that the loading branches in the continuous branch group are lumped together and represented by a single “segment-shaped” symbol. Figure 10 also shows DAMRAE-assigned branch labels for these branches. These labels are ASCII characters.[2] For a particular branch, DAMRAE forms the branch identifier by concatenating the letters assigned to each preceding connected branch. This method of assigning the branch labels enables DAMRAE to locate the order of a branch in a group of branches and to identify the identifier of the preceding connected branch so that the connectivity matrix can be developed. For the example event tree shown in Figure 9, the connectivity matrix is shown in Figure 11 (a). The number of columns in the connectivity matrix corresponds to the number of branch levels in the event tree and the number of columns corresponds to the number of pathways in the event tree in the form shown in Figure 10.

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[2] Up to 95 unique ASCII characters.

a.

Connectivity Matrix

$$\begin{bmatrix} A & AA & AAA & AAAA \\ A & AA & AAA & AAAB \\ A & AB & ABA & ABAA \end{bmatrix}$$

b.

Pedigree Matrix

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 2 \\ 1 & 1 & 2 & 1 \\ 1 & 1 & 2 & 2 \\ 1 & 1 & 3 & 1 \\ 1 & 1 & 3 & 2 \\ 1 & 2 & 1 & 1 \end{bmatrix}$$

Figure 11.Connectivity and pedigree matrices for the example event tree shown in Figure 9.

Beginning with the terminal branch labels in the right column of the connectivity matrix, the next column immediately to the left is filled with the branch labels for the branches that are linked to each terminal branch in Figure 10. This process continues until all columns in the connectivity matrix are populated.

The connectivity matrix is combined with the branch index numbers to produce the pedigree matrix. The number of columns in the pedigree matrix corresponds to the number of branch levels in the event tree and the number of rows corresponds to the number of terminal nodes or branches in the complete event tree with all continuous branches and all collapsed nodes fully expanded. Using this convention, the pedigree matrix for the event tree shown in Figure 9 can be generated as shown in Figure 11(b) for the example of i = 3. The pedigrees shown in each row of Figure 11(b), starting on the right side and moving to the left, can be related to the original event tree diagram in Figure 9 by noting that they are simply the branch index numbers for each pathway in the event tree that one's finger would trace from a terminal branch on the extreme right side of the event tree back to the first branch level on the extreme left side of the event tree.

Using the connectivity and pedigree matrices with the user-assigned branch variable codes, a branch code matrix is produced. The branch code matrix has the same dimensionality as the pedigree matrix but its entries are the branch variable codes, which are the user-assigned branch identifiers, instead of the branch index numbers, which are assigned internally by the program.

Step 2. Branch state value assignment and branch probability calculation

For each branch in the event tree, state and branch probability values are assigned or calculated based on the user-assigned input relationships. These state and branch probability matrices are populated with the state and branch probability values, respectively. These matrices follow the same form as the pedigree matrix described in the previous subsection for Step 1. The probability matrix is then used to calculate the total probabilities of failure for each different failure mode identified from the state value matrix and based on the event tree structure originally defined by the user. If non-mutually exclusive failure events are included in the event tree, then DAMRAE automatically applies a common-cause adjustment method developed by Bowles, Anderson, and Chauhan (2001) and also described by Hill et al. (2003). The adjustments are applied to the entries in the probability matrix before the total failure probabilities for each failure mode are calculated; but unadjusted probabilities are also saved for use in the preparation of sensitivity analysis outputs during post-processing.

Step 3. Branch and annualized consequences calculation

Consequence values for each consequences branch are calculated based on the user-specified input and calculation method. These calculated values are placed in the consequence matrices for economic losses and life loss. These matrices have the same number of rows as the pedigree and branch code matrices but separate columns for each different consequences center.

The consequences are calculated as incremental consequences (i.e. the difference between failure and no-failure consequences for flood-induced failure modes), although total consequences can be obtained by defining no-failure consequences as zero. Annualized (incremental) consequences are calculated for each row in the consequences matrix, corresponding to each terminal branch or unique event tree pathway. Total annualized (incremental) consequences for each failure mode are calculated by summing over each column for different consequences centers and exposure scenarios for life loss in the consequence matrices.

Step 4. Post-processing

This step is performed to generate the final output summary table containing estimates of the failure probabilities and associated annualized consequences. Using the failure modes defined in the event tree by the user, DAMRAE displays the list of failure modes by their user-defined names. The user can then select which failure modes to display in the summary table, including grouping some together to show subtotals and total in a flexible user-defined arrangement.

In addition, an F-N Chart can be developed from the probability and consequences matrices to evaluate the dam against the ANCOLD (2003) societal risk guidelines and the Reclamation (2003) Portrayal of Risks Chart can be developed to evaluate the dam against the Reclamation Public Protection Guidelines.

CHAPTER V

DAMRAE DEMONSTRATION

Introduction

The prototype version of DAMRAE was verified and demonstrated using risk analysis studies for four dams that have been completed using independently verified spreadsheet calculation. To demonstrate the generality of computational structure and associated calculation logic, the flood and earthquake event trees for these risk four dams were redrawn and requantified using DAMRAE. One of these four studies, a risk-based evaluation of operating restrictions to reduce the risk of earthquake-induced dam failure of Success Dam is presented here to demonstrate the features of the present version of DAMRAE.

Success Dam: A Dam Safety Risk Analysis Study

Bowles et al. (2004) performed the risk assessment of Success Dam for the Sacramento District of the U.S. Army Corps of Engineers. This study comprises the flood and earthquake induced dam failure risk analysis for the Main Dam and the Frazier Dike located on the Lake Success. Although, the main focus of this study was to examine the seismic performance of the dam, Flood (i.e. overtopping and wave erosion) and Flood-internal (i.e. piping and slope instability) failure modes were included so that tolerable risk guidelines could be fully implemented. For the demonstration of DAMRAE, both the earthquake and flood event trees were implemented in DAMRAE and results obtained were compared with those obtained from the original study. Along with describing the original event tree structures and their inputs, the following sections also present details of the event trees and inputs in the form used in DAMRAE.

Flood Event Tree

The original flood event tree for Success Dam is shown in Figure 12 and the DAMRAE version of shown in Figure 13. Figure 12 includes the initial loading, failure and exposure branches while the DAMRAE version also includes the economic and life-loss consequences and other state function branches as needed in DAMRAE.

Event tree structure

The first level of branching in the original flood event tree (Figure 12) represents the peak reservoir loading intervals as initiating branches. The second level of branches includes the no failure and other failure branches for the Main Dam and the Frazier Dike. The subsequent branch levels (shown as A and B) represent the seasonal and day/night exposure branches.

The DAMRAE version of the flood event tree comprises seven branch levels. The first branch level includes the peak reservoir elevation loading intervals as a continuous branch (PRE). In the second level, a state function branch (OTD) has been added to calculate the overtopping depth of the reservoir from the peak reservoir elevation and the dam crest elevation. Level 3 includes the no-failure and eight failure branches. Levels 4 and 5 represents the seasonal and day/night exposure scenarios, respectively, and the economic loss and life-loss consequences branches have been added as Levels 6 and 7, respectively.

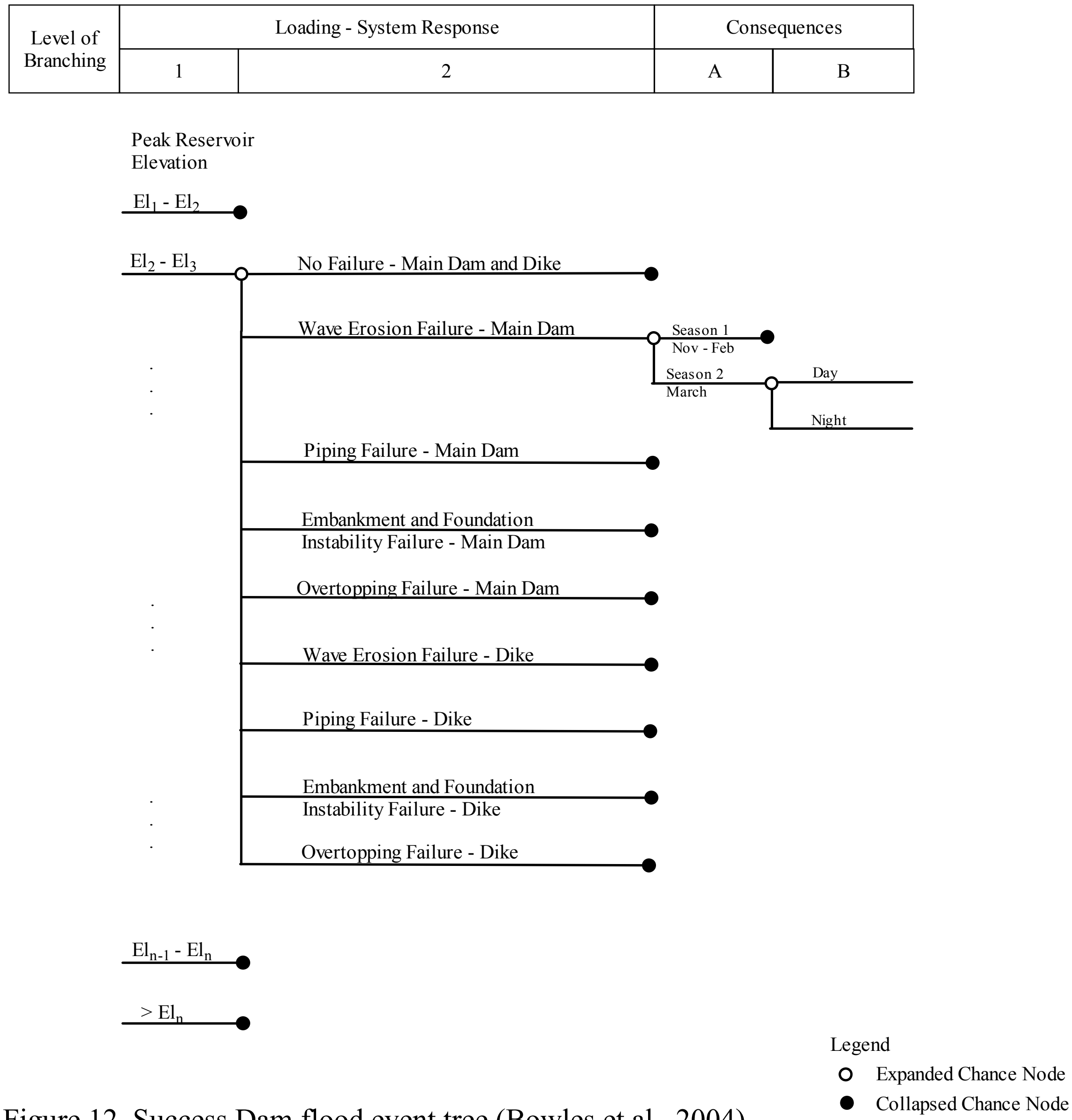


Figure 12. Success Dam flood event tree (Bowles et al., 2004).

In the DAMRAE event tree representation, the nodes of same color with the label ‘D’ or ‘H’ have a similar subsequent branch structure and inputs. The nodes labeled ‘D’ are donor nodes, which include a visible display of the next levels of branch structure. The nodes labeled ‘H’ are the host nodes and use the same subsequent branch structure

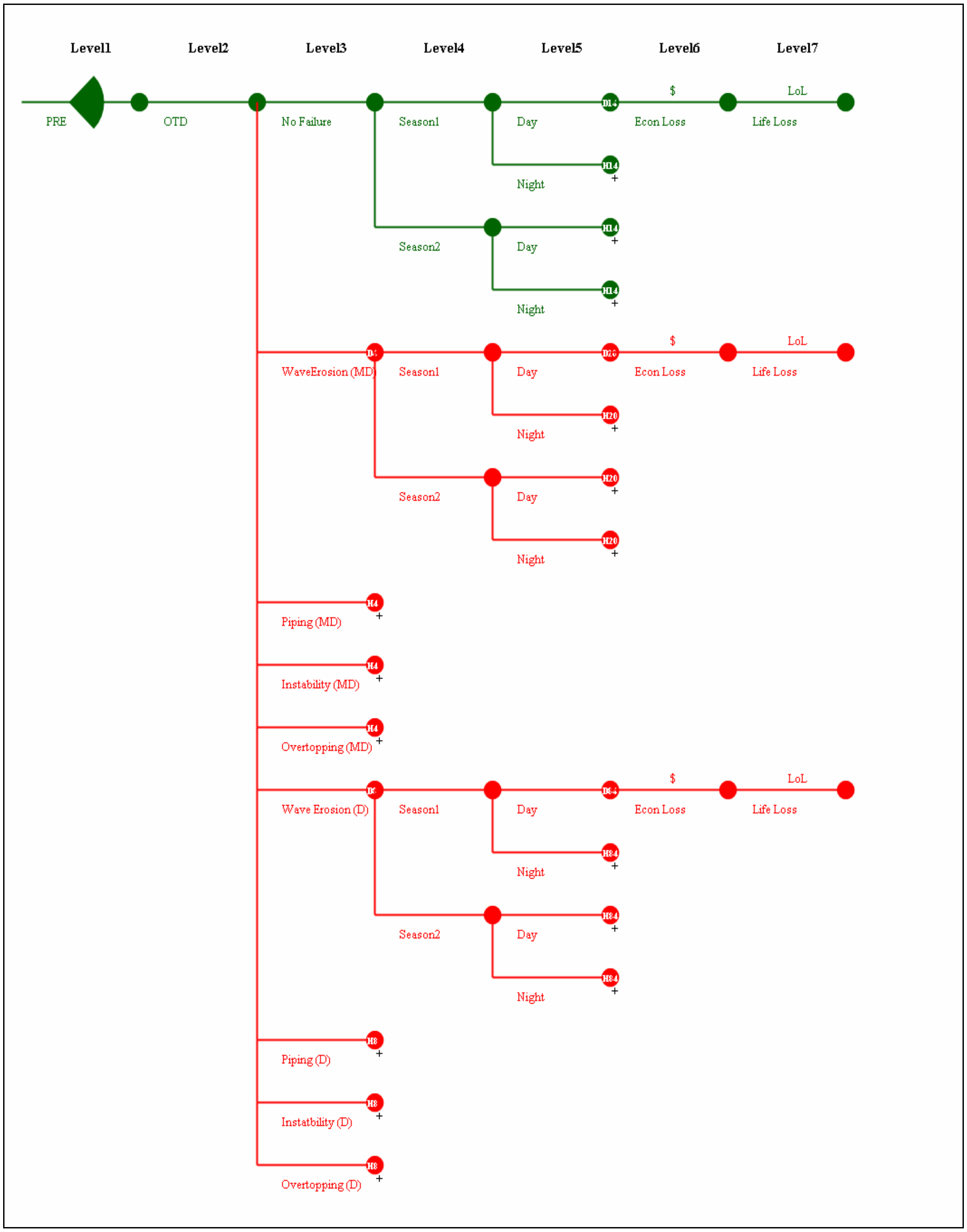


Figure 13. DAMRAE representation of the Success Dam flood event tree, displaying event tree branch levels at the top.

and inputs as the donor node with the same color and which is located above them in the same level of the event tree.

Event tree Inputs

The assignment of inputs to different branches of the event tree in DAMRAE is described below for each branch level. The basis for estimating the probability and consequences inputs is described in Bowles et al. (2004).

Level 1: The Level 1 continuous branch is assigned the branch variable code, ‘PRE’. The ‘probability’ input option is selected for this branch and the ‘tabular interpolation’ method for calculating state variables is selected. The input file for this branch is shown in Table 1. A one-way linear interpolation method using z-variates is used for estimating the peak stage for the 21 values of annual exceedance probabilities (AEP) values obtained in a range of 0.0309185 and 0.0000001.

Table 1. Flood loading input table: peak reservoir stage versus AEP

Peak Stage(ft MSL)	AEP(/yr)
652.50	0.0309185
658.33	0.0169082
663.00	0.0100000
667.75	0.0050000
672.50	0.0020000
675.25	0.0010000
689.40	0.0000100
691.50	0.0000044
700.66	0.0000001

Level 2: this branch level is a state function branch with the assigned branch variable code, 'OTD'. The calculation method for estimating the overtopping depth is selected as the 'user-specified function'. For Success Dam the dam crest elevation is 691.5 ft, so that the overtopping depth is calculated using the function, 'PRE-691.5'.

Level 3: this branch level contains all eight flood-induced failure mode branches. The first branch in this failure branch group is the no-failure branch and the remaining branches represent the different failure modes. There is no input assignment for the no-failure branch since the no-failure probability is calculated by the program as (1- sum of failure probabilities). The inputs for the failure branches are as follows:

1. WaveErosion (MD): this failure branch represents the wave erosion failure mode for the Main Dam. The system response probability for this branch is calculated from Table 2 using a one-way linear interpolation method based on PRE.

2. Piping (MD): this failure branch represents the piping failure mode for the Main Dam. The one-way linear interpolation method is used to calculate the SRP for this failure branch from PRE using Table 3.

Table 2. Wave erosion SRP for the Main Dam

PRE	Main Dam Wave Erosion SRP
686.5	0
691.5	0.01
691.6	0.01

Table 3. Piping SRP for the Main Dam

PRE	Main Dam Piping SRP
652.50	0
662.25	3.0195E-07
680.75	2.6775E-06
691.50	4.0873E-06
700.50	4.0873E-06

3. Instability (MD): this branch represents the slope instability failure mode for the Main Dam. To estimate the SRP for this branch, an internal failure mode calculation function, ‘InternalFM’ is used. This internal failure mode calculation function is defined as follows:

$$InternalFM(k1, k2, k3, DCE, PRE)$$

The k1, k2 and k3 constants in this function are 0.302007, 1 and 0, respectively. The dam crest elevation (DCE) is 691.5 ft and peak reservoir elevation (PRE) value is branch variable ‘PRE’, which is assigned in the Level 1 branches.

4. Overtopping (MD): this branch represents the overtopping failure mode of the Main Dam. The one-way linear interpolation method is applied to Table 4 for the overtopping depth versus failure probability table to estimate the overtopping failure system response probability.

5. WaveErosion (D): similar to wave erosion failure mode branch for the Main Dam, the Frazier Dike wave erosion failure branch uses the one-way linear interpolation method in the PRE versus SRP relationship shown in Table 5.

Table 4. Overtopping SRP for the Main Dam

OTD	Main Dam Overtopping SRP
0	0
1	0.25
2	1.00
10	1.00

Table 5. Wave erosion SRP for the Frazier Dike

PRE	Frazier Dike Wave Erosion SRP
679.5	0
691.5	0.1
691.6	0.1

Table 6. Piping SRP for the Frazier Dike

PRE	Frazier Dike Piping SRP
660	0
662.25	0.000030195
680.75	0.00026775
691.5	0.000408729
700.5	0.000408729

6. Piping (D): the piping failure mode branch for the Frazier Dike uses the one-way linear interpolation method in the piping SRP relationship shown in Table 6.

7. Instability (D): similar to the Main Dam instability failure mode function, this failure branch uses the following internal failure mode function:

$$InternalFM(0.302007, 1, 0, 691.5, PRE)$$

8. Overtopping (D): the overtopping failure mode branch for the Frazier Dike uses the one-way linear interpolation method in the overtopping SRP relationship in Table 7.

At this level, to account for the non-mutually exclusive failure modes, an option to perform the common-cause adjustment (CCA) to all eight flood-induced failure modes was selected.

Level 4: this branch level shows the seasonal exposure branches. The fixed exposure factors values assigned to the 'Season1' and 'Season2' exposure branches are 0.33 and 0.67, respectively.

Level 5: this branch level contains the day and night exposure branches. The day and night exposure branches connected with 'Season1' in previous branch level are assigned fixed exposure factor values of 0.46 and 0.54, respectively, and those connected with 'Season2' are assigned as 0.67 and 0.33, respectively.

Levels 6 and 7 branches are consequence branches. These branches represent economic and life-loss consequences for three consequence centers, which are assigned the following names: Success, Tulare, and King County.

Table 7. Overtopping SRP for the Frazier Dike

OTD	Frazier Dike Overtopping Failure SRP
0	0
0.5	0.25
1	1.00
10	1.00

Level 6: Level 6 branches are the economic consequence branches. All the branches in this level have fixed user-specified values as input. Table 8 shows the no-failure and the Main Dam failure economic consequence values for the three centers. Economic consequence values for the Frazier Dike failure are assigned as 0 for all three centers.

Level 7: This branch level is the life-loss consequence branches. These consequence branches also have user-specified fixed values, which are shown in Table 9 for the Main Dam. The Frazier Dike failure life-loss branches are assigned as 0 life loss.

Risk analysis output

The DAMRAE calculation for the above mentioned inputs produces six data matrices (Pedigree, Branch Code, Probability, State Value, Economic Consequence, and Life Loss Consequence) as output. It also estimates the final failure probability values for all the failure modes and associated consequences values as shown in Table 10. Table 10 also shows the results of event tree simulation performed by Bowles et al. (2004).

Table 8. Economic consequence values for the Main Dam

	Success	Tulare	KingCounty
No Failure	0	529	0.9
Failure	0	1051	3.2

Table 9. Life-loss consequence values for the Main Dam

	Success	Tulare	King County
No Failure	1.00E-12	12.03	0.78
Failure	1.00E-12	25.95	1.56

Table 10. Flood event tree failure probabilities and annualized economic and life-loss

	Probability of Failure		Incremental Risk Cost		Annualized Incremental Life Loss	
	DAMRAE (/yr)	Bowles et al.2004 (/yr)	DAMRAE ($/yr)	Bowles et al.2004 ($/yr)	DAMRAE (lives/yr)	Bowles et al.2004 (lives/yr)
WaveErosion (MD)	1.06E-07	1.05E-07	55.5	55	1.56E-06	1.55E-06
Piping (MD)	1.42E-08	1.42E-08	7.45	7	2.09E-07	2.09E-07
Instability (MD)	1.45E-05	1.40E-05	7614.17	7352	2.13E-04	2.06E-04
Overtopping (MD)	1.42E-06	1.00E-06	743	529	2.08E-05	1.48E-05
WaveErosion (D)	6.99E-06	6.75E-06				
Piping (D)	1.22E-06	1.21E-06				
Instability (D)	1.45E-05	1.40E-05				
Overtopping (D)	1.82E-06	2.30E-06				

Earthquake Event Tree

Figure 14 shows the event tree structure used by Bowles et al. (2004) in the seismic risk analysis of Success Dam. This event structure is composed of six branching levels where third level has been subdivided as 3a and 3b. Exposure and consequences branches are not displayed in the Figure. The DAMRAE version of this event tree structure is shown in Figure 15. This Figure includes the required state function branches and also the exposure and consequence branches.

Event tree structure

The earthquake event tree model developed by Bowles et al. (2004) begins with two initiating branches. These branches represent the earthquake magnitudes of 5.75 and 8.0. In the DAMRAE implementation, these two earthquake magnitudes are shown separately in two different event tree drawings. Figures 14 and 15 show the event tree structure beginning with the M 5.75 earthquake as an initiating branch. To analyze the M 8.0 earthquake, a separate drawing with the same event tree structure but with different inputs was used. Although, multiple initiating branches can be handled in DAMRAE, to ease the process of drawing and also to verify the results separately for M 5.75 and M 8.0, two event trees are developed and analyzed separately.

The DAMRAE version of the earthquake event tree comprises fourteen branch levels. The first level is an initiating branch for earthquake magnitude, which is displayed with ‘M 5.75” as the branch variable code in Figure 15. The second and third level branches are continuous branches for peak ground acceleration (PGA) and pool elevation (PE), respectively. Levels 4, 5 and 6 are state function branches for estimating the dam failure peak discharge rate (Q), and the vertical deformation (VD) and horizontal deformation (HD) of the dam, respectively. Level 7 is an overtopping failure mode

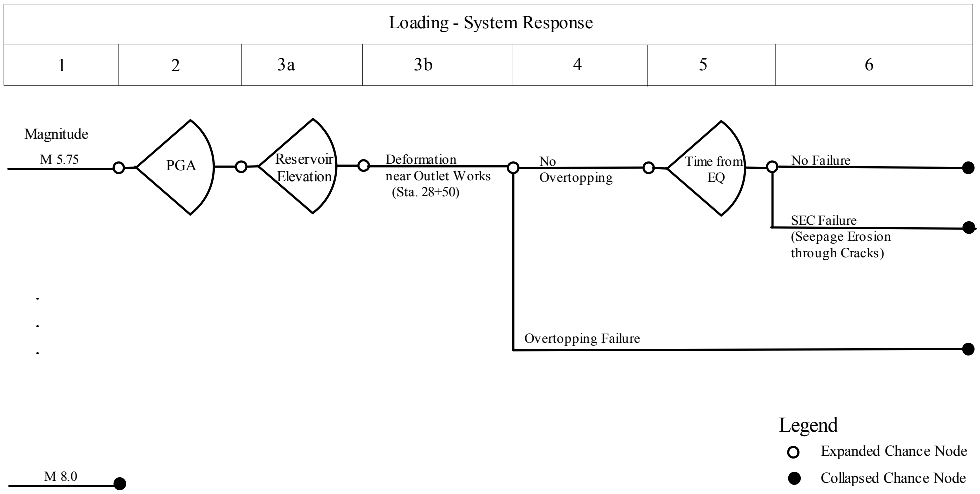


Figure 14. Success Dam earthquake event tree (Bowles et al., 2004).

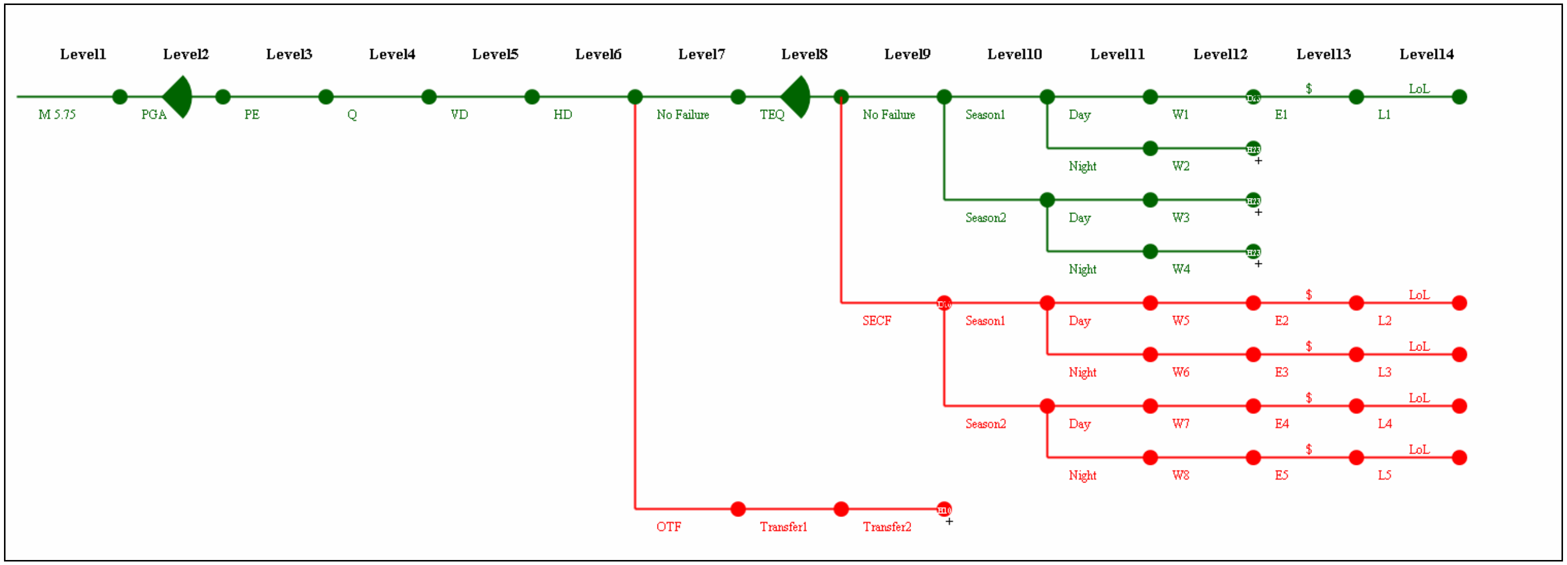


Figure 15. DAMRAE version of the Success Dam earthquake event tree (M 5.75), including exposure and consequences branches.

branch group with no-failure as the first branch and the overtopping failure mode (OTF) as the second branch. Level 8 contains a continuous branch, which is connected to the no-failure branch in Level 7, for the time from the occurrence of the earthquake until dam failure (TEQ). The lowest branch in Level 9 (marked as 'Transfer1'), which is connected to the failure branch in Level 7, is a dummy discrete branch. It has no contribution in the failure probabilities and is used to make the event tree structure even at each level. Level 9 includes the seepage erosion through cracks failure (SECF) branch group and the lowest branch in this level (marked as 'Transfer2') is again a dummy discrete branch. Seasons and day/night exposure scenarios are included in the Levels 10 and 11, respectively. All the branches in Level 12 are state function branches. These branches (marked as W_i, where i = 1, 2, 3…) represent the warning time, which is a function of TEQ. Levels 13 and 14 represent the economic and life-loss consequence branches, respectively. As mentioned above, nodes with same color and labeled 'D' or 'H' carry the same following branch structure and associated inputs.

Event tree inputs

Inputs assigned to different branches in each event tree branch level are described in the following subsections.

Level 1: Level 1 is a discrete branch with branch variable code 'M 5.75' and a fixed user-specified probability value of 1.0. In case of M 8.0 earthquake, a branch variable name 'M 8.0' is assigned to this branch and the assigned probability value is the same as 1.0.

Level 2: Level 2 is a continuous branch with the branch variable code ‘PGA’. The user-specified input for this branch is selected as ‘State Value’ and ‘Tabular Interpolation’ method for calculating probabilities was chosen. The one-way log-log interpolation method is used to estimate the annual exceedance probability for 20 earthquake loading intervals. Tables 11 (a) and (b) show the PGA - annual exceedance probability input tables for M 5.75 and M 8.0, respectively. For M 5.75 and M 8.0, the modified 21 PGA values used to divide the assigned range into 20 intervals, are shown in Tables 12 respectively.

Level 3: Level 3 is the pool elevation (PE) continuous branch. With user-specified input as ‘State Value’, the one-way linear interpolation method is used for the relationship in Table 13 to calculate the probabilities for each of 32 pool elevation intervals. The pool elevation values assigned to divide the pool elevation range in 32 intervals are shown in Table 14.

Table 11. Earthquake loading: PGA - annual exceedance probability relationships

PGA	AEP
0.0250	0.218522
0.0500	0.0369878
0.1000	0.0060653
0.1500	0.0020033
0.2000	0.0008701
0.2500	0.0004299
0.3000	0.0002301
0.4000	0.0000787
0.5000	0.000032
0.6000	0.0000148
0.6500	0.0000098

(a) M 5.75

PGA	AEP
0.0250	0.08426
0.0500	0.01627
0.1000	0.00131
0.1500	0.00018
0.2000	0.00002

(b) M 8.0

Table 12. PGA values for specifying the earthquake loading intervals

M 5.75	PGA	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
	PGA	0.21	0.22	0.23	0.3	0.37	0.44	0.51	0.58	0.65	0.65	
M 8.0	PGA	0.04	0.045	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.085	0.9
	PGA	0.1	0.1	0.105	0.11	0.128	0.15	0.16	0.18	0.2	0.2	

Table 13. Stage-duration relationship

Stage	Percent	Stage	Percent
576.39	1	629.59	0.25
579.12	0.997	635.03	0.19
580.1	0.99	636.48	0.18
581.9	0.98	638.73	0.16
583.45	0.97	639.63	0.15
586.83	0.94	641.42	0.13
588.15	0.92	643.65	0.1
589.03	0.9	644.86	0.09
593.08	0.82	648.82	0.06
594.88	0.77	651.55	0.0375
601.25	0.6	652.41	0.0175
608	0.51	656.12	0.003472
610.05	0.48	656.4	0.002003
613.49	0.43	656.51	0.000467
623.95	0.32	658.33	6.68E-05

Table 14. Pool elevation interval values

PE	589	591	593	595	597	599	601	603	605
	607	609	611	613	615	617	619	621	623
	625	627	629	631	633	635	637	639	641
	643	645	647	649	651	654			

Table 15. Pool elevation vs. discharge relationship

PE	Q
590	60466
630	362481
634	425264
652.5	684805

Level 4: this branch level includes a state function branch to estimate the dam failure peak discharge rate (Q) from the reservoir. The calculation method for this branch is selected as 'Tabular Interpolation' with one-way linear interpolation used to calculate the estimated dam failure peak discharge rate values from the Table 15.

Level 5: this branch level is used to obtain estimates the vertical crest settlement using a state function branch 'VD'. Bowles et al. (2004) provided a parametric vertical crest settlement (Figures 16 and 18) for calculating the vertical deformation state values for given pool elevations, earthquake magnitude and PGA. In DAMRAE, these relationships and the plots in Figures 17 and 19 are included in tabular formats as shown in Table 16 and 17.

Tables 16 and 17 are used as the 'VD' state function branch input tables for the earthquake event trees for M 5.75 and M 8.0, respectively. The interpolation method selected for these tables is two-way linear interpolation and the two variables assigned for the interpolation are 'PGA' (denoted as X) and 'PE' (denoted as 'Y). 'LInterP' is a linear interpolation routine, which is built into DAMRAE to take an independent variable (shown as 'Y') and interpolation table (shown as 'VST') as functional arguments.

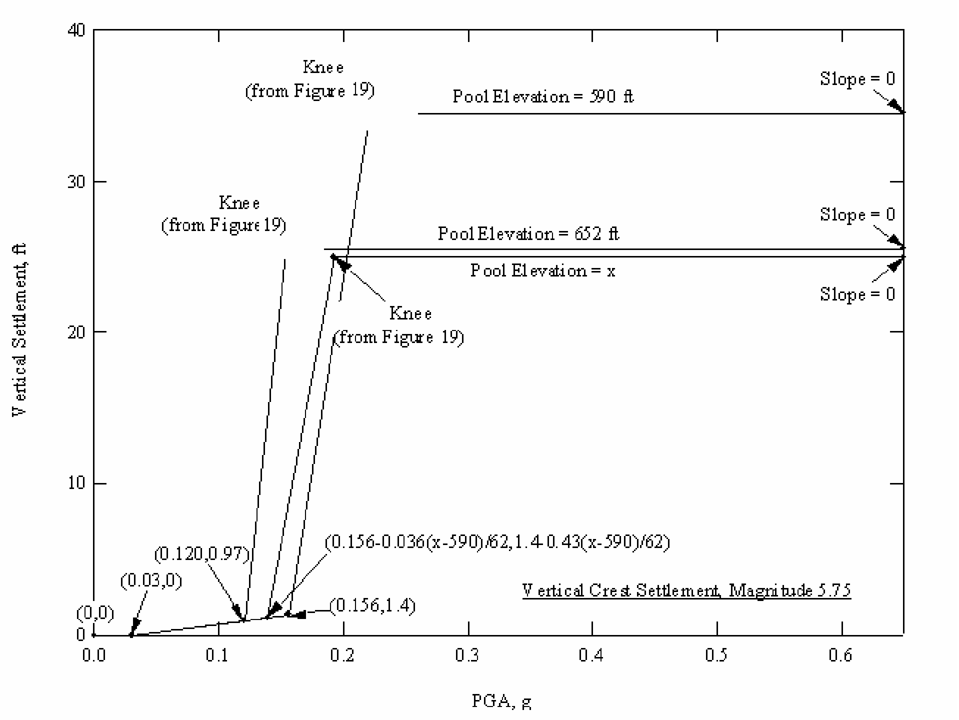
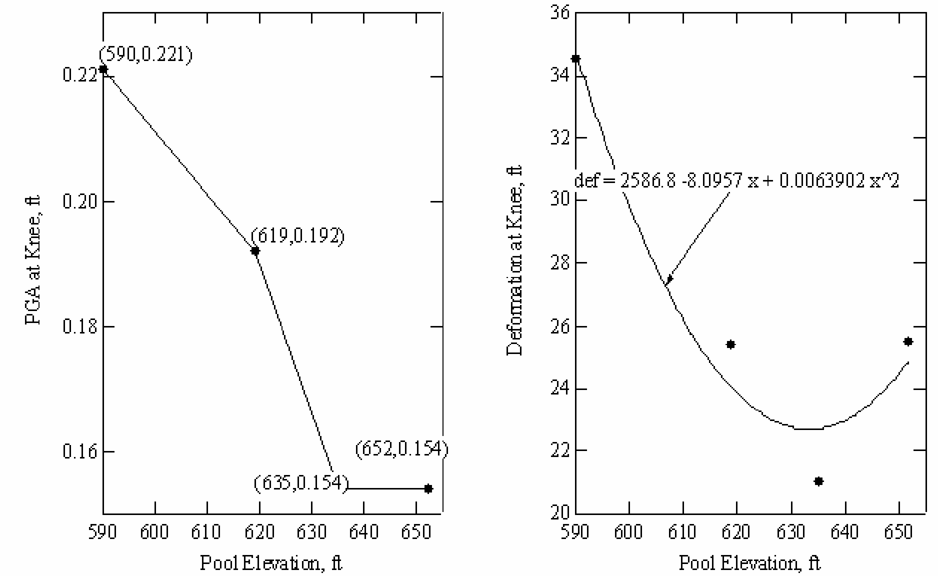


Figure 16. Vertical crest settlement at M 5.75 as a function of pool elevation and PGA.



(a) PGA at knee

(b) Deformation at knee

Figure 17. Estimated position of knee in Figure 16.

Table 16. Tabular interpolation approach for estimating vertical deformation for M 5.75

PGA	VD
0	0
0.03	0
(0.156-0.036*(Y-590)/62)	(1.4-0.43*(Y-590)/62)
LInterP(Y,VST)	(2586.8-8.0957*Y+0.0063902*Y*Y)
0.65	(2586.8-8.0957*Y+0.0063902*Y*Y)

a. PGA vs. VD table for M 5.75 transformed from the Figure 16

PGA	PE
590	0.221
619	0.192
635	0.154
652.5	0.154

b. VST table used in (a)

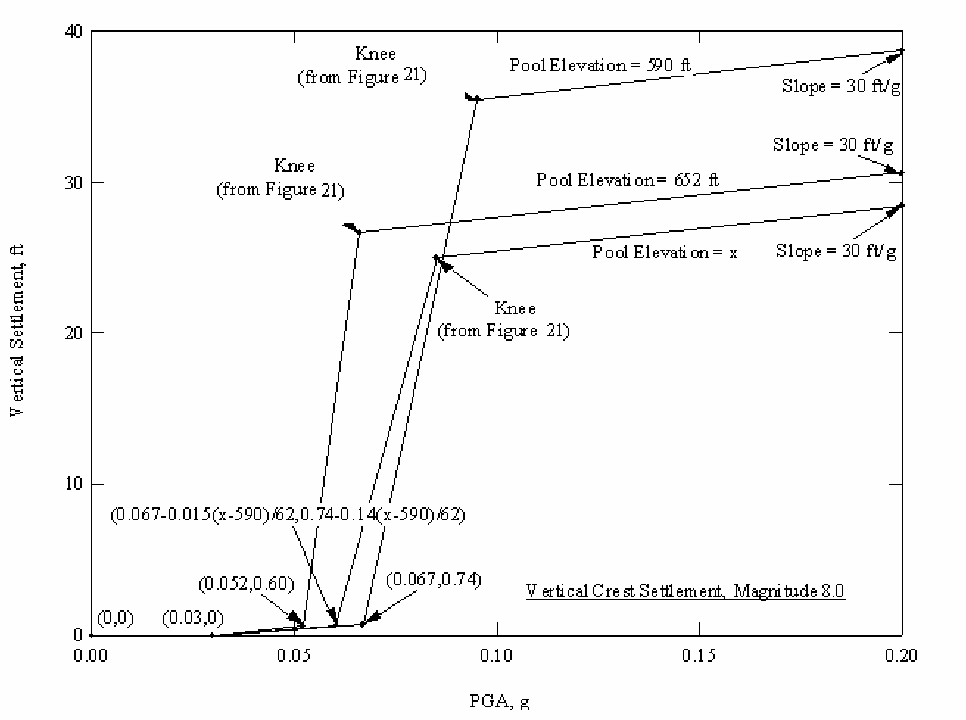
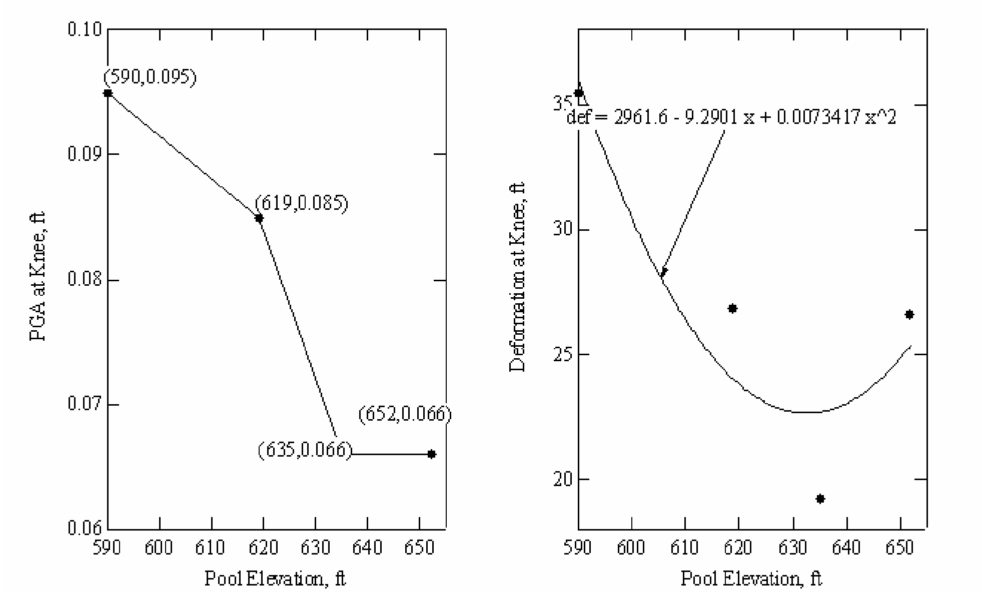


Figure 18. Vertical crest settlement at M 8.0 as a function of pool elevation and PGA.



(a) PGA at knee (b) Deformation at knee

Figure 19. Estimated position of knee in Figure 18.

Table 17.Tabular interpolation approach for estimating vertical deformation for M 8.0

PGA	VD
0	0
0.03	0
(0.067-0.015*(Y-590)/62)	(0.74-0.14*(Y-590)/62)
LInterP(Y,VST)	(2961.6-9.2901*Y+0.0073417*Y*Y)
0.2	(2961.6-9.2901*Y+0.0073417*Y*Y)+((0.20-LInterP(Y,VST))*30)

a. PGA vs. VD table for M 8.0 transformed from the Figure 18

PGA	PE
590	0.095
619	0.085
635	0.066
652.5	0.066

b. VST table used in (a)

Level 6: this branch level is similar to Level 5, but is to estimate the horizontal deformation values (HD) instead of the vertical deformation (VD) values. Tables 18 and 19 are used for M 5.75 and M 8.0 earthquakes, respectively. These tables are transformed from Figures 20 and 22, respectively.

Level 7: Level 7 includes the no-failure and overtopping failure (OTF) branches. For estimating the overtopping failure probabilities user specified function is assigned as

$$Trig(691.5, VD, PE)$$

'Trig' is a program inbuilt function that uses the crest elevation, vertical deformation and pool elevation values to calculate the overtopping system response probability (Bowles et al., 2004).

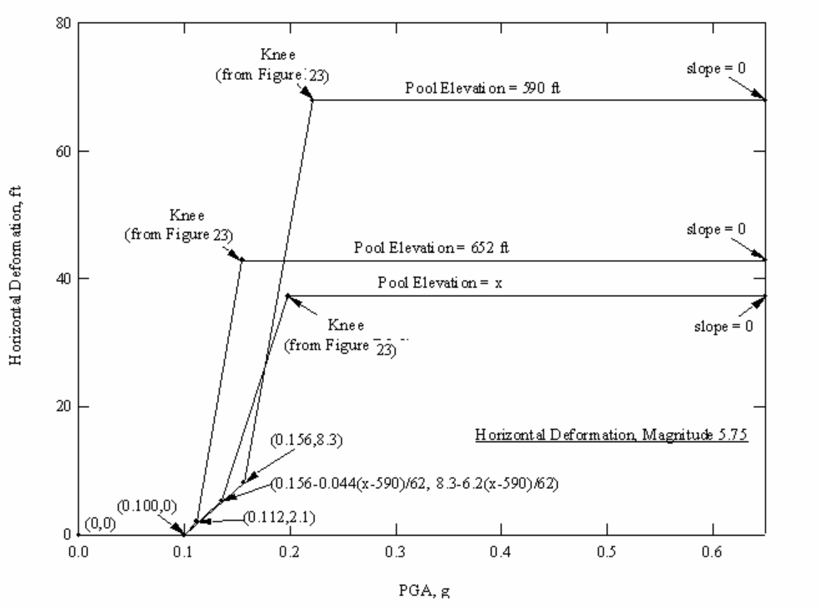
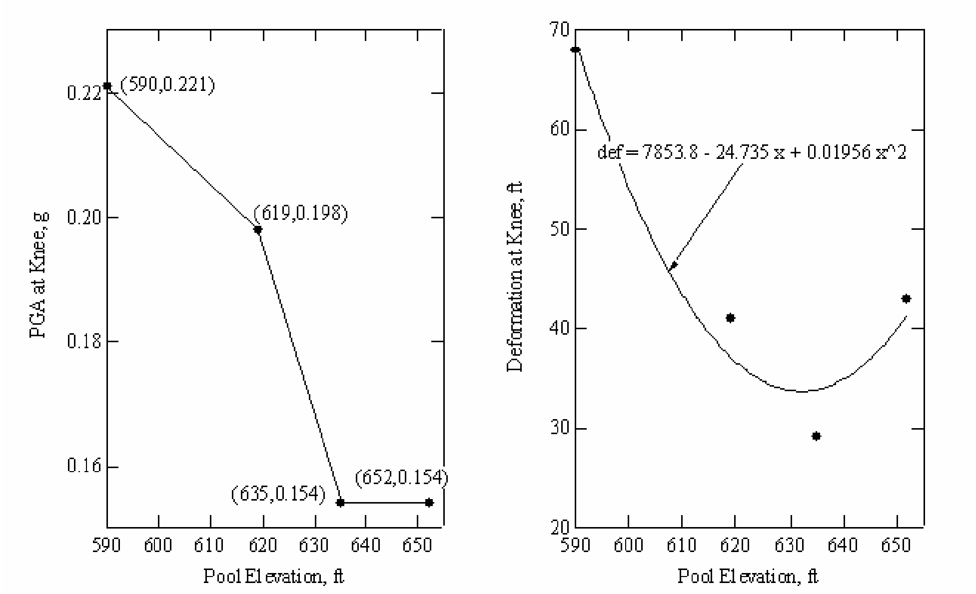


Figure 20. Horizontal deformation at M 5.75 as a function of pool elevation and PGA.



(a) PGA at knee (b) Deformation at knee

Figure 21.Estimated position of knee in Figure 20.

Table 18.Tabular interpolation approach for estimating horizontal deformation at M 5.75

PGA	HD
0	0
0.1	0
0.156-0.044*(Y-590)/62	8.3-6.2*(Y-590)/62
LInterP(Y,HST)	7853.8-24.735*Y+0.01956*Y*Y
0.65	7853.8-24.735*Y+0.01956*Y*Y

a. PGA vs. HD table for M 5.75 transformed from the Figure 20

PGA	PE
590	0.221
619	0.198
635	0.154
652.5	0.154

b. HST table used in (a)

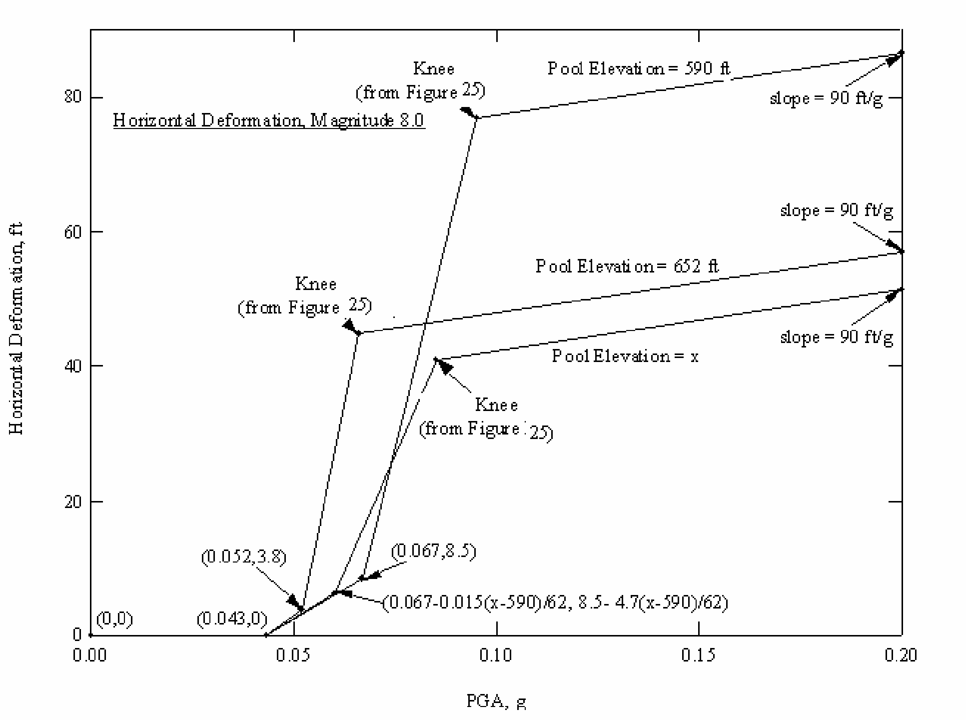
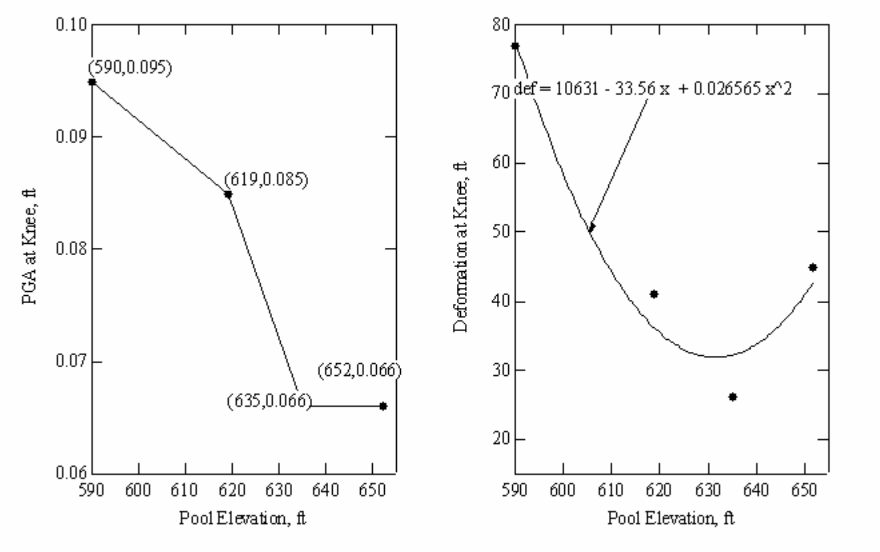


Figure 22. Horizontal deformation at M 8.0 as a function of pool elevation and PGA.



(a) PGA at knee (b) Deformation at knee

Figure 23. Estimated position of knee in Figure 22.

Table 19.Tabular interpolation approach for estimating horizontal deformation at M 8.0

PGA	HD
0	0
0.043	0
(0.067-0.015*(Y-590)/62)	8.5-4.7*(Y-590)/62
LInterP(Y,HST)	10631-33.56*Y+0.026565*Y*Y
0.2	(10631-33.56*Y+0.026565*Y*Y)+((0.20-LInterP(Y,HST))*90)

a. PGA vs. HD table for M 8.0 transformed from the Figure 22

PGA	PE
590	0.095
619	0.085
635	0.066
652.5	0.066

b. HST table used in (a)

<u>Level 8:</u> user specified input for the continuous branch 'TEQ' in Level 8 is selected as state value and two-way linear interpolation method is used to estimate the probability values for 20 equally spaced intervals of time to failure ranging from 30 hr to 315 hr. Table 20 is used as input for this branch and 'TEQ' state values and 'PE' values are assigned as independent variables for the interpolation.

The other branch in this level (labeled as 'Transfer1') is a discrete branch with user assigned probability value of 1.

<u>Level 9:</u> failure branch group connected with the 'TEQ' continuous branch represents the no-failure and seepage erosion through cracks failure mode. For estimating the 'SECF' branch probabilities, two-way linear interpolation method is used with 'HD'

and 'PE' as assigned independent variables. The input table for this branch is shown in Table 21.

Table 20. Two-dimensional relationship of time to failure after earthquake and pool elevation for estimating SRP

Time to Failure (hr)	590	630	652.5
30	0	0	0
315	0	0	0.43
360	0	0.02	0.5
600	0	0.13	0.55
900	0	0.26	0.61
1440	0	0.5	0.71
2880	0.33	0.67	1
3600	0.5	0.75	1

Table 21. Two-dimensional relationship of horizontal deformation and pool elevation for estimating the SECF probabilities

HD	590	592	614	638	662
0	0	0	0	0	0
2	0	0	0	0	0
10	0	0	0	0.23	0.44
20	0	0	0.15	0.51	1
24	0	0	0.21	0.63	1
30	0	0.02	0.3	0.8	1
40	0	0.04	0.45	0.83	1
50	0	0.07	0.6	0.86	1
100	0	0.20	0.82	1	1
140	0	0.3	1	1	1

The other branch in this branch level (labeled as ‘Transfer2’) is again a discrete branch with user assigned probability value of 1.

Level 10: this branch level shows the season exposure branches. The fixed probability value assigned to ‘Season1’ exposure branch is 0.33 and ‘Season2’ exposure branch is 0.67.

Level 11: this branch level shows the day and night exposure branches. The day and night exposure branches connected with ‘Season1’ in previous branch level are assigned fixed probability values of 0.46 and 0.54 respectively and those connected with ‘Season2’ are assigned as 0.67 and 0.33, respectively.

Level 12: all the branches in this level represent the warning time state function branch. Input function for calculating the warning time linked with the day exposure branch is assigned as $TEQ-60$ and for branches linked with the night exposure it is assigned as $TEQ-90$.

Levels 13 and 14 branches are consequences branches. These branches represent economic and life-loss consequences for three consequence centers, which are assigned the following names: Success, Tulare, and King County.

Level 13: this branch level contains the economic consequence branches. Inputs for no-failure consequence branches are assigned fixed user-specified values of 0. For other branches, the interpolation input tables contained in Table 22 are used for various exposure seasons and consequences centers. One-way linear interpolation is used with dam failure peak discharge rate (‘Q’) as the independent variable.

Table 22. Economic consequences input table

Q	Economic Losses
60466	0
362481	0
684805	0

(a) Success Center for Season1

Q	Economic Losses
60466	0
362481	0
684805	0

(b) Success Center for Season2

Q	Economic Losses
60466	0
362481	0
684805	0

(c) Tulare Center for Season1

Q	Economic Losses
60466	0
362481	0
684805	0

(d) Tulare Center for Season2

Q	Economic Losses
60466	0
362481	0
684805	0

(e) King County Center for Season1

Q	Economic Losses
60466	0
362481	0
684805	0

(f) King County Center for Season2

Level 14: this branch level represents the life-loss consequence branches. Branches linked with no-failure branches have 0 life loss. For other branches, the appropriate life-loss input table is entered based on the seasonal and day/night exposures. Input interpolation tables for different centers are given in Tables 23 to 26. The main interpolation input table uses the two-way linear interpolation method with ‘Q’ and ‘W_i’ (where i = 1, 2, 3…) as the independent variables to calculate the life-loss values. The input table includes a function ‘TWLinear’, which is a two-way linear interpolation routine that is built into DAMRAE. The ‘TWLinear’ function uses ‘Q’ values (denoted as ‘X’) and warning time ‘W_i’ (denoted as ‘Y’) and an interpolation table as functional arguments.

Table 23. Success consequence center life-loss input tables

Q	LL
60466	TWLinear(X,Y,SSDT)
362481	TWLinear(X,Y,SSDT)
425264	TWLinear(X,Y,SSDT)
684805	TWLinear(X,Y,SSDT)

a. Success consequence center life-loss input.

Q WT	60466	362481	425264	684805
-30	1.00E-12	1.00E-12	1.00E-12	0.0028
-15	1.00E-12	1.00E-12	1.00E-12	1.00E-12
0	1.00E-12	1.00E-12	1.00E-12	1.00E-12
15	1.00E-12	1.00E-12	1.00E-12	1.00E-12
30	1.00E-12	1.00E-12	1.00E-12	1.00E-12
45	1.00E-12	1.00E-12	1.00E-12	1.00E-12
60	1.00E-12	1.00E-12	1.00E-12	1.00E-12
75	1.00E-12	1.00E-12	1.00E-12	1.00E-12
90	1.00E-12	1.00E-12	1.00E-12	1.00E-12
105	1.00E-12	1.00E-12	1.00E-12	1.00E-12
120	1.00E-12	1.00E-12	1.00E-12	1.00E-12
135	1.00E-12	1.00E-12	1.00E-12	1.00E-12
150	1.00E-12	1.00E-12	1.00E-12	1.00E-12
165	1.00E-12	1.00E-12	1.00E-12	1.00E-12
180	1.00E-12	1.00E-12	1.00E-12	1.00E-12
195	1.00E-12	1.00E-12	1.00E-12	1.00E-12
210	1.00E-12	1.00E-12	1.00E-12	1.00E-12
225	1.00E-12	1.00E-12	1.00E-12	1.00E-12
240	1.00E-12	1.00E-12	1.00E-12	1.00E-12

b. SSDT interpolation table used in Table (a)

Table 24. Tulare center life-loss input tables

Q	LL
60466	TWLinear(X,Y,TSD1T)
362481	TWLinear(X,Y,TSD1T)
425264	TWLinear(X,Y,TSD1T)
684805	TWLinear(X,Y,TSD1T)

a. Day

Q	LL
60466	TWLinear(X,Y,TSD2T)
362481	TWLinear(X,Y,TSD2T)
425264	TWLinear(X,Y,TSD2T)
684805	TWLinear(X,Y,TSD2T)

b. Night

Table 25. Tulare center life-loss supplement input tables

Q WT	60466	362481	425264	684805
-30	9.43	9.72	9.78	325.94
-15	9.43	9.72	9.78	309.92
0	9.43	9.72	9.78	293.91
15	9.43	9.72	9.78	277.89
30	9.43	9.72	9.78	261.87
45	9.43	9.72	9.78	245.85
60	9.43	9.72	9.78	229.84
75	9.43	9.72	9.78	213.82
90	9.43	9.72	9.78	197.8
105	9.43	9.72	9.78	179.78
120	9.43	9.72	9.78	161.76
135	9.43	9.72	9.78	143.74
150	9.43	9.72	9.78	125.72
165	9.43	9.72	9.78	107.7
180	9.43	9.72	9.78	89.68
195	9.43	9.72	9.78	71.66
210	9.43	9.72	9.78	17.6
225	9.43	9.72	9.78	17.6
240	9.43	9.72	9.78	17.6

a. TSD1T interpolation table used in Table 24(a)

Q WT	60466	362481	425264	684805
-30	9.43	9.72	9.78	614.67
-15	9.43	9.72	9.78	563.73
0	9.43	9.72	9.78	512.79
15	9.43	9.72	9.78	461.84
30	9.43	9.72	9.78	410.9
45	9.43	9.72	9.78	359.96
60	9.43	9.72	9.78	309.02
75	9.43	9.72	9.78	258.07
90	9.43	9.72	9.78	207.13
105	9.43	9.72	9.78	188.18
120	9.43	9.72	9.78	169.22
135	9.43	9.72	9.78	150.27
150	9.43	9.72	9.78	131.32
165	9.43	9.72	9.78	112.37
180	9.43	9.72	9.78	93.41
195	9.43	9.72	9.78	74.46
210	9.43	9.72	9.78	55.51
225	9.43	9.72	9.78	36.55
240	9.43	9.72	9.78	17.6

b. TSD2T interpolation table used in Table 24 (b)

Table 26. King county center life-loss input tables

Q	LL
60466	TWLinear(X,Y,KSDT)
362481	TWLinear(X,Y,KSDT)
425264	TWLinear(X,Y,KSDT)
684805	TWLinear(X,Y,KSDT)

a. King county life-loss input tables

Q WT	60466	362481	425264	684805
-30	1E-12	0.18	0.22	1.31
-15	1E-12	0.18	0.22	1.31
0	1E-12	0.18	0.22	1.31
15	1E-12	0.18	0.22	1.31
30	1E-12	0.18	0.22	1.31
45	1E-12	0.18	0.22	1.31
60	1E-12	0.18	0.22	1.31
75	1E-12	0.18	0.22	1.31
90	1E-12	0.18	0.22	1.31
105	1E-12	0.18	0.22	1.3
120	1E-12	0.18	0.22	1.28
135	1E-12	0.18	0.22	1.27
150	1E-12	0.18	0.22	1.25
165	1E-12	0.18	0.22	1.24
180	1E-12	0.18	0.22	1.22
195	1E-12	0.18	0.22	1.21
210	1E-12	0.18	0.22	1.16
225	1E-12	0.18	0.22	1.16
240	1E-12	0.18	0.22	1.16

b. KSDT interpolation table used in table (a)

<u>Risk analysis output</u>

The final output failure probabilities and consequence values obtained in two separate runs for the M 5.75 and M 8.0 earthquake event tree models are summarized in Table 27 for the DAMRAE runs and from the original Bowles et al. (2004) study.

Table 27. Earthquake event tree failure probabilities and annualized economic and life-loss

		Probability of Failure		Incremental Risk Cost		Annualized Incremental Life Loss	
		DAMRAE (/yr)	Bowles et al. 2004 (/yr)	DAMRAE ($/yr)	Bowles et al. 2004 ($/yr)	DAMRAE (lives/yr)	Bowles et al. 2004 (lives/yr)
M 5.75	SECF	9.49E-04	8.29E-04	6020796	543457.84	2.55E-02	2.75E-02
	OTF	0	0	0	0	0	0
M 8.0	SECF	3.03E-03	2.67E-03	1958169.5	1760752	8.42E-02	9.12E-02
	OTF	7.40E-07	7.36E-07	543.1	545.89	3.12E-04	3.88E-04

Post-processing

The user can summarize the results by combining individual failure mode result for wave erosion and overtopping results to obtain the total flood failure probability and by combining results for piping and slope instability results to obtain the total flood-internal failure probability. Similarly, the failure probabilities obtained from the two earthquake magnitude event trees can be combined as a total earthquake failure probability over all earthquake-related failure modes. Post processing of all three event trees together produces the ANCOLD (2003) F-N plot and the USBR Portrayal of Risks plot as shown in Figures 24 and 25, respectively.

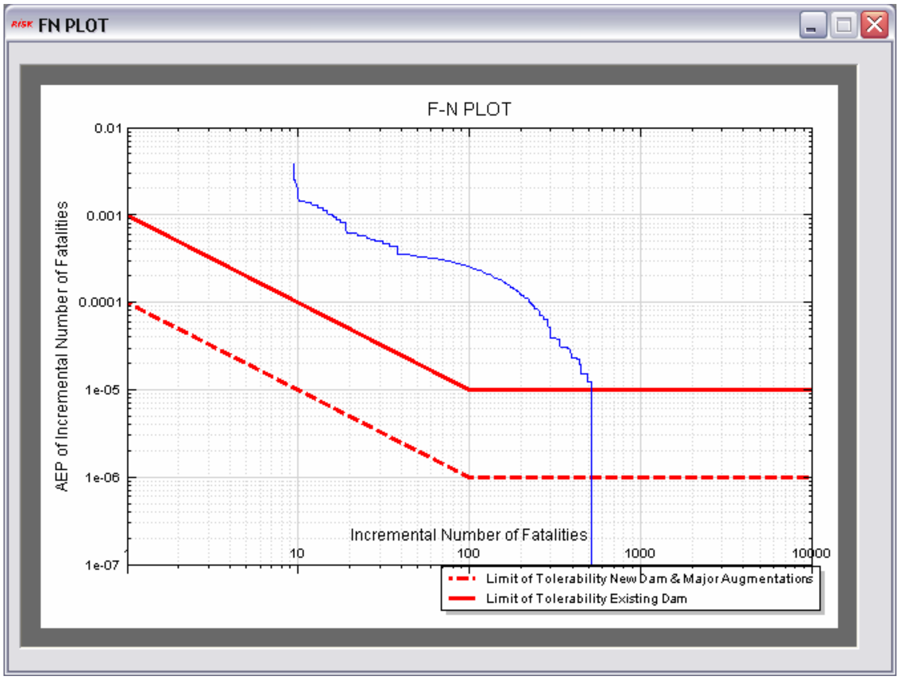


Figure 24. ANCOLD F-N plot for combined outputs from flood and earthquake event trees.

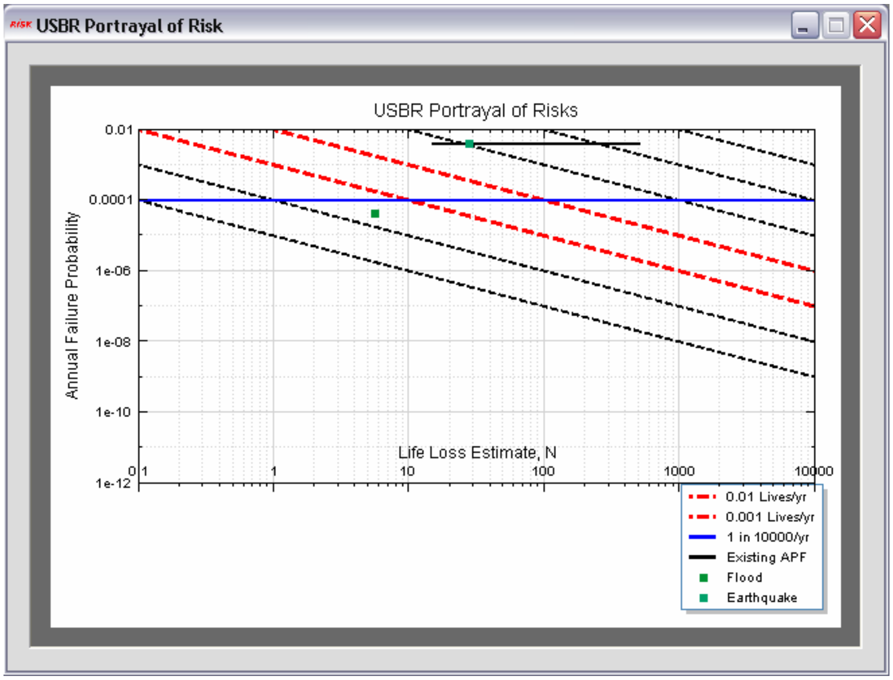


Figure 25. Flood and earthquake event tree output on the USBR Portrayal of risks plot.

Discussion

The implementation of the Success Dam flood and earthquake event trees in DAMRAE shows that the developed tool has flexible functionalities for drafting, quantifying and reporting a complex dam safety event tree analysis. The comparable results obtained from the event tree analyses verify the credibility of the employed computational logics. The slight difference in obtained results from the Bowles et al. (2004) study can be justified as follows:

1) In the Bowles et al. (2004) study, the event tree models were developed using the MS Excel and a VB macro. MS Excel has its own inbuilt function for estimating the z-variate while an approximate algorithm has been used in DAMRAE to calculate the z-variate. Since the flood event tree analysis uses the z-variate method for interpolation, the functional difference in performing the z-variate interpolation account for the differences in the values of flood failure probabilities obtained in DAMRAE.

2) In the Bowles et al. (2004) study, the number of intervals the for time after earthquake continuous branch are different for each different PGA loading while in the DAMRAE implementation same number of intervals are used for all PGA loading intervals. This difference appears to be the source of variation in seepage erosion through cracks probabilities obtained in earthquake event tree analysis performed using DAMRAE.

CHAPTER VI

SUMMARY, CONCLUSION, AND FUTURE WORK

Summary

Event tree analysis is a well-established method for risk analysis in the nuclear, chemical and aerospace industries. It has also become the most commonly-used tool for risk analysis in the field of dam safety. To facilitate event tree analysis, several software tools have been developed. However, all these tools are dedicated to some specific applications and unfortunately they are somewhat cumbersome to use for dam safety event tree analysis. Most commonly spreadsheet-based approach have been used for dam safety risk analyses and in some cases VB macros and other Excel add-ons have made these use more efficient. This thesis points out the shortcomings of existing event tree modeling tools and techniques. It also emphasizes the need for generalized software for efficient processing in practical dam safety event tree analysis. To highlight the differences in the details of the applications of the mathematical calculations employed in dam safety risk analysis from other risk analysis fields, this thesis describes the standard event tree structure and propose some differences in calculation details that are better suited to the dam safety risk analysis.

The development process for a new dam safety event tree analysis tool has been divided in two parts: its theoretical development and its computational development. The theoretical development includes the refined event tree terminology and additional variables. The computational development includes the computational logic involved in

DAMRAE. Finally, the capabilities of the developed tool have been demonstrated using the Success Dam case study by Bowles et al. (2004).

Conclusion

The purpose of designing and building DAMRAE is to enable users to rapidly develop and quantify event trees. The present version of DAMRAE has been built using Visual Basic.NET and can be executed on any windows-based operating system. Unlike other existing dam safety event tree modeling tools, DAMRAE is stand-alone software and is easy and intuitive to use. The underlying concept of transforming the event tree structure into a computationally-adapted matrix form is a novel idea of this work. Based on this structure-transformed-matrix or Connectivity Matrix, branch probabilities and consequences can be calculated. Standard methods have been incorporated to calculate and assign the state values, SRPs, exposure weights and consequence values to each branch. DAMRAE also includes the functionality to perform the common-cause adjustment in case of non-mutually exclusive failure events. Failure modes are identified from the event tree graphics and for each of these failure modes, failure probabilities and associated annualized consequences are displayed such that reports can be generated interactively using a flexible post-processing functionality. The present version of DAMRAE has been developed as a prototype to prove the concept of the generalized algorithm for dam safety event tree analysis. It effectively addresses all the limitations identified in the "*Introduction*" chapter of this thesis.

Future Work

Application of DAMRAE to Corps of Engineers risk assessments is planned to begin in 2008. However, continued development is planned after that initial deployment. These future developments are planned to include uncertainty and sensitivity analysis options, along with providing some enhanced graphics options, additional reporting capabilities, and code optimisation to improve program performance and memory usage. An automatic feature for selecting the number of computational branches for continuous branches, such as initiating events or loading events, will be developed based on user-specified error criteria similar to those used in other types of numerical models.

A facility for importing standard event tree templates and adapting them for application to a specific dam will be added.

Database aspects will be enhanced to facilitate the consideration of risk reduction measures. A capability for performing sensitivity and scenarios analyses will be developed, together with post-processing to support these capabilities, including features needed for the prioritisation of risk reduction measures and investigations in portfolio applications.

A capability similar to that for invention branch groups will be developed to calculate the contributions of spillway gate reliability and spillway plugging by debris on estimates of failure risks, including the combined effects of intervention.

DAMRAE will be tested and evaluated for additional some dams, including some that will be selected because of unique and complex aspects to their event tree structures.

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APPENDIX

(DAMRAE USER MANUAL)

Introduction

DAMRAE has been developed as **independent** software using the VB.NET environment. The executable file of the developed software **RiskManagement.exe** can be run on any windows platform independent of the requirement to install the Microsoft Visual Studio.NET. Other than the inbuilt programming code, the software also uses some dynamic-link library (*dll*) files. These external files are Interop.ADODB, Interop.MSScriptControl, Interop.Scripting, and NPlot. They are required to be placed in the same folder with the software's executable file. Upon creating an event tree project, the program generates several text, MS Access and XML files. The MS Access file stores the event tree structure information and the text and XML files store the intermediate calculation values and final output values. A detailed description of the steps involved in developing and computing an event tree project is included in this Appendix

Menu Bar Description

Upon running the software executable file, the program displays a Dam Safety Risk Analysis Engine (DAMRE) tool bar on the screen. This tool bar includes several options as shown in Figures 26 and 27.

A. New Project

The first step in developing an event tree model in DAMRAE is to establish the directory in which you wish to work in and to enter a title for the new project. The default directory is the location of the executable file of this software. To start a new project, either use the **File** menu on the toolbar and select the **New Project** option or click the icon **A** from the toolbar menu icons. This will bring up a New Event Tree Analysis Project window as shown in Figure 28.

The user is required to enter a proper filename for the new project and to save it in the desired directory. The filename should be alphanumeric and should not include any special characters, such as decimals, commas or question marks, etc. The program creates a folder with the user-assigned name in the selected directory and within that folder a file with extension "**.eap**" is generated. This ".eap" file is the main project file and its name or extension should not be changed by the user.

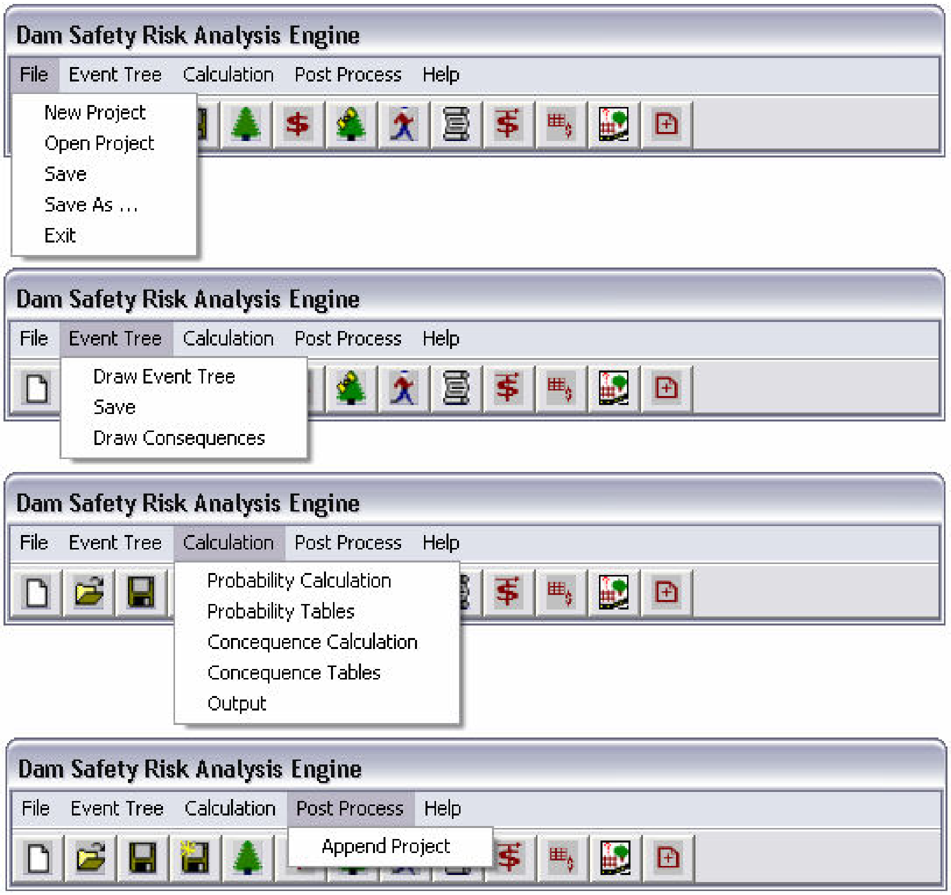
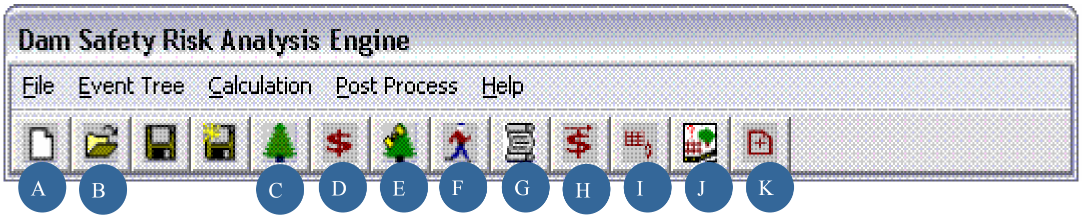


Figure 26. Menu bar options.



A. New Project
B. Open Project
C. Draw Event Tree
D. Draw Consequences
E. Save Event Tree
F. Run Probability Calculation
G. Show Probability Tables
H. Run Consequences Calculation
I. Show Consequences Tables
J. Failure Probability and Consequence Values
K. Add External Data File

Figure 27. Menu bar icons.

After saving the project file, the next window that comes up is the **Project Info** window, which is shown in Figure 29. This window has preliminary information input options related to the project. These inputs are completely optional. None of these is used in the event tree calculation; and hence they can be left blank if desired. To proceed to the next step, click the **Enter Input** button, or if you wish to cancel the project, click the **Cancel** button.

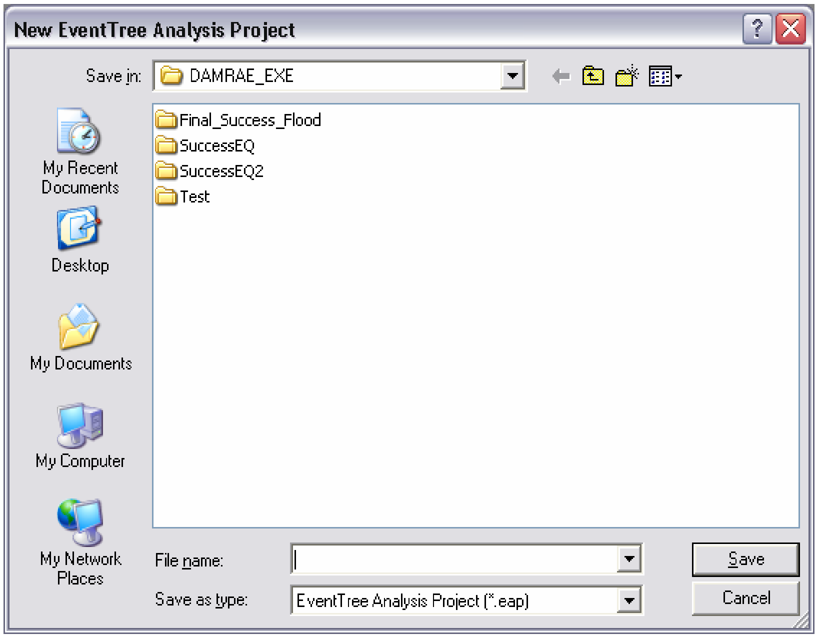
B. Open Project

To open an existing Event Tree Analysis Project (EAP), select the **Open Project** option from the **File** menu, or click the icon **B** in the menu bar icons. This brings up an **Open Event Tree Analysis Project** window, as shown in the Figure 30. To open an existing project, go to the appropriate directory and select the project name file with an extension **".eap"**. If the **Open** project option is chosen, it will bring up the **Project Info** window. The **Project Info** window shows the information that was saved while creating the project. These inputs can be changed, and then to proceed to next step **Enter Input** button should be clicked.

C. Draw Event Tree

After entering the project information inputs, the next step is to draw the event tree structure. Event tree drawing can be initiated by selecting the **Draw Event Tree** option under the **Event Tree** menu or by using the icon **C**.

The **Draw Event Tree** window (Figure 31) has two checkboxes. If the event tree structure initiates with a discrete branch, such as for a certain magnitude of earthquake loading, then select the option **Start Event Tree with Discrete Branch** and if event tree starts with a continuous branch, for example, flood loading, then select the option **Start Event Tree with Continuous Branch**.

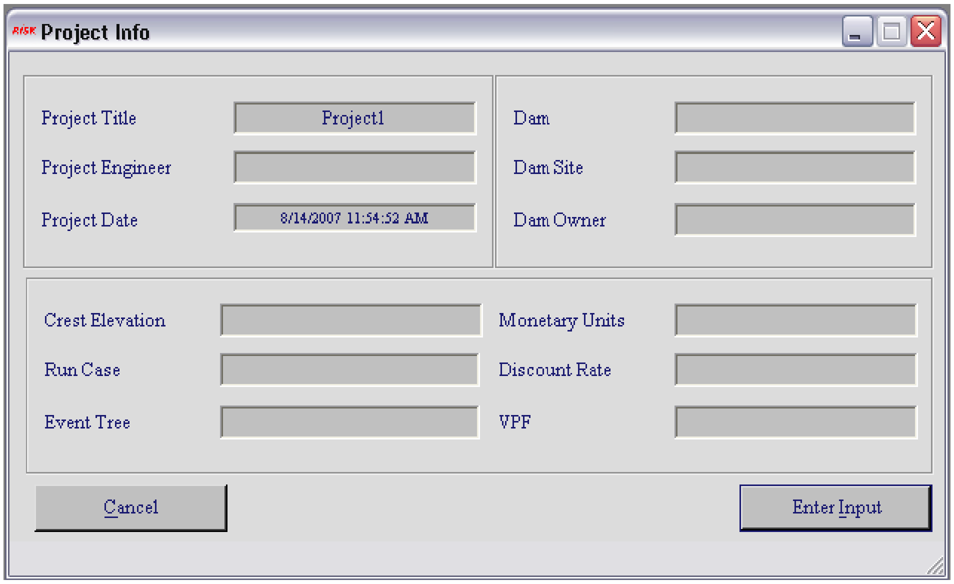


Save in: DAMRAE_EXE

File name:

Save as type: EventTree Analysis Project (*.eap)

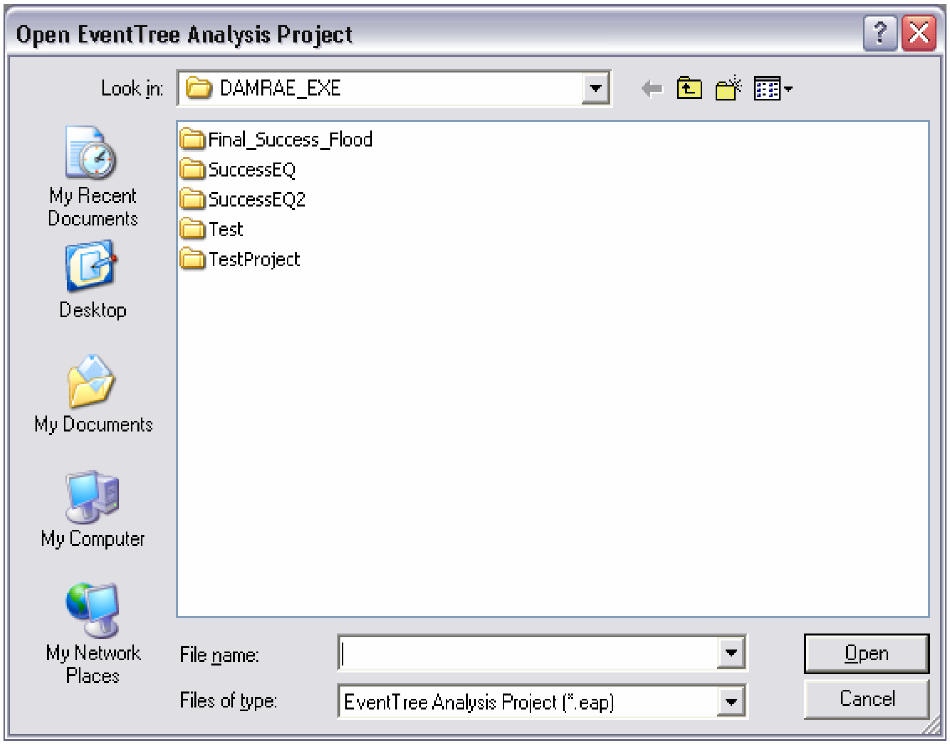
Figure 28. New event tree analysis project window.



Project Title: Project1

Project Date: 8/14/2007 11:54:52 AM

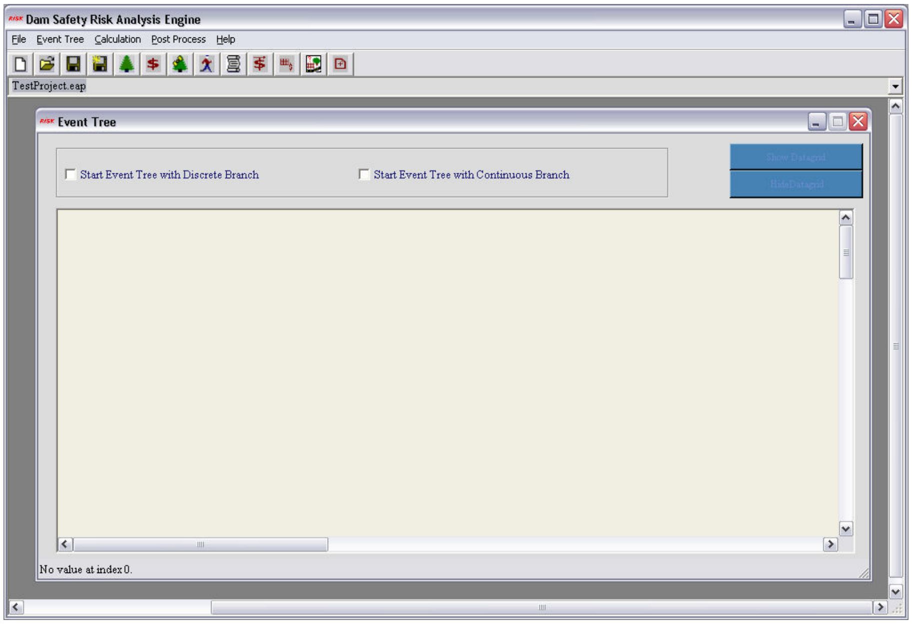
Figure 29. Project information window.



Look in: DAMRAE_EXE

Files of type: EventTree Analysis Project (*.eap)

Figure 30. Open event tree analysis project window.

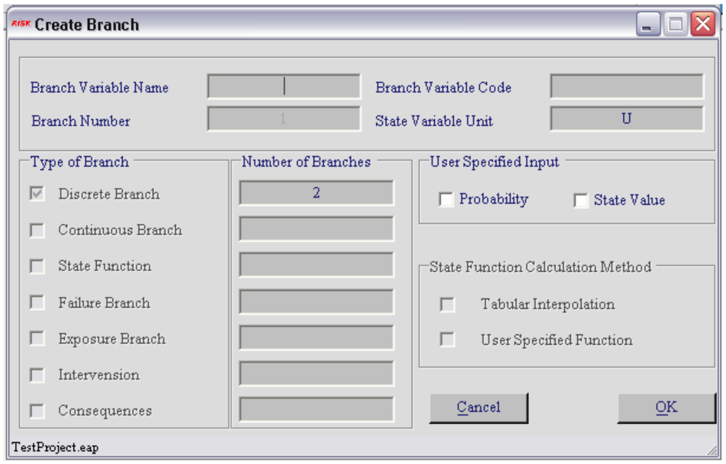


☐ Start Event Tree with Discrete Branch

☐ Start Event Tree with Continuous Branch

No value at index 0.

Figure 31. DAMRAE interface displaying the window for drawing the event tree structure.



Branch Variable Name

Branch Variable Code

Branch Number 1

State Variable Unit U

Type of Branch

☑ Discrete Branch

☐ Continuous Branch

☐ State Function

☐ Failure Branch

☐ Exposure Branch

☐ Intervention

☐ Consequences

Number of Branches 2

User Specified Input

☐ Probability ☐ State Value

State Function Calculation Method

☐ Tabular Interpolation

☐ User Specified Function

Figure 32. Create branch window displaying the inputs required to draw a branch on the DAMRAE interface.

When the desired initiating branch option is selected, it brings up a **Create Branch** window, as shown in Figure 32. This window includes different branch inputs, which are described in the following subsections. After assigning all the appropriate required inputs, the **OK** button should be clicked to draw the initiating branch on the

DAMRAE interface, or otherwise **Cancel** button can be clicked to cancel the initiating branch selection.

After drawing the initiating branch, subsequent branches can be added by using the right click menu of the previous branch node. A detailed description of the different types of branch inputs and the node-right-click-menu is given under the **Drawing Details** subsection below.

D. Draw Consequences Branches

Before economic and life-loss consequences branches can be added to an event tree structure, it is required to define the number of consequence centers for which the consequence analysis is being done. The number of centers and their names can be defined by using the **Draw Consequence** option under the **Event Tree** menu, or by using the icon **D**. This option brings up a window as shown in Figure 33.

To add the number of consequence centers and their names into the program database, it is required to transfer the names of centers to the data grid. Names can be transferred to data gird one by one by entering the name in the **Name of Centers** input box and then clicking the **Add** button. A name can be removed from the data grid by selecting the desired row in the data grid and then using the **Remove** button. The number of Names in the data grid should be same as the number of consequence centers in the **Number of Centers** input box. After entering all the names, the **OK** button should be clicked. After this step, the consequence branches can be added to the event tree using the node-right-click-menu.

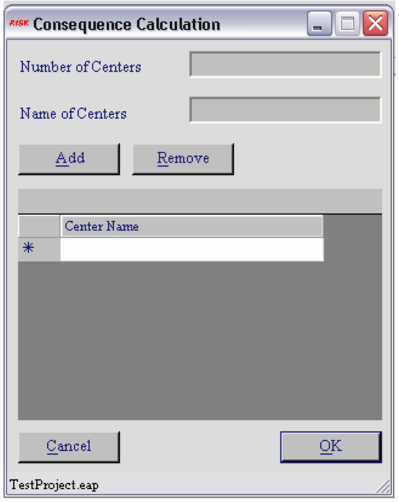


Figure 33. Consequences calculation window for assigning the number of consequence centers and their names.

E. Save Event Tree

This option provides the facility to save the event tree graphic into the program database at any time. Although all the graphics details and input values are automatically saved to the database when the user exits the program, it is a good idea to save the graphics frequently while creating the event tree structure and inputs.

F. Run Probability Calculation

After completing the event tree structure and entering all the inputs for each branch, either **Probability Calculation** under the **Calculation** menu, or the icon **F**, can be used to perform the event tree calculation. This calculation generates four matrices namely, the **Pedigree**, **Branch Code**, **Probability** and **State Value** matrices. The details of these matrices have been included under the **Output Details** subsection below.

The **Probability Calculation** option brings up a window containing four buttons to select each type of output matrix and a progress bar displaying the percentage completion of the calculation. A screenshot of the DAMRAE interface with the matrices output window and progress bar is shown in Figure 34. After completion, the calculation output matrices can be viewed by clicking the corresponding tab to select each matrix.

G. Show Probability Calculation

Although, the **Probability Calculation** option displays the probability calculation output tables, to reopen the window either the **Probability Tables** option under teh **Calculation** menu or the icon **G** must be used.

H. Run Consequences Calculation

The consequence calculation is performed to assign the consequence values to each loading interval for each consequence center and to calculate the annualized incremental risk cost and life loss associated with each failure mode. The consequence calculation can be performed using the **Consequence Calculation** option under the **Calculation** menu or by using the icon **H**. These will option bring up a **Consequence Table** window, as shown in Figure 35. Upon completion of the calculation, economic and life-loss consequences tables can be viewed using the buttons imbedded in this window.

I. Show Consequences Tables

Although the **Consequence Calculation** displays the consequence table window, to reopen this window, the **Consequence Table** under the **Calculation** menu or the icon **I** must be used.

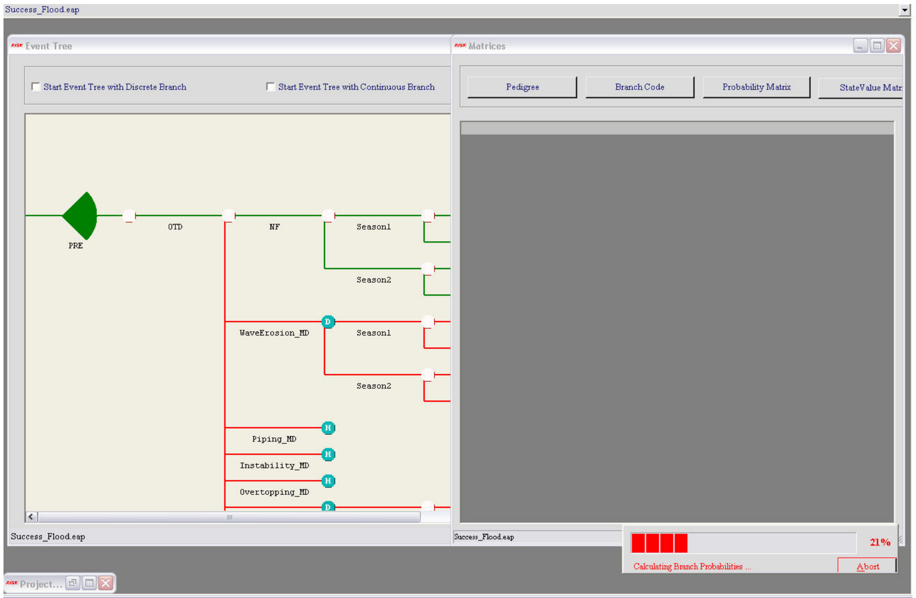


Figure 34. DAMRAE interface displaying the probability calculation progress bar and the output matrices window.

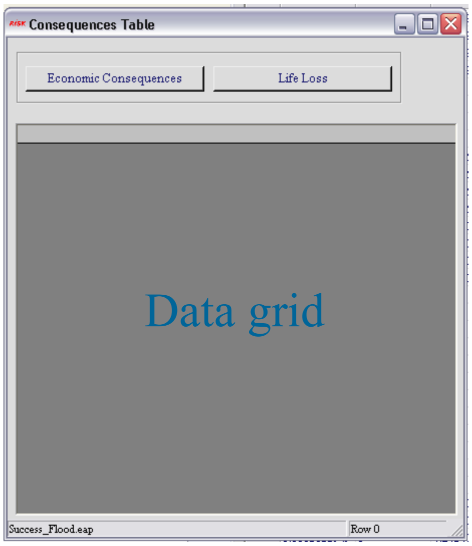
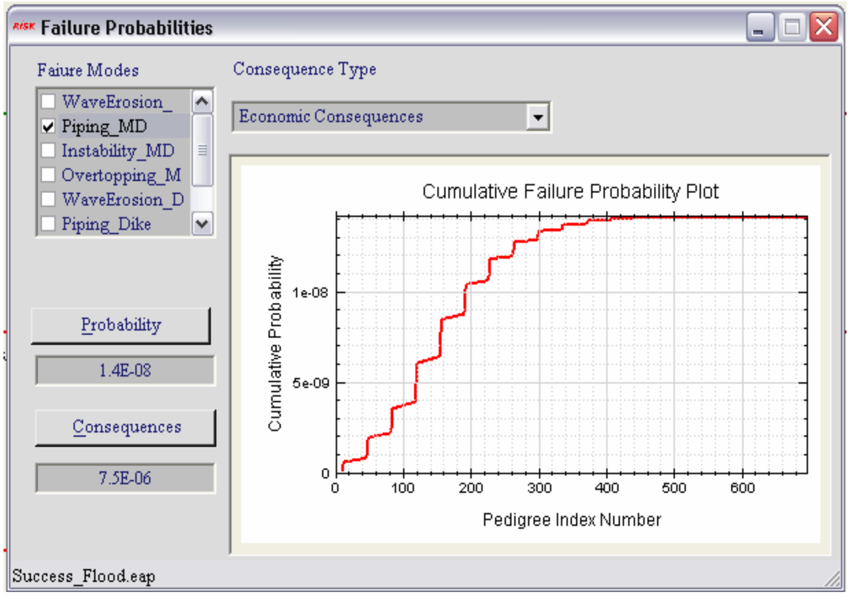


Figure 35. Consequence table window displaying the embedded economic and life-loss consequences buttons.

J. Failure Probability and Consequences Values

The **Failure Probabilities** window, shown in Figure 36, contains the calculated probability and associated consequence values for each failure modes. This window



☐ WaveErosion_
☑ Piping_MD
☐ Instability_MD
☐ Overtopping_M
☐ WaveErosion_D
☐ Piping_Dike

Economic Consequences

1.4E-08

7.5E-06

Success_Flood.eap

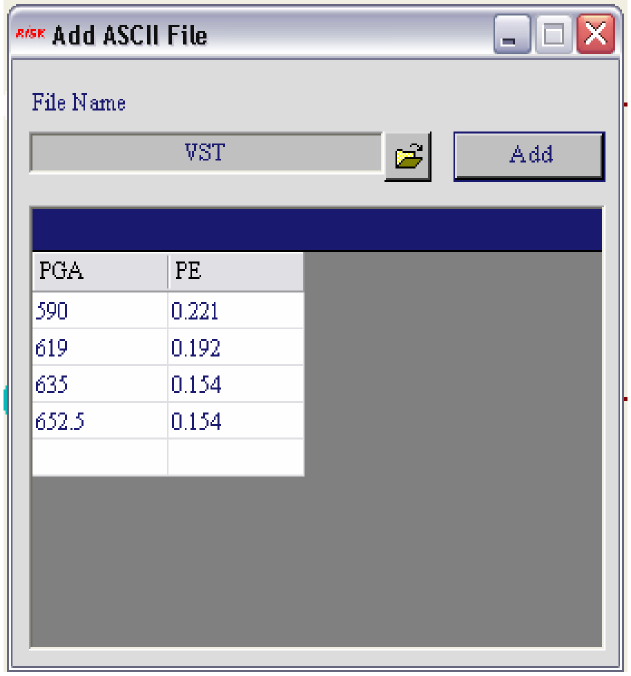
Figure 36. Failure probabilities and consequence output window

contains a list box displaying the failure modes and a combo box displaying consequence types. To find out the probability and consequence value for a failure mode, check the failure mode in the list box and select the consequence type in the combo box, and the use the **Probability** and **Consequences** buttons to view the output values.

The **Failure Probabilities** window also contains a '**Cumulative Failure Probability Plot**', which contains a plot of the cumulative probability for the selected failure mode vs. the pedigree row number.

K. Add External Data File

To add an external interpolation text file, the icon **H** can be used. This option brings up an **Add ASCII File** window, as shown in Figure 37. To find the file location, use the browse folder button and type in the name of the file in the input box. To transfer the content of the file into the program database, click the **Add** button. The added content of the file are displayed in the data grid.



PGA	PE
590	0.221
619	0.192
635	0.154
652.5	0.154

Figure 37. Add external text data file window.

Drawing Details

The construction of the event tree is sequential with the usual convention being from left to right. The construction process begins with an initiating event, for example a range of magnitudes of large flood peak water levels in the reservoir, and the sequence of subsequent events that might lead to dam failure are drawn, typically in the order that they occur. To draw the initiating event branch, one of the two check boxes should be selected, as appropriate. If the initiating branch represents a discrete value of the initiating event, select the **Start Event Tree with Discrete Branch**. If the initiating branch represents a range of values for the initiating event, then select the **Start Event Tree with Continuous Branch**. As the appropriate initiating branch type is selected a Create **Branch** window is displayed, as shown in Figure 32. This window contains the inputs required for drawing the branch on the software interface. The descriptions of these inputs are present in the following subsections.

Branch Variable Name: This is assigned for the branch identification. This name is not used by the program in any calculation so it can be any length depending upon the user's choice.

Branch Variable Code: This represents the variable name for a branch which is used to access the probability or state value of that branch. Other than this, Branch Variable Code is also used in generating the Branch Code Matrix. So, it is required to assign a short unique name to each branch (or group of branches in case of a discrete branch, failure branch or exposure branch).

Branch Number: This denotes the branch level starting from the left side of the event tree with the initiating branch as Level 1. The branch number is assigned by the program and hence the input window is disabled.

State Value Unit: Not functioning in the current version of DAMRAE.

Types of Branches: Based on the functionality of different events that are useful in dam safety event trees, DAMRAE includes seven types of branches from which an event tree structure can be built. Typically, the initiating branch is either a discrete branch or a continuous branch.

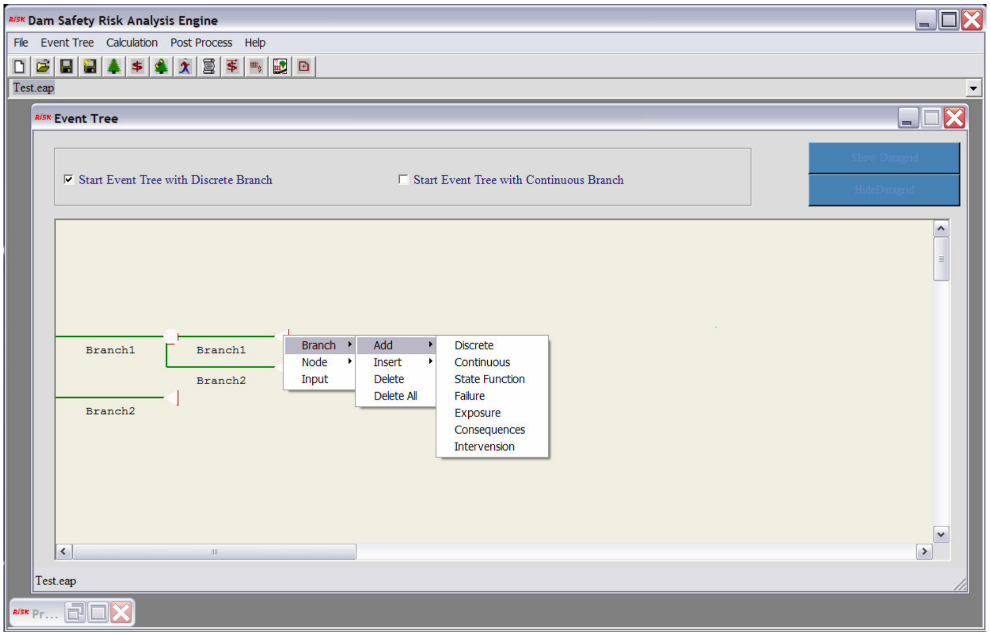
Number of Branches: Next to the each of type of branch, there is an input box for assigning the required number of branches. For the discrete, failure and exposure types of branch, multiple branches can be added under the same branch variable name and branch variable code. The default branch number for these branches, assigned by the program, is 2; but the actual number can be changed by the user as required. The state function, consequence and intervention types of branches have a fixed number of branches and hence, for these types of branches, the numbers of branches in the input boxes are disabled.

User Specified Input: This option is enabled for discrete, continuous and exposure branch types. For these branch types, the user has a choice to input the probability values or the state values for the branch.

State Function Calculation Method: This option is enabled for the state function and failure types of branches. For a state function branch, the state value can be computed either by selecting the tabular interpolation option or by entering a user-specified function. The tabular interpolation option requires the appropriate text file input containing the related branch variable codes as the heading of columns in the text file. The user-specified function option requires defining the functional relationship between the state value in the state function branch and state values in preceding branches with the equation written using their branch variable codes. The equation of functional relationship could be an algebraic equation or it could be a predefined function included in the program.

After drawing the initiating branch on the DAMRAE interface branches can be added to the event tree moving from left to right by using the options available in the node-right-click menu, as shown in Figure 38. A detailed description of the node-right-click menu, which can be accessed from each branch node is present in the next subsection.

Node-Right-Click Menu Options: The first level of right click menu includes the following three options:-



☑ Start Event Tree with Discrete Branch
☐ Start Event Tree with Continuous Branch

Figure 38. Event tree drawing window displaying the node-right-click menu options.

1. Branch: This option provides the facility to add, insert or delete the next level of branch to a node. The second level of this menu, following this Branch option includes four options, as follows:

   a) Add: To add the subsequent event branches to an initiating branch, the **ADD** option next to the branch right click menu is used. The next level of the **ADD** menu includes different options for each branch type. To add a new branch, select the desired branch type, and enter all the required inputs in the **Create Branch** window that will appear.

   b) Insert: To insert a new branch between two existing branches the **ADD** option cannot be used. To do so, the **INSERT** option must be used. Similar to the **ADD** option, the next level of the **INSERT** option includes the same branch type options and requires the same steps as for the ADD option.

c) Delete: This option is used to delete a branch from the last branch level. If this option is selected for a branch level other than the last branch level, the selected branch and all other subsequent branches connected to the selected branch will be deleted.

d) Delete All: This option deletes all the branches from the program database and also clears the entire draw event tree window. To restart the event tree drawing, select the desired branch type option for the initiating branch and continue as before.

2. Node: The next level of right click menu attached to the **Node** option includes the **Copied Collapsed Node** and **Cloned Collapsed Node** options. If it is desired to copy the sub tree following a particular node to an underlying node, the **Copied Collapsed Node** option should be used. If, in addition to copying the sub tree it is desired to use the same inputs in the new location, the **Cloned Collapsed Node** option should be used. The node from which the sub tree is copied is known as a ‘Donor Node’ and the ‘copied collapsed node’ or a ‘cloned collapsed node’ is known as a ‘Host Node’. To set a node as a ‘copied collapsed node’ or a ‘cloned collapsed node’ the appropriate option must be selected, which brings up a message box with a command for the user to click on the ‘Donor Node’. As the user clicks on the ‘Donor Node’, the program asks the user to confirm the location of the ‘Donor Node’. If the selected node is the desired ‘Donor Node’, click the **Yes** button on the message box, otherwise click the **No** button. If at this stage the user decides not to set the node as a ‘Host Node’ the **Cancel** button must be clicked. If the ‘copied collapsed node’ option is selected for a node, as **Yes** button is clicked on the message box, the sub tree branch structure of the ‘Donor Node’

is copied to the ‘Host Node’. This copied branch structure has all the inputs from the donor node sub tree but any changes must be made separately in the donor and host nodes sub trees. If the ‘cloned collapsed node’ option is selected, upon clicking the **Yes** button, the program marks the ‘Donor Node’ with a label ‘D’ and the ‘Host Node’ with a label ‘H’. As a ‘cloned collapsed node’ has the same following branch structure and associated inputs as its ‘Donor Node’, the program does not make a copy of the branch structure on the interface and the user is not required to assign inputs in the cloned sub tree because the inputs in the donor sub tree will continue to be used in the host sub tree. Some requirements for the ‘Donor Node’ and ‘Host Node’ are that a ‘Host Node’ and its ‘Donor Node’ must be in the same branch level and the Donor Node must be above the ‘Host Node’ in that level of the event tree. A node can be a ‘Donor Node’ for multiple ‘Host Nodes’ and it is preferred not to set a ‘Host Node’ as a ‘Donor Node’ for some other nodes.

3. Input: Input for a branch can be entered using the right-click-menu of the node attached to the end of that branch. Inputs can be filled simultaneously while creating the event tree structure or after completing the event tree drawing. Upon selecting the **Input** option, the appropriate input window comes up based on the type of branch. Details of inputs for different branch types are described in the following subsection.

Input Details

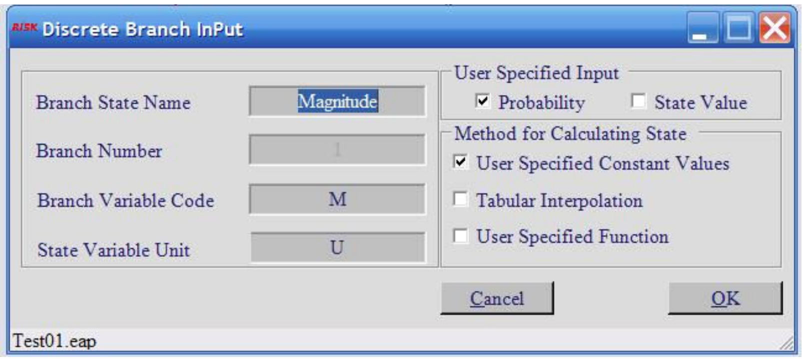
In general, the branch inputs for calculating the probabilities or state values can be assigned in any of the following three ways: (a) User-specified Constant Values, (b)

Tabular Interpolation, or (c) a User-specified Function. All the three options are available only for the discrete, exposure, and consequence types of branches. For the state function and failure types of branches either the Tabular Interpolation or User-Specified Function method can be used. If a failure branch is assigned a fixed user-specified value, it can be assigned as a User-specified Function input. For the intervention branch, the user only has the option to enter the fixed probability value for the successful intervention and the unsuccessful probability value is calculated as the complement of the successful intervention value. A detailed description of input assignment for different types of branches is included in the following subsections.

Discrete Branch Input

Upon selecting the **Input** option for a discrete branch, an input window, as shown in Figure 39, shows up. **User-Specified Input** can be either a Probability or a State Value; but the present version of the DAMRAE has only been tested for the probability option. The **Method for Calculating State Value/ Probability** has the following three options:

1. User-specified Constant Values: To enter a user-specified value of a probability or a state value, the first option must be checked. Upon clicking the **OK** button, another window, as shown in Figure 40, comes up and includes the discrete branch labels and branch values in a data grid. Discrete branches included in the data grid are the branches that emerge from a common preceding node. If the event tree starts with a discrete branch group, all the discrete branches will be included in the data grid.

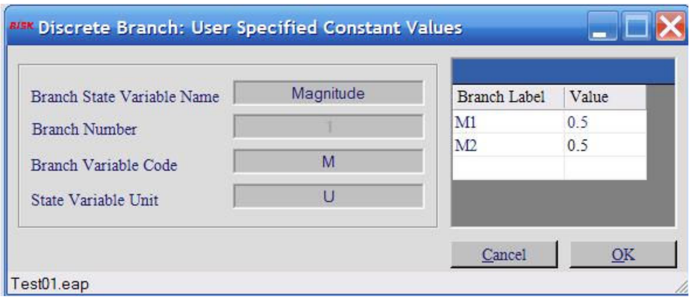


Branch State Name: Magnitude
Branch Number: 1
Branch Variable Code: M
State Variable Unit: U

User Specified Input
☑ Probability ☐ State Value

Method for Calculating State
☑ User Specified Constant Values
☐ Tabular Interpolation
☐ User Specified Function

Figure 39. Discrete branch input window.



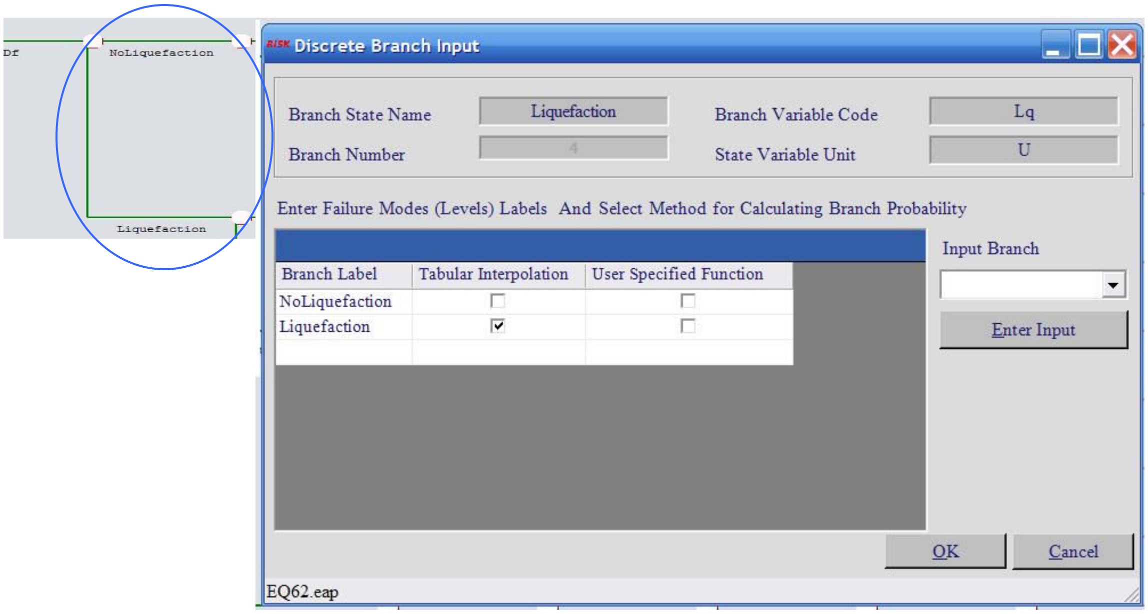
Branch State Variable Name: Magnitude
Branch Number: 1
Branch Variable Code: M
State Variable Unit: U

Branch Label	Value
M1	0.5
M2	0.5

Figure 40. User-specified constant value input window for a discrete branch group.

The default branch name for a discrete branch is ‘Branch (index)’, where the index is the number of the branch. The user can reassign both the branch name and the branch value in the data grid. To save the data in the program database, click the **OK** button. If a new name is assigned for a branch, the event tree drawing on the interface displays the new name for that branch.

2. Tabular Interpolation: If a single discrete branch or a discrete branch in a group of discrete branches, which are linked with a common preceding node, will use the tabular interpolation calculation method, the user should select the second **Tabular Interpolation** check box. Upon clicking the **OK** button, a Discrete Branch Input window, as shown in Figure 41, comes up. This window contains a data grid, which



Branch State Name: Liquefaction
Branch Variable Code: Lq
Branch Number: 4
State Variable Unit: U

Enter Failure Modes (Levels) Labels And Select Method for Calculating Branch Probability

Branch Label	Tabular Interpolation	User Specified Function
NoLiquefaction	☐	☐
Liquefaction	☑	☐

Input Branch

EQ62.eap

Figure 41. Discrete branch input window including the option for tabular interpolation and a user-specified function.

includes the names of the discrete branches connected to a common preceding node. To enter the input for a branch, check the desired option from the data grid columns and highlight the branch name in Input Branch combo box.

If the Tabular Interpolation option is checked for a discrete branch, upon clicking the button, a Tabular Interpolation input window, as shown in Figure 42, comes up. This window includes several inputs that are required to compute the probability or state value for a discrete branch, as follows:

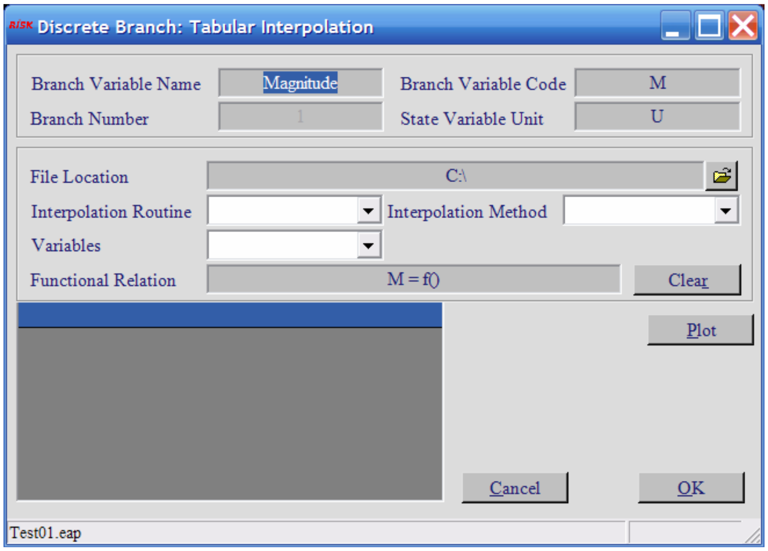
a. File location: Use the browse folder icon to locate the path of the desired interpolation text file. The text file columns should be tab separated and the first row of the text file should contain the heading each columns, which must match the appropriate branch variable codes. If the file format and the file location are correct, the input file content is displayed in the data grid.

b. Interpolation routine: If the input interpolation file has two columns, select the one-way interpolation routine. In this routine, the first column of the input text file is treated as the input value column for the interpolation and the second column is the output value column. The names of both columns must match the appropriate branch variable codes. If the input text file has three variables and more than two columns, select the two-way interpolation routine. The first column of the text file is the input column and its heading must match the appropriate branch variable code. The other columns are the output value columns, which must have headings that correspond to the appropriate numerical values of the third variable.

c. Interpolation method: The interpolation method can be linear, log-log or semi-log. In the present version of the DAMRAE only linear and log-log interpolation methods are functional. Select the desired interpolation method from the combo box.

d. Variables: This combo box shows the list of available branch variable codes which have been defined by the user and which are therefore available to be used as the columns heading in the input text file.

e. Functional relation: To incorporate the dependencies of a probability or a state values on different variables, this input box displays a relationship as *Probability* or *state value = f (Input Branch Variable Code or Codes)*, where the user is required to assign the input branch variable codes.



Branch Variable Name: Magnitude
Branch Variable Code: M
Branch Number: 1
State Variable Unit: U
File Location: C:\
Functional Relation: M = f()
Test01.eap

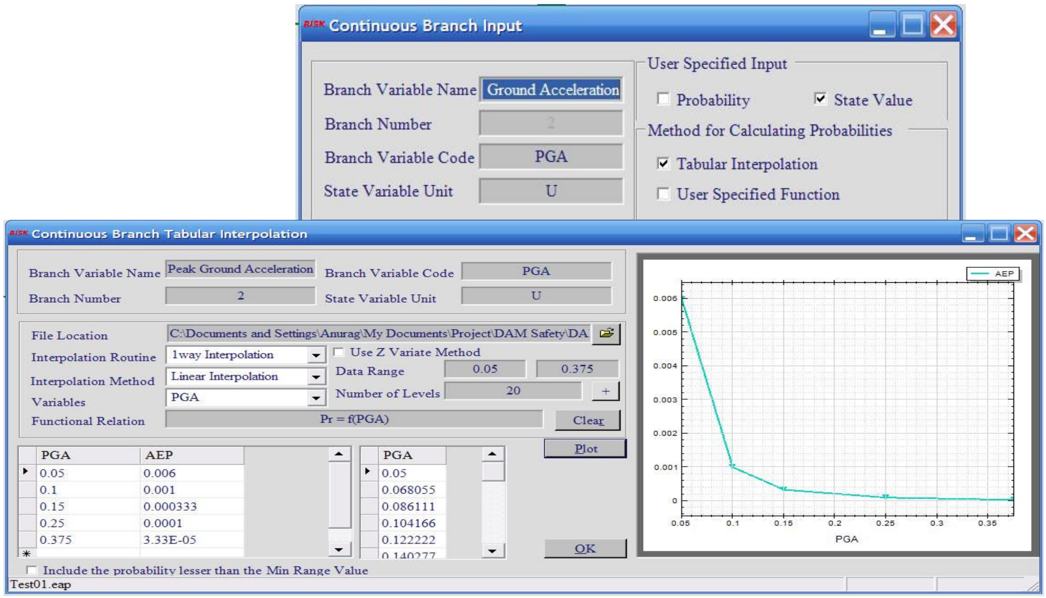
Figure 42. Tabular interpolation input window for a discrete branch.

f. To include the input branch variable code(s) within the parentheses in the expression above, select the appropriate code(s) from the combo box of available branch variable codes. In case of two-way interpolation, the input branch codes should be added in sequence

g. Plot: To see a plot of an input variable versus an output variable from the interpolation text file, click the **Plot** button. The plot is based on the type of interpolation method chosen. To hide the plot, click the **Plot** button again.

Continuous Branch Input

The input option for a continuous branch brings up a Continuous Branch Input window, as shown in Figure 43. User-specified input can be either a probability or state value. If the calculation method is checked as Tabular Interpolation, another ‘Continuous Branch: Tabular Interpolation’ input window comes up. Most of the inputs for this



Branch Variable Name: Ground Acceleration
Branch Number: 2
Branch Variable Code: PGA
State Variable Unit: U
☐ Probability ☑ State Value
☑ Tabular Interpolation
☐ User Specified Function

Branch Variable Name: Peak Ground Acceleration
Branch Variable Code: PGA
Branch Number: 2
State Variable Unit: U
File Location: C:\Documents and Settings\Anurag\My Documents\Project\DAM Safety\DA
Interpolation Routine: 1way Interpolation
☐ Use Z Variate Method
Interpolation Method: Linear Interpolation
Data Range: 0.05 0.375
Variables: PGA
Number of Levels: 20 +
Functional Relation: Pr = f(PGA)

PGA	AEP
0.05	0.006
0.1	0.001
0.15	0.000333
0.25	0.0001
0.375	3.33E-05

PGA
0.05
0.068055
0.086111
0.104166
0.122222
0.140277

☐ Include the probability lesser than the Min Range Value
Test01.eap

Figure 43. Continuous branch input and continuous branch tabular interpolation windows.

window are similar to the discrete branch tabular interpolation input window as described above except for a few additional inputs, as described below.

a. Data Range: It is required to assign the minimum and maximum values of the input variable in the data range input boxes. By default, the minimum and maximum value assigned to these boxes are the first and last values of the input data column in the data grid but these values can be reassigned by the user.

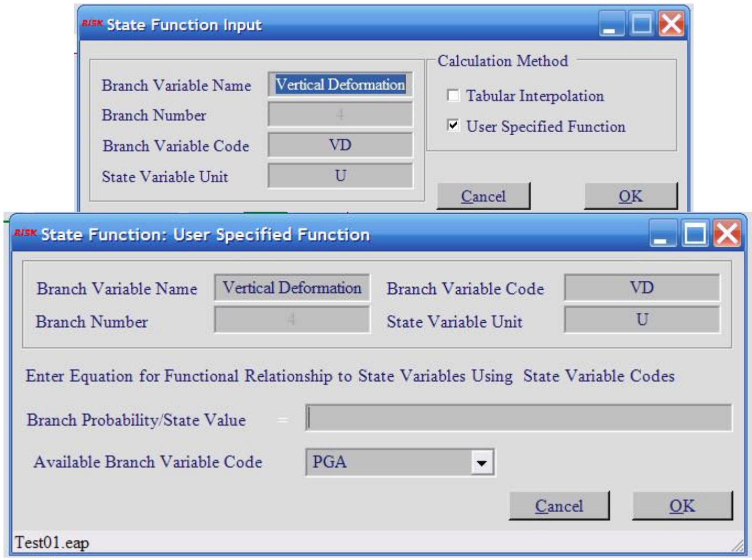
b. Number of Levels: This represents the number of intervals for the input variable data range. After entering the number of intervals, click the ‘+’ button. This will divide the data range into the assigned number of intervals with equal spacing. These values of the input variable will be added to the data grid. To change the spacing of the input variable values, values can be modified in the data grid.

c. z-Variate Method: This option is checked to use the z-variates of the input variable in interpolation.

d. Include the probability lesser than the Min Range Value: Sometimes, when the minimum data range value does not has a probability of 1.0, it may be desired to include the probability that values lower than the assigned minimum data range value will occur.

State Function Input

The State Function Input window for a state function branch is shown in Figure 44. If the User-specified Function option is checked, upon clicking the **OK** button, another window for State Function Input comes up.


State Function Input

Branch Variable Name: Vertical Deformation
Branch Number: 4
Branch Variable Code: VD
State Variable Unit: U

Calculation Method
☐ Tabular Interpolation
☑ User Specified Function

State Function: User Specified Function

Branch Variable Name: Vertical Deformation
Branch Variable Code: VD
Branch Number: 4
State Variable Unit: U

Enter Equation for Functional Relationship to State Variables Using State Variable Codes

Branch Probability/State Value =
Available Branch Variable Code: PGA

Test01.eap

Figure 44. State function input and state function user-specified function windows.

To calculate the state value of a state function branch, an algebraic equation or a predefined program functions can be used. The variables used in the functional relation should be in terms of the available branch variable codes. A list of available branch codes can be seen in the '**Available Branch Variable Code**' combo box.

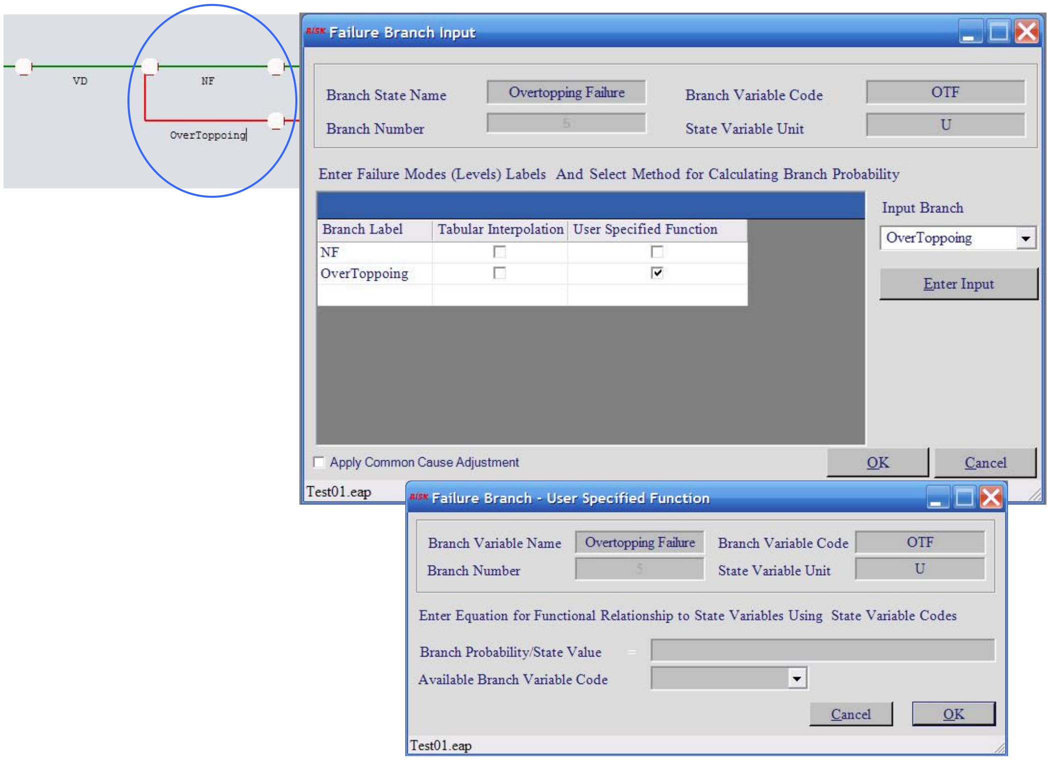
Failure Branch Input

The failure branch input window, shown in Figure 45, is similar to a discrete branch input window, shown in Figure 41. The first row in the data grid is always 'NF' (i.e. the no-failure branch) and the other rows of the data grid display the name for each of the other failure modes. Since the probability for a no-failure branch is always (1- sum of failure branches) so there is no need to enter any input for a no-failure branch. For the failure branches, either tabular interpolation or the user-specified method can be selected. For the selected calculation method, the input is assigned in the same way as described for the discrete branch tabular interpolation, above.

When failure modes are not mutually exclusive, the total probability of failure can be calculated based on the common-cause adjustment approach (Hill et. al, 2003). In order to perform the common-cause adjustment (CCA) for the failure modes, a check box option added at the bottom of the failure branch input window must be selected.

Exposure Branch Input

Exposure branch inputs assignment is similar to a discrete branch inputs assignment, which is described above.



Failure Branch Input

Branch State Name: Overtopping Failure
Branch Variable Code: OTF
Branch Number: 5
State Variable Unit: U

Enter Failure Modes (Levels) Labels And Select Method for Calculating Branch Probability

Branch Label	Tabular Interpolation	User Specified Function
NF	☐	☐
OverToppoing	☐	☑

Input Branch: OverToppoing

☐ Apply Common Cause Adjustment

Failure Branch - User Specified Function

Branch Variable Name: Overtopping Failure
Branch Variable Code: OTF
Branch Number: 5
State Variable Unit: U

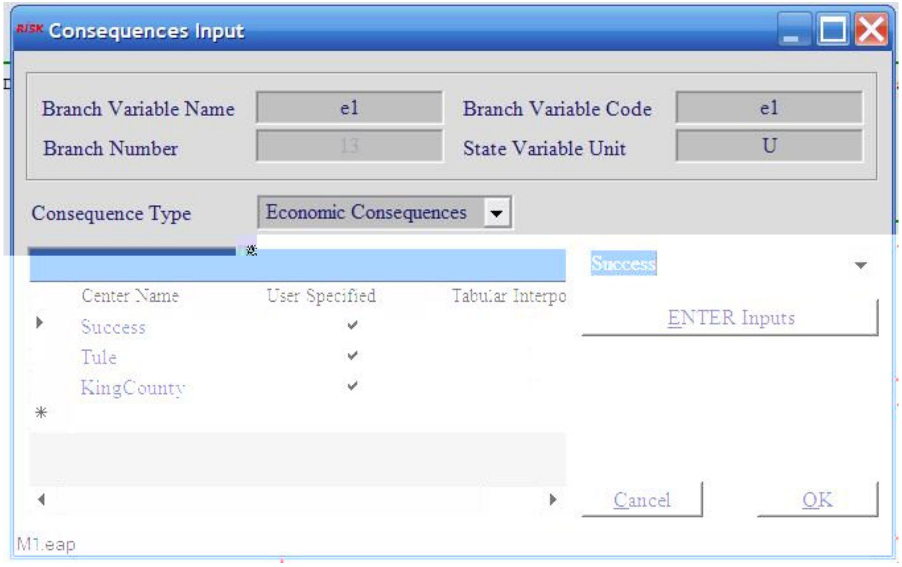
Enter Equation for Functional Relationship to State Variables Using State Variable Codes

Branch Probability/State Value =
Available Branch Variable Code

Figure 45. Failure branch input and failure branch user-specified function input windows.

Consequence Branch Input

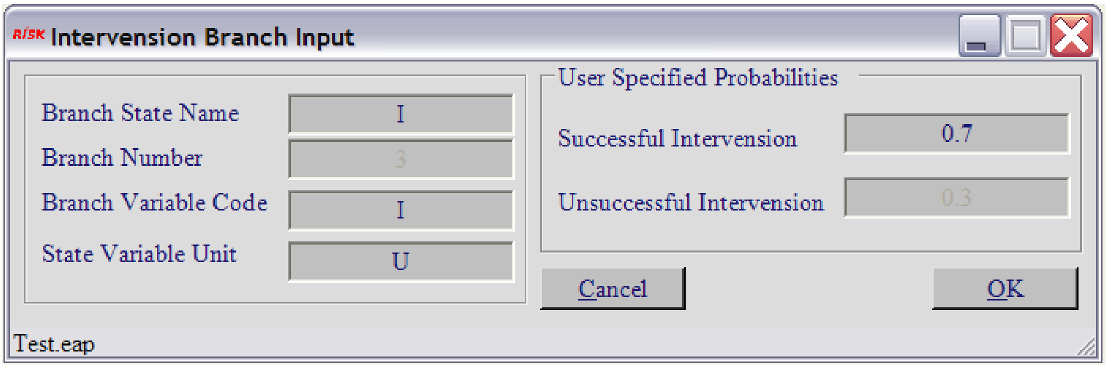
The consequence branch input window, shown in Figure 46, is similar in format as a discrete branch input window, shown in Figure 40, except for a few differences. The first column of the data grid shows the name of the consequence centers, which were entered by the user before starting the drawing of the consequence branches. Before inputs can be entered for these centers, it is required to select the **Consequence Type** from the combo box. It is necessary to assign the same consequence type to all the consequence branches in the same branch level.



Branch Variable Name: e1
Branch Variable Code: e1
Branch Number: 13
State Variable Unit: U
Consequence Type: Economic Consequences
Success

Center Name	User Specified	Tabular Interpo
Success	✓	
Tule	✓	
KingCounty	✓	

Figure 46. Consequence branch input window.

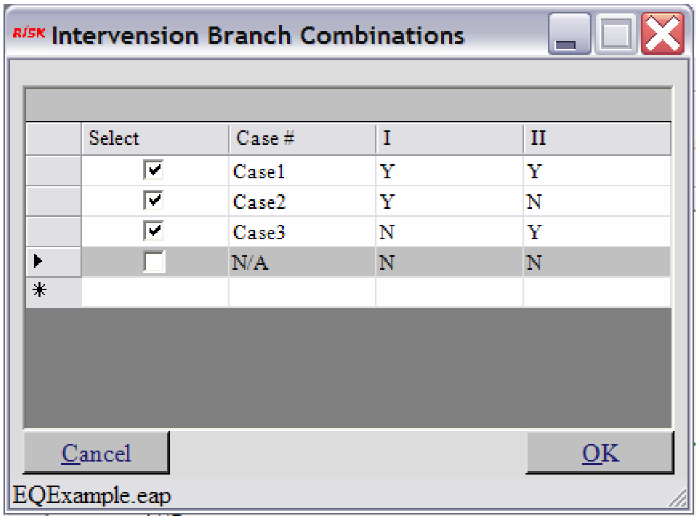


Branch State Name: I
Branch Number: 3
Branch Variable Code: I
State Variable Unit: U
User Specified Probabilities
Successful Intervension: 0.7
Unsuccessful Intervension: 0.3

Figure 47. Intervention branch input.

Intervention Branch Input

The **Input** option for an intervention branch brings the window shown in Figure 47. As mentioned above, the intervention branch is a pair of branches representing successful intervention and unsuccessful intervention. This input window has input boxes for both the branches in the pair. The user can specify a fixed probability value for



	Select	Case #	I	II
	☑	Case1	Y	Y
	☑	Case2	Y	N
	☑	Case3	N	Y
▶	☐	N/A	N	N
*				

Figure 48. Intervention branch combination window displaying different possible ‘with’ and ‘without’ intervention cases for two intervention branch pairs in the event tree.

the successful intervention branch and the unsuccessful intervention branch probability is calculated by the program as (*1- successful intervention probability*).

Event Tree Evaluation

After the completion of the event tree drawing and assigning the inputs to all the nodes on the DAMRAE interface, the next step is to calculate the event tree for estimating the failure probabilities and associated consequences. The event tree calculation is performed in two steps: (a) probability calculation, and (b) consequence calculation. The probability calculation is performed using the **Probability Calculation** option and then consequences are calculated using the **Consequence Calculation** as described under the heading of menu bar details.

If an event tree structure includes an intervention branch pair, upon selecting the **Probability Calculation** option from the menu bar, the program displays an

Intervention Branch Combination window, as shown in Figure 48. For an intervention branch pair it is typically desired to evaluate the event tree with and without the inclusion of the intervention branch pair in the event tree structure. For the ‘with intervention’ case, the actual successful intervention probability value assigned by the user is used in calculating the event tree. In case of the ‘without intervention’ case, the program uses a fixed zero probability value for the successful intervention. The program provides a flexible facility for the user to calculate the event tree either for the ‘with intervention’ case, or for the ‘without intervention’ case, or for both. In case of more than one intervention branch pairs in the event tree structure, the **Intervention Branch Combination** window shows the ‘with intervention’ and ‘without intervention’ combinations for different intervention branch pairs. In Figure 48, four rows of possible combinations for the two intervention branch pairs are shown, where ‘**Y**’ denotes the ‘with intervention’ case and ‘**N**’ denotes the ‘without intervention’ case for the respective column headings. The column headings include the branch variable codes for the intervention branches. The user is required to select the check boxes for the desired combination of different intervention branch pairs. Upon clicking the **OK** button, the program performs the probability calculations for the selected number of cases. After the probability calculation, when the **Consequence Calculation** option is selected, the program performs the consequence calculation for the same number of cases as they were selected for the probability calculation.

Output Details

The program outputs are divided into three parts: (a) probability matrices output, (b) consequence matrices output, and (c) failure probability and consequence values output. As mentioned above, the probability matrices can be viewed using either the **Probability Tables** option under the **Calculation** menu or the icon **G** shown in Figure 27. The probability matrices output includes the 'Pedigree', 'Branch Code', 'Probability' and 'State Value' matrices. The consequence matrices output can be accessed using either the **Consequence Table** option under the **Calculation** menu or the icon **I**, shown in Figure 27. This output includes the economic and life-loss consequence values for each consequence centers in two separate tables. These tables have different columns based on the number of consequence centers and each column shows the respective consequence value for all the pedigree rows. The last column in the economic consequence table shows the total annualized incremental economic consequence values for all the rows and the last column in the life-loss table shows the total annualized incremental life-loss values for all the rows. The failure probability and consequence value outputs are accessed using the output window, shown in Figure 36. This output window lists the name of all the failure modes. The probability of occurrence of the selected failure modes and the annualized consequence values associated with that failure mode can be printed in the text boxes. The output window also shows the plot for the cumulative probability of occurrence of the selected failure mode vs. the pedigree row index.

Post-processing Details

The post-processing step can be initiated by using the **Append Project** option under the **Post Process** menu bar tab, shown in Figure 26. Upon selecting this option, the program opens a separate **Project Summary** window, shown in Figure 49. This new window contains the **Post Process** option in the menu bar. For appending an already-calculated event tree project into the post-processing step, the user is required to select the **Append Project** sub-menu option under the **Post Process** menu bar option. This option brings up the window shown in Figure 50. Using the browse folder icon, the user can point to the location of the desired event tree project. After including the name of the desired event tree project in the project file input box, the **OK** button must be clicked to display the window, shown in Figure 51, which displays all the failure modes present in the selected event tree project. These failure modes are displayed under the heading of the **Calculated Failure Modes**. Using the four arrow buttons available in this window, the user can include or exclude selected failure modes in the summary table. The selected failure modes and their probability and associated consequences values are then displayed in the bottom data grid of the **Project Summary** window.

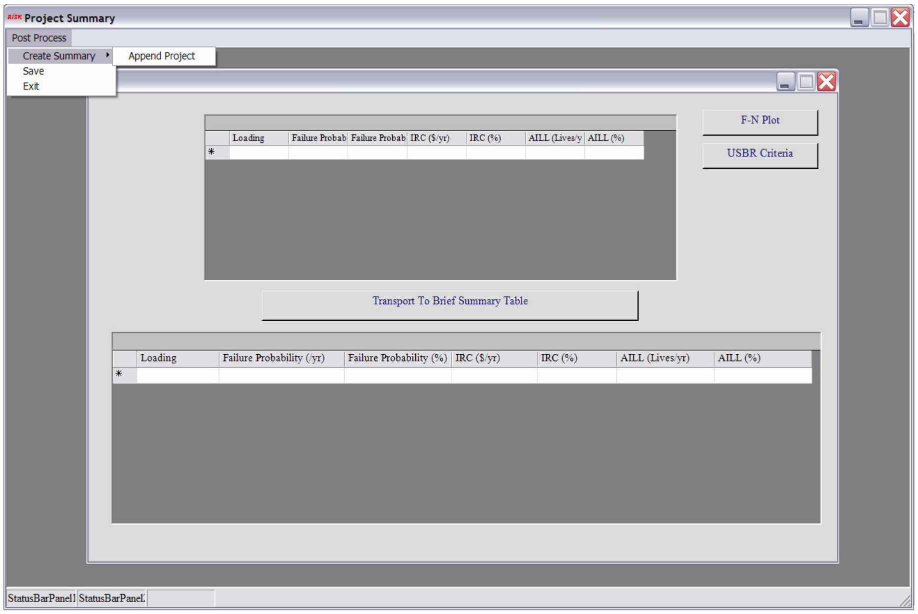


Figure 49. Project summary window used in the post-processing step.

To create a brief summary table by combining the probabilities and associated consequences for some different failure modes, the user can select the desired rows in the bottom data grid by using the <*ctrl* + *click*> and then using the **Transport To Brief Summary Table** button available in the center of the **Project Summary** window. Upon clicking the **Transport To Brief Summary Table** button, the user is required to assign a name for each group of combined failure modes.

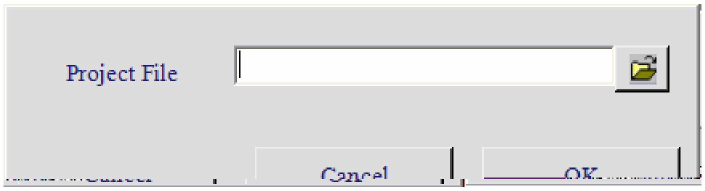


Figure 50. Event tree project file input window.

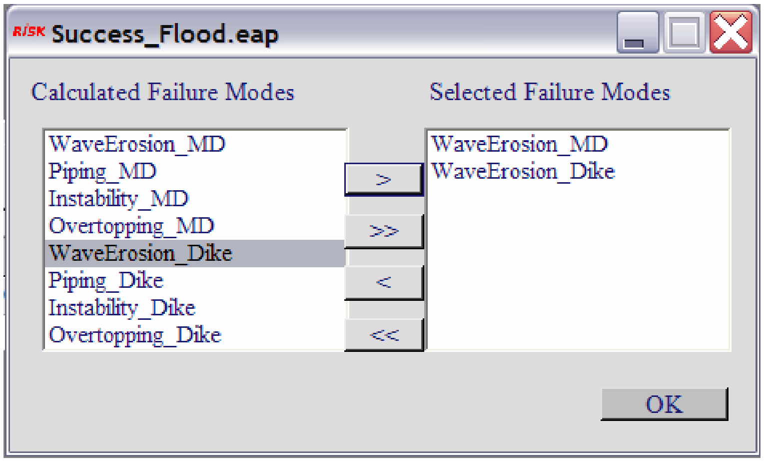


Figure 51. Append project sub-window displaying the failure modes of a selected event tree project.

To include more than one event tree projects in the same summary table, the user is required to repeat all the steps described above from the beginning.

After creating the brief summary table, the user can use the **F-N plot** and **USBR Criteria** buttons to plot the ANCOLD F-N plot and USBR Portrayal of Risks plot for the selected event tree projects.