Q.76 - R.

ICOLD

20th Congress
Beijing, China

U.S. BUREAU OF RECLAMATION'S USE OF RISK ANALYSIS AND RISK ASSESSMENT IN DAM SAFETY DECISION MAKING (*)

John M. CYGANIEWICZ, P.E.
Senior Geotechnical Engineering Specialist

John D. SMART, P.E.
Dam Safety Officer

U.S. Bureau of Reclamation

USA

1. INTRODUCTION

The Bureau of Reclamation is responsible for over 350 storage dams that have been built over the last nearly 100 years. These dams form a significant part of the water resources infrastructure of the western United States. As the owner of these dams, Reclamation is committed to providing the public and the environment with adequate protection from the risks which are inherent in collecting and storing large volumes of water for later distribution and/or release. Since much of Reclamation's dam inventory was neither designed nor built to current industry practices for new construction combined with changes in the risk environment, Reclamation is faced with a continuous sequence of decisions concerning the continued operation of these facilities.

In making these decisions, Reclamation strives to provide its decision makers with information which is pertinent and is founded upon current or emerging water resources management and public safety practices. One key aspect of water resources decision making is that the process always requires the evaluation of multiple objectives such as public safety, national economic development benefits which can be derived from additional capital investment, resource protection, and consideration

---

* ***Insert French Translation of Title here***

of social concerns. To categorize and evaluate the information with regard to the multiple objectives, Reclamation is making use of risk analysis techniques in the Dam Safety decision making process [1].

For purpose of discussion, risk analysis and risk assessment are viewed as distinct parts of the process. Risk analysis is where loading conditions, failure modes, and consequences are presented in a

$$Risk = \begin{bmatrix} Probability \\ of \\ Load \end{bmatrix} x \begin{bmatrix} Probability \\ of\ Adverse \\ Response \\ Given \\ Load \end{bmatrix} x\ Consequences\ Given\ Response$$

consistent manner in a probabilistic framework. The basic risk equation used is:
Risk analysis communicates these aspects of risk in quantitative terms amenable to the risk assessment process.

It is in the risk assessment process where risk analysis results are blended with other important factors to reach a final decision as to an appropriate coarse of action to take on any particular dam. These other factors will typically include operational, economic, public involvement, water use, and legal requirements. Reclamation has developed guidelines which it uses to assess the criticality of the risk imposed by the structure. The risk assessment process and risk guidelines are described by others [2].

The remainder of this paper will discuss the risk analysis process being developed and used by Reclamation.

2. RISK ANALYSIS BENEFITS

Risk analysis has many benefits including the following:

Communicating Risk - A primary purpose of the risk analysis is to communicate risk, both to the decision maker and within the study team itself. Whereas a deterministic dam safety analysis may identify potential dam safety deficiencies, communicating the associated risks enhances information content by expressing judgments about the relative severity and amount of consequences. Quantified risk analysis results provide a common basis for comparison of risks that result from a variety of threats to the structures, both for a given dam and among different dams.

Improved Understanding of Dam Behavior - The safety of a dam can most effectively be improved if its design, construction, and behavior are thoroughly understood. Therefore, another primary purpose of risk analysis is to enhance this understanding by more explicitly identifying the features and conditions of the dam that contribute to its vulnerability or robustness.

Identifying Information Needs - A further purpose of risk analyses is to provide a road map for guiding any additional dam safety investigations. Logically, those failure modes that produce the largest risk contributions should receive greatest attention. The analysis also points to areas of greatest uncertainty in risk. If these uncertainties are critical to decision making, ways to reduce the uncertainty are explored. Conversely, further investigations may provide fewer benefits for those failure modes shown to contribute little to total estimated risk.

Formulating Corrective Action Alternatives - When it is necessary to develop alternatives for reducing risk at a particular structure, the information developed in the course of preparing a risk analysis will aid in formulating alternatives which effectively mitigate the risks identified. By understanding the goal of risk reduction, the nature of the risks involved, and the operational needs of the project, a group of effective alternatives can be developed and evaluated. During the study of the risk reduction, the study can also lead to information on the risk posed by the potential construction activities. When risk reduction becomes an evaluation criterion along with cost optimization and any other appropriate objectives, the resulting evaluation criteria provide an effective framework for developing alternatives.

Allocating Resources - Reclamation's available resources for studying dam safety issues are finite. Limitations may include availability of key personnel, equipment, funding, and/or time. In each of these cases, choices must be made concerning the priorities for addressing the various risks at Reclamation facilities. A relative ranking of risk between dams helps make these choices.

With a large number of dams categorized as high hazard structures, Reclamation is constantly analyzing load, response, and consequence data for its inventory of dams. While the analysis may not be a detailed one, it provides a general indication of which dams contribute the greatest risks to the public, and therefore, require additional investigation to better quantify the risks and support decisions of whether or not to make dam safety related modifications to reduce risk at a dam. The challenge is to identify or prioritize dams with a variety of information available to ensure those representing the greatest risk are receiving priority funding either in evaluation or in risk reduction. Prioritization of issues can occur for a given dam or for a group of dams.

3. CATEGORIES AND TYPES OF RISK ANALYSIS

There are two basic categories of risk analyses that Reclamation uses for it's Dam Safety Risk Management process. The first is a baseline risk analysis that determines the risk represented by the existing structure as it now stands under current operating conditions and monitoring. If there is a decision made that the baseline risk is or may be unacceptable, then a second category of risk analysis is employed. This second category is a risk reduction analysis that determines the potential risk reduction from the baseline condition for various risk reduction alternatives that might be applicable at the site.

The different types of risk analyses for each category are described below.

Baseline Risk Analysis. **-** The purpose of a baseline risk analysis is to determine the risk posed by the existing structure as it now stands and is now operated. The estimate of existing risk is used to determine if the risk at the site is unacceptable; if there is a need for additional data gathering or studies to better define risk; or to form the basis from which risk reduction alternative can be compared. There are three types of baseline risk analyses:

- Portfolio Risk Analysis: A technical ranking system has been in use for more than a decade to prioritize dams for dam safety funding. That system, however, portrayed the risk by weighting hydrology, seismic, and static performance with only a small, additive influence for potential consequences. Therefore, Reclamation has developed a parallel risk-based profiling system that is based on the basic risk equation given above. Points are assigned to the dam under static, hydrologic, seismic, and operation & maintenance categories. Dams with more points represent a higher potential for failure. These points are then multiplied by a factor that estimates the population at risk below the dam as adjusted for such things as probable rate of breach development, warning likely to be provided to the downstream population, emergency preparedness of the downstream population, reservoir evacuation potential, and expected flooding intensity. A risk index is then determined from this multiplication. A'socio-economic' index, based on the non-adjusted population at risk, is formulated to aid decision makers in impacts other than life loss. The indices allow ranking of a large number of dams on the basis of risk related factors with relatively low analysis effort. Ranking a dam requires less than a day.

- Comprehensive Facility Review: Every 6 years a team within Reclamation conducts a comprehensive review that examines the past performance of each dam, changes in the state-of-the-practice of dam design, and potential upcoming issues associated with the dam. As part of the process, senior engineers prepare a report of findings including an estimation of the risk posed by the existing structure. The results are generally reported in terms of Reclamation's risk guidelines [2] and, while typically less refined than the project team analysis described below, the report of findings still establishes a baseline risk analysis of the structure. If a project team risk analysis exists (see below), then the senior engineer will review that analysis and determine if changes have occurred since the time the analysis was made that would change the risk estimates. The risk analysis includes a definition of loading conditions, failure modes, and consequences for all load classes (static, hydrologic, and seismic). Structural failure modes are identified to improve understanding of the dam's behavior, however, response probabilities and associated uncertainties are typically only considered in a global sense and detailed event trees are usually not prepared. These estimates are based on the experience of the engineer and on the data which are readily available. The results of this risk analysis are used by program managers to prioritize future dam safety work.

All the information on the dam that exists at the time the facility review is prepared is used as input to the risk analysis including information gained from a site inspection. Hydrologic and seismic hazard studies are also prepared for the review and are used by the senior engineer when performing the risk analysis for the structure.

- Project Team Risk Analysis: This level of risk analysis is the most detailed of the baseline risk analyses. A team is asked to determine the existing risk by considering previous risk analyses, additional data that may have been obtained since any previous risk analysis were performed and to consider additional expertise while estimating risk.

  The team estimates risk in accordance with Reclamation's methodology [3] and results are presented in terms of Reclamations risk guidelines. Uncertainties are portrayed in the results as ranges in risk estimates.

  This level of risk analysis typically involves developing event trees describing failure modes, estimating structural response probabilities, load probabilities, and consequences. At this stage, the appropriate technical staff becomes involved in the process by sharing their knowledge of the dam and how it will respond to various loads as well as participating in estimating response probabilities. Areas of uncertainty may be identified for consideration by the decision makers during their assessment of the risk. The team may identify data needs where data collection would be expected to significantly improve risk estimates at an economical cost in terms of time and money.

Over time, there may be multiple project team risk analyses commissioned to continue to refine the baseline risk as more data is collected, different site information is obtained, other expertise is brought in, or as modifications are made to the structure. The goal is to progress to a level of understanding of the baseline risk that is adequate for the decision makers to assess the appropriate response to take for the structure.

<u>Risk Reduction Analysis.</u> **-** A risk reduction analysis is an analysis that examines alternatives and their impacts on the baseline risk. This category of analysis is begun once the baseline risk is or may be deemed unacceptable.

- Alternative Identification Analysis - At this level of analysis, the goal is to determine what alternatives would potentially reduce the risk to acceptable levels so that further design concepts and cost estimates can be developed. While a team approach is typically used, the team is small and the process at first is not very rigarous. The team would examine the baseline risk for the components that contribute the highest risk and brainstorm alternatives that would have a good chance of economically reducing risk to acceptable levels. Alternatives could be both structural and non-structural and consider all the components of the risk. The risk reduction may not be actually quantified but, at a minimum, the key risk reduction components are reported.

- Alternative Evaluation Analysis - At this level of analysis the goal is to examine well defined risk reduction alternatives in more detail. The team uses all previous analyses and information to estimate the potential risk reduction of the alternatives. If alternatives include structural modifications, a certain level of design detail is typically needed to make the estimates so that the strengths and weaknesses of the proposed modifications can be studied. Previously developed event trees can be revised to study and quantify the effects of the alternatives on the components of risk. In addition, this type of analysis can be used to identify risks posed by the potential construction activities.

4. PROJECT TEAM BASELINE RISK ANALYSIS

While the risk-based profiling system and a comprehensive facility review level of risk analysis are useful for prioritization purposes, the project team analyzes of baseline risk is the most instructive as to Reclamation's methodology [3] for risk analysis. Therefore this process will be summarized.

The process begins by establishing a team to perform the analysis. Typically included on the project teams are personnel from the Reclamation's Technical Service Center in Denver, Colorado, who bring an understanding of the designs employed during original design, information on the construction techniques used in building the dam, and information on the performance of the dam as determined from any instrumentation at the dam. Also included on the team are personnel from the Area and Regional Offices who bring detailed information on the operation and performance of the structure. A senior dam engineer knowledgeable in the risk analysis methodology facilitates the team analysis.

Prior to the actual meeting, background information is assembled concerning the dam to be studied. Pertinent design memoranda, construction records, monitoring information, and other dam safety records specific to each team members area of expertise are reviewed. Information on the probabilistic loading for seismic and hydrologic events along with potential consequences from the events are also prepared in advance for use by the team.

At the start of the meeting, the objectives of the team meeting are reviewed. Assignments are made for preparation of the final report, calculation of risk estimates by using computer software, and peer review.

The team then reviews the dam and its appurtenant structures to gain an understand of the physical features and operational aspects of the dam. An overview of all failure modes to be analyzed by the team is provided to describe the scope of the study to be performed and to screen out failure modes that are judged to be trivial. A potential failure mode is an existing inadequacy or defect originating from a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.

Following this, event trees are prepared. Event trees are used to represent sequences or progressions of events that could result in adverse consequences when a dam or associated structure responds to various loading conditions. Event trees are constructed in accordance with the basic risk equation given above and the following discussions are organized accordingly.

5. PREPARING EVENT TREES

By providing a graphical representation of the logic structure for the progression of each failure mode, an event tree becomes the template for subsequent assignment of event probabilities and calculation of risk. The event tree is also a tool for evaluating changes in risk given certain actions and assumptions. In addition, it is a means for identifying where the greatest potential risks are. Perhaps most importantly, it fosters common knowledge and understanding of failure modes, and synergetic discussion of various issues associated with failure modes. An event tree consists of a series of linked nodes and branches. Each node represents an uncertain event or condition. Each branch represents one possible outcome of the event or one possible state that a condition may assume. Together, all of the branches emanating from a node should represent the mutually exclusive and collectively exhaustive set of possible outcomes or states.

The potential failure modes should be identified and each event in the progression of the event tree should be explicitly and unambiguously documented (such that all team members have a common understanding of the potential failure modes) for later use in the structural response probability estimation phase. Considerable effort should be devoted to determining atypical failure modes that might be unique to the dam in question.

Case histories provide additional insight for identifying failure modes and for breaking down the modes into sequences of events, a process sometimes called failure mode decomposition. Failure and incident information provided in case history reports describe the progression and sequence of the events that have occurred for other dams. This information provides the means for conceptualizing and specifying the occurrences, conditions, and failure interventions that could be pertinent to the dam under consideration. For many dam types and applicable failure modes, there is often one or more especially well-documented failure or incident that chart the progression of events in some detail. Incidents that have progressed nearly to failure but have stopped for some reason provide information that is as valuable as information regarding complete failures.

The size and complexity of the event tree depend on what is known about the dam and its expected behavior under different loading conditions, on the complexity of the failure modes considered, on the number of load ranges needed, and on the purpose of the risk analysis. Too little detail in the event tree can reduce the ability to target specific risk contributors and can create problems in making reasonable structural response probability estimates. Too much detail, and the event tree becomes unmanageable or incomprehensible to a degree that important insights are lost. Techniques for achieving an appropriate level of detail in the event trees include the following:

- Truncate non-failure branch pathways as early as possible - There is no need to propagate event sequences once it becomes apparent that they cannot lead to an uncontrolled reservoir release. The reasons for truncating an event sequence is an important part of the risk analysis documentation.

- Construct separate event trees for each load type, and sometimes, for each load increment - These trees will often be similar or identical, but constructing them separately and sequentially better organizes the process.

- Use a staged approach - As with any other engineering analysis, it is unreasonable to expect that everything can be fully captured in an event tree on the first pass through the problem. A comparatively simple initial effort can identify the key elements in the tree that need to be expanded and less important parts that can be eliminated in subsequent iterations.

- Limit the number of load increments for initiator events - Bounds for load increments should be chosen specifically to bracket load ranges where it is expected that the structural response or the consequences of dam failure will be fundamentally different from the structure's response or the dam failure consequences in other load ranges. Sometimes load ranges are selected to represent information available from related analyses. Dividing the full range of possible loading values into a few increments is usually sufficient for most problems. While any number of increments can be used, there must be sufficient reason to suspect that considering different load increments will lead to different structural responses or to some fundamental change in the adverse consequences.

6. LOAD RANGES AND INCREMENTS

The flood or earthquake initiator events can assume any value over very wide limits. It is necessary to confine these limits to a sensible range of values that can affect the structural response or consequences in a significant way. The number of increments and how they are defined have important implications on design of the event tree that affect its size and the ease with which subsequent structural response probabilities can be estimated. Two threshold load levels are naturally suggested: a threshold below which no structural damage or adverse consequences are expected, and a threshold above which structural failure is almost certain to happen. Between these thresholds, there is a load range where structural damage or adverse consequences is possible to varying degrees. Within this range, other threshold load levels can be identified where significant changes in structural response or possible adverse consequences take place.

Often, the maximum load already experienced by the dam may be selected as the threshold below which no structural damage or adverse consequences are expected. The dam has survived this load, and one can usually assume that the dam will survive a repeat of this load, unless there is some progressive degradation mechanism at work. Parametric studies conducted as part of a previous dam safety analysis can also provide insight regarding this lower bound.

The lowest load range is very important due to its relatively high occurrence probability. This load range should establish the load range for which the dam is expected to perform without failure. Typically, this load range is called the “threshold” range for initiation of failure. Participants must be careful to assess the failure threshold value realistically. A conservative threshold estimate which underestimates the load level at which failure can occur will significantly increase the perceived risk at the dam.

Examples of these approaches to developing load ranges are:

Hydrologic Loading - Using the flood of record to establish the threshold of adequate spillway performance. The spillway either passed or did not successfully pass the flood of record.

Seismic Loading - A comparison of available liquefaction susceptibility studies to potential earthquake induced peak horizontal accelerations at a damsite can be used to set the reasonable lower bound of earthquake shaking that a structure can withstand without failure of the structure.

Static (normal) Loading - There may be a geologic feature located at an elevation within a reservoir storage area where inundation by water begins development of potentially adverse seepage conditions. Below the elevation of this geologic feature, dam performance related to seepage is adequate. The time period the reservoir water surface is below the elevation of the geologic feature would be one bound on the static loading.

7. ESTIMATING LOAD PROBABILITIES

The three categories of loading typically required in risk analysis are static, flood, and earthquake. Each of these loading categories is briefly described in the following paragraphs.

Static Loads. - The static loading condition encompasses a wide variety of specific loading conditions to which a dam is routinely exposed during the course of normal operation. These loads can include hydrostatic loads imposed by the reservoir, static and dynamic loads imposed by operating various components of the dam and its appurtenant structures, loads induced by landslides at the dam or on the reservoir rim, or by the hydraulic phenomena such as seepage, erosion, and cavitation associated with water passing through and around the dam.

Most static loading conditions are related to the reservoir level either in terms of the magnitude of the load, time of exposure to the load, or the potential for adverse consequences. Therefore, historical reservoir elevation records are an important information source for assessing the likelihood of failure modes associated with static loading conditions. When evaluating the historical reservoir information, it is important to consider the data in a fashion which is consistent with the failure mode being developed. In the case of gates, the exposure is directly related to exposure time above a given reservoir water surface elevation. In the case of piping, the exposure may be more related to whether or not the reservoir has reached a specific level at some previous time. In each case, the historical data must be organized in a fashion which yields meaningful information for the anticipated potential failure mode.

Flood Loads. - The development of flood frequency relationships and reservoir inflow hydrographs are important inputs to the risk analysis process. For risk analysis, the focus of flood evaluations shifts from a single maximum event, like the probable maximum flood, to describing a range of plausible inflow flood events. The products developed for a particular risk analysis depend on the level of study and the information available.

Traditional sources of information used in flood frequency analysis and flood hydrograph development include gauged streamflow records, indirect discharge measurements, and precipitation records. Generally these data sources have records that are less than 100 years in length. The framework for developing hydrologic inputs to risk assessments uses the length of record to determine the extrapolation limits used in the flood frequency analysis. Since risk assessments require estimation of floods with return periods in the 10,000- to 100,000-year range and beyond, emphasis is put on developing flood frequency relationships with regional hydrometeorological data and paleoflood information. The uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute for the characterization of hydrologic inputs.

No single approach is capable of providing the needed characterization of hydrologic inputs over the full range of exceedance probabilities required for risk assessment. Therefore, results from a number of approaches need to be combined to yield a composite flood risk description; this means several methods and sources of data are needed. The application of several independent methods applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.

Seismic Loads. - For utilization within a risk-based framework, seismic hazard evaluation must explicitly contain information on the frequency of occurrence of relevant loading parameters. The currently accepted practice within Reclamation for evaluating and conveying seismic hazard information in this fashion is probabilistic seismic hazard assessment. The first step in any seismic hazard evaluation is source characterization. For use in risk analyses, both fault and areal (background or random) sources should be incorporated into the hazard evaluation. Uncertainty is incorporated in source characterization by allowing for alternative source and recurrence models as well as uncertainty in recurrence parameters. For fault sources, uncertainty in source dimensions, sense of slip, and orientation and hence maximum magnitude should be incorporated for detailed studies. Definition of earthquake recurrence for both areal and fault sources should incorporate some estimate of the uncertainty in seismicity rate and the assumed magnitude/recurrence relationship. The ultimate goal is specification of ground motions and their recurrence. For use in risk analysis, ground motion estimation should incorporate uncertainties in source-site distance, selection of attenuation relationships, and observed variability in ground motions in the final product.

This approach integrates contributions over the entire spectrum of magnitude and distance from each defined source and then sums contributions from each source to develop a distribution of ground motion level for each annual frequency of exceedence. The most frequently used seismic hazard product is a simple hazard curve that relates a ground motion parameter to annual probability of exceedence. This curve contains contributions from all sources, magnitudes, and distances.

For use in liquefaction evaluations, consideration of ground motions organized by magnitude levels is often quite useful. Risk contributions from the various magnitude levels are then summed. This allows for integration with commonly used geotechnical parameters such as magnitude adjustment factor when evaluating liquefaction likelihood. Likewise, acceleration spectrum intensities is commonly used as input for the structural analysis of concrete dams, spillways, and outlet works intake towers when subjected to seismic loads. This information can then be used to estimate the probabilities of the various responses of the dam or appurtenant structures to the seismic loading conditions being evaluated.

8. ESTIMATING STRUCTURAL RESPONSE PROBABILITIES

Estimating structural response probabilities is generally the most difficult and time-consuming activity faced by a risk analysis team. Summarized below is a process for making structural response probability estimates that has been found to work well for various risk analyses. All steps described below are performed jointly by all the participants of the risk analysis team.

Step 1. - The first step is to be sure each team member has a clear understanding of each node of the event tree. An event tree node represents a choice at which the preceding event must be considered to have happened and two or more subsequent events could take place. This is best done by having the facilitator write out the description of the node. An open discussion usually takes place during this step where team members freely discuss their understandings of the event node and the wording being proposed. The facilitator should then capture the thoughts of the team into the description of the node. For instance, a node description for unfiltered seepage exit might be:

> "The soil particles that are being carried by seepage flow must exit from the dam at a location where there is no filter present to trap the soil. A filter is defined as a soil that reasonably meets the design standard for filters."

Step 2. - The team then brainstorms any and all information that is pertinent to the event node being discussed. Each piece of information is listed on the flip chart as either a factor leading to a higher probability or a factors leading to a lower probability depending on whether the information is can be used as evidence to support or oppose belief in the event. The listing is visually placed immediately below the node description. The team should agree that the factors are being placed in the correct category. Disagreements are usually solved by using clear wording that describes the information or by adding an opposing view in the opposite category. The purpose of this step in the process is to display all the information that will be used in making the estimate for all team members to see, discuss, and eventually use in making their estimates. As described below in step 3, the team members may judge for themselves the importance of the information being listed as they make their estimates.

Nearly any type of information is permissible to be listed if it helps the team members make their estimates. For instance, "gradation limits in construction specification meet filter criteria" might be listed as a factor leading to a lower probability unfiltered exit description discussed above in step 1. Others might be "93 out of 95 gradation tests of as-constructed earthfill showed acceptable limits were achieved" [factors leading to a lower probability]; "2 out of 95 gradation tests of as-constructed earthfill failed the limits and were left in place" [factors leading to a higher probability]; "the specified gradation is likely to segregate during placement" [factors leading to a higher probability].

Step 3. - Once a clear understanding of what the node of the event tree represents has been established (step 1), and all relevant issues by team members related to that node have been aired and summarized (step 2), then a probability estimate may be made for the node of interest.

Reclamation employs its own unique process of expert elicitation for estimating event probabilities when there is no statistical information to use as a basis for assigning probabilities In using this process, the facilitator obtains a "reasonable high" and "reasonable low" probability estimates for each event node. Event nodes are estimated by using a list of verbal-to-numeric transformations to help experts assign a numeric value based on their verbal assessment of the information being presented. The use of such a table provides consistency to the estimation process and can help alleviate the reluctance of the experts in assigning a numerical estimate.

For example, the team members can use the qualitative and quantitative information that was generated during step 2 to judge if the event tree node designated unfiltered exits is more likely or unlikely relative to the verbal descriptors. The transformations used are as follows:

VERBAL DESCRIPTORS
VERBAL-TO-NUMERIC TRANSFORMATIONS

Descriptor	Probability
Virtually Certain	0.999
Extremely Likely	0.995
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Extremely Unlikely	0.005
Virtually Impossible	<0.001

Step 4. - The risk analysis participants then identify the factors from step 2 that had the greatest effect on the probability estimate generated in step 3. Returning to the information containing the factors pertinent to the event, the team should identify for the record those items which were most important in arriving at the probability estimates. In addition, the team indicates why it believes the most significant factors should receive more weight than others.

Step 5. - The facilitator ensures the risk analysis participants have reached consensus on the probability and uncertainty estimates. This does not mean that the facilitator must force all members to accept a single estimate. Rather, the facilitator must sense the team's feeling as discussion takes place, suggest a reasonable starting place as a best estimate, and canvass the team's validation of the estimate.

If the team cannot agree on an estimate, the divergent opinions must be accounted for in the analysis. At this point, the facilitator focuses more on getting agreement on the possible range of the estimates. The facilitator leads the discussion of the opposing views to identify the underlying premises or key evidence supporting each argument. This is a very fruitful area to obtain ideas that would suggest further exploration or analysis to resolve the differences.

If the team cannot agree that a range or distribution will adequately characterize their judgement, then the analysis is conducted using each representative estimate in separate calculations. The separate calculations for risk would then be reported along with the descriptions of the conflicting ways the team members saw the problem.

Step 6. - Once consensus is reached on the specific response probability estimate and uncertainty, the process continues by repeating steps 1 through 5 for each remaining node of the event tree.

When steps 1 through 6 have been completed for all the event nodes, the risk analysis process continues by considering and quantifying what adverse consequences may result from the failure modes.

9. ESTIMATING CONSEQUENCES

Potential consequences resulting from an uncontrolled release of a reservoir have several different dimensions. In addition to the economic losses related to lost project benefits and potential damage to property in the inundated area, there is the potential for life loss, alteration of the habitat and environment, social impacts on the local community, and loss of confidence in the dam owner and operators. Since these consequences may not be directly commensurable, the weights given to each for decision making are generally made separately from the technical analysis. The process of weighing different values in decision making is part of the risk assessment, as opposed to risk analysis. However, certain technical data is required by the decision makers to understand the magnitudes of the various dimensions of the consequences.

Potential loss of life is the single consequence considered in all Reclamation project team risk analyses performed to date. In estimating potential loss of life, complex factors such as inundation areas, warning time, time for dam breach, flood wave travel time, and emergency response preparedness are all considered. Case histories of past events are also studied for information on possible fatality rates of the population at risk. This information is typically provided to the project team that is analyzing the risk by in-house staff knowledgeable in the area. However, the team may also consider adjustments to the life loss estimates based on their particular knowledge of conditions either at the site or downstream.

10. RESULTS OF RISK ANALYSES

Risk is computed by finding the product of probabilities and consequences for each path in the event tree. By summing the values from all paths, the total risk can be determined. Spreadsheets and decision analysis software provide for rapid reduction of the vast quantity of numbers generated during a risk analysis. Monte Carlo simulations may be performed to combine the variations in estimates and to portray the range in final results.

At the end of the meeting, results are reviewed by the team to determine if the quantitative values given are representative of the overall sense of the teams judgement of risk. The results are compared to other estimation methods, such as those for the failure rates of embankment dams by piping [4] and adjusted accordingly.

When the results appear reasonable to the team members, it is frequently beneficial for the team to develop a summary of their findings. Six questions have been developed as a means of addressing key areas of summary. The questions are:

- Which failure modes contribute the greatest risk?
- What uncertainties enter into the estimates of risk?

- What information could be generated to reduce the uncertainty?
- What outcomes could reasonably be expected to result from collecting the information?
- How would the risk be affected by each of these outcomes?
- What are reasonable options/courses of action?

After the team meeting, a report is prepared and edited by the team. The report is provided as input to decision makers.

11. COMPLETION OF RISK ANALYSES

Reclamations methodology for analyzing risk includes a profiling system, a risk analysis performed by a single senior engineer as part of an internal facility review process, and a team based approach. Risk analyses performed by the risk-based profiling system take an average of about 5 hours to complete. Senior engineers can take on the order of 1-2 days to complete the risk portions of a comprehensive facility review. Project teams can take one or more weeks to complete a risk analysis by the project team risk analysis method.

Nearly all of Reclamation's major decisions made in recent years concerning dam safety have had risk analysis input. At the time of publication of this paper, most of Reclamation's dams will have been profiled with the risk-based profiling system. About one half of its inventory of dams will have had a baseline risk analysis associated with the comprehensive facility reviews. Reclamation will be performing project team risk analyses at a rate of about 20 analyses per year.

12. ADDITIONAL GUIDANCE DOCUMENTS

Reclamation is preparing a series of appendices to its methodology to guide teams in their analysis of risk. Approximately twenty separate appendices are envisioned. While description of each appendix is beyond the scope of this paper, some of the key ones are briefly described in the following:

<u>Seepage and Piping of Embankment Dams</u> - This appendix will discuss the main components to be considered when analyzing the risk posed to the structure from seepage and piping concerns. It will suggest uses for existing studies on the historical performance of dams and will provide a method for sorting through the many available case histories to provide site specific ones for consideration.

<u>Seismic Response of Embankment and Concrete Dams</u> - These appendices will provide information on the factors to be considered when analyzing the risk posed to the structure from seismic events. Effects from liquefaction and embankment cracking will be considered.

<u>Determining Loading Conditions for Hydrologic and Seismic Events</u> - These appendices will provide information on the development and use of loading information in the event trees.

Estimating Loss of Life Consequences - This appendix will discuss the many factors to be considered when estimating life loss. Such factors include detection of the event, decision processes, notification processes, and dam breach processes. Suggestions for fatality rates will be provided to estimate life loss from the population at risk.

Other appendices that will be prepared will be on such topics as operational failures, breach parameters, portraying uncertainty, and detection systems.

13. SUMMARY

Reclamation distinguishes between Risk Analysis and Risk Assessment. Risk Analysis determine the risk at a particular site in qualitative and quantitative terms. Risk Assessment is the process that blends Risk Analysis results with other factors to make a decision on the coarse of action to take at the site.

Risk analyses are undertaken to determine the baseline risk represented by the structure as it now stands and is now operated and monitored and risk reduction analyses can be undertaken to determine impacts of proposed alternatives.

Reclamation's current methodology for the project team risk analysis begins with formulation of a project team that includes experts in pertinent technical areas. Once formed, the team begins its analysis with input on load probabilities for hydrologic and seismic events along with input on possible consequences. The team then considers all the possible failure modes for the structure, eliminates the ones considered to be trivial, and moves forward to construction of event trees for those remaining. Event trees are constructed to decompose the failure modes into a logical series of events for further study by the team. Included in the event trees are a breakdown of the loading information into appropriate ranges, events to capture the important steps of the structure's response to the load, events to capture the likelihood of intervention, and finally the consequences from the potential dam failure. Consequences in terms of life loss are always considered with consideration of other types of consequences as-needed.

Once the event trees are constructed, the teams consider all pertinent information on each node of the event tree. Then a form of expert elicitation is used to estimate the likelihood of each event taking place. Once each node of the event tree has been estimated, the product of the events is taken to represent the risk of this failure mode. The analysis team then considers the result in terms of Reclamation's risk guidelines to determine if it accurately represents the team's overall perception of the issue.

Reclamation utilizes risk analysis as an integral part of its decision making process. Risk analysis assists in determining the impacts of additional data collection at the site or the value of more engineering analyses. Risk analyses determine the relative risk between different failure modes or to prioritize between different dams such that the decisions made are balanced. Finally, risk analyses are part of the communication of Reclamation's decisions to others.

REFERENCES

[1] Achterberg, D., “Bureau of Reclamtion’s Dam Safety Program,” *Nineteenth Annual USCOLD Lecture Series, Dealing with Aging Dams, Atlanta, Georgia, May 17-21, 1999,* 41 through 50.

[2] Hennig, C., Dise, K., Muller, B. (1997): “Achieving Public Protection with Dam Safety Risk Assessment Practices,” *Risk-Based Decision Making in Water Resources VIII, Proceedings of the Eighth Conference, ASCE*, Haimes, Moserand, Stakhiv, editors, 19 through 32.

[3] “Dam Safety Risk Analysis Methodology,” U.S. Bureau of Reclamation, October, 1998.

[4] Foster, M., Fell, R., and Spannagle, M. “Analysis of Embankment Dam Incidents,” University of New South Wales, UNICIV Report No. R-374, September 30, 1998.

1 U.S. BUREAU OF RECLAMATION'S USE OF RISK ANALYSIS AND RISK ASSESSMENT IN DAM SAFETY DECISION MAKING

6 **Risk Analysis**, risk assessment, risk profile, risk reduction, **event tree**, **expert elicitation**, consequences, **dam safety**, dams

7 This report discusses Reclamation's methodology in performing risk analyses for helping make dam safety decisions. Different levels are described including risk profiling, risk analysis by event tree decomposition, and risk reduction analyses. Estimating the recurrence frequencies for seismic and hydrologic loads, estimating the structural response to these loads and estimating the consequences from a potential dam failure from these failure modes are discussed. Expert elicitation is used to estimate the dam's structural response the loads.

8 Risk Analysis

9 Cyganiewicz J., Smart J. (USA)

10 U.S. Bureau of Reclamation's Use of Risk Analysis And Risk Assessment in Dam Safety Decision Making

11 ICOLD 20, Beijing 2000, Vol. , Q76, R