Achieving Public Protection with Dam Safety Risk Assessment Practices

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Abstract

In 1978, the Bureau of Reclamation implemented a dam safety program in accordance with the Safety of Dams Act of 1978. In the early years of the program, the most significant safety risks to the public were readily apparent to decision makers and were corrected. With many of the most serious dam safety deficiencies corrected, Reclamation has been challenged with identifying and prioritizing future corrective actions in a manner which will provide reasonable improvements in public protection. While Reclamation has previously used risk assessment approaches for the evaluation of potential economic losses, the agency is now implementing regular use of risk assessment to evaluate and prioritize issues involving the personal safety of the public. Two key elements of the implementation of risk assessment methods include agency guidelines for achieving public protection and measures to be employed in identifying estimated risks to the public.

The Dam Safety Challenge

The Bureau of Reclamation is responsible for the safety of 382 high and significant hazard dams in the 17 western states. Approximately 50 percent of this inventory is more than 50 years old. In addition, approximately 90 percent of the inventory was constructed before many of the current state-of-the-art design and construction practices in use today. Reclamation faces significant challenges to ensure that this aging inventory of dams can continue to safely perform beyond their original design intents, which were based on the design practices in use when these

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structures were built. Integrating risk management principles into dam safety decisions is essential to help focus resources toward those activities that achieve the most effective and efficient risk reduction.

Meeting the Dam Safety Challenge

As structures age, continued safe performance becomes a greater concern. The Bureau places great reliance on recurring and ongoing dam safety activities to detect, intervene, and effectively respond to dam safety incidents. These activities include structural performance monitoring, emergency action planning, operator training, and an aggressive examination program to help identify developing problems and issues that may require additional investigations. A blanket level of risk management, or risk reduction, is provided across the inventory by such recurring and ongoing dam safety activities.

More emphasis is being placed on methods to enhance monitoring practices by identifying site-specific failure modes and customizing monitoring to effectively observe the performance associated with each failure mode. Methods to automate the detection of significant changes in performance, such as increased seepage and changes in reservoir levels, are also being pursued where beneficial. Emergency action plans are being updated to include site-specific indicators of developing problems along with education of downstream officials and testing of the plans. The examination program consists of ongoing visual monitoring, an annual inspection, and periodic and comprehensive examinations which alternate on a three-year basis. The periodic examination is a complete condition inspection and status review conducted every three years by a specialist. These activities are repeated during the comprehensive examination with the additional participation of a senior-level dam design engineer. Additional activities during a comprehensive examination include a complete review of performance monitoring requirements and an assessment of issues that may be affected by current state-of-the-art practices.

Risk assessment practices are also being integrated into the Dam Safety Program to help understand the many uncertainties associated with the continued safe performance of existing dams and their impacts on risk. Risk assessment approaches are intended to be an additional tool that leads to improved decisions by helping to accomplish the following objectives:

- Recognizes all dams have some risk of failure
- Considers all factors contributing to risk
- Identifies the most significant factors influencing risk and uncertainty, which facilitates efficient targeting of additional data and analyses
- Identifies a full range of alternatives to manage risk, including monitoring and other non-structural methods

- Focuses funding and resources toward risk-reduction actions that achieve balanced risk between dams and between failure modes on individual dams
- Establishes stakeholder credibility and due diligence for risk-reduction actions

The Role of Risk Assessment in Dam Safety Practices

Using risk assessment approaches to assess dam safety is not a new idea. The Federal Guidelines for Dam Safety encouraged the development of risk-based approaches to dam safety. These guidelines were implemented for dams regulated by the federal government by a presidential memorandum dated October 4, 1979. Risk assessment practices were initially focused on evaluating the economics of proposed corrective actions. However, their use diminished as experience showed that most dam safety decisions are driven by concerns for the safety of the public. During the past 10 to 15 years, most dam safety deficiencies were relatively obvious. Issues such as active piping did not require extensive investigations to assess the reliability of continued safe dam performance and need for modifications. Dam safety issues today are typically becoming more complex as the continued safe performance of existing dams, especially during extreme earthquake and flood events, are more central problems. Risk assessment practices facilitate the evaluation of complicated risk factors and the influences introduced by associated uncertainties.

The Bureau of Reclamation quantifies risks to public safety based on the expected values of the consequences:

$$\text{Risk} = \text{Estimated Average Annualized Loss of Life}$$
$$= (P_{Load})\,(P_{Failure})\,(P_{Exposure})\,(\text{Consequences})$$

Where:

P_{Load} = Probability of load
$P_{Response}$ = Probability of an adverse response given the load
$P_{Exposure}$ = Probability of being exposed to adverse conditions or consequences
Consequences = Estimated loss of life for the conditions analyzed

For each load category (seismic, flood, and static), risks are evaluated under a full range of loads. An event tree is constructed around the framework of this expression to represent the various failure modes and linked events associated with the full development of each failure mode. Consequences may include economic losses, potential for loss of life, or other adverse consequences associated with uncontrolled releases from a dam.

Why should we, as dam safety professionals, want to assess dam safety in this manner? To help answer this question, let's consider the objective of dam safety. The key dam safety questions are:

- How can an existing dam fail?
- How safe is it?
- How safe is safe enough?
- How can risks be managed?

Dam safety is fundamentally different from dam design. The designer's paradigm uses design standards and safety factors to evaluate the safety of existing dams in relation to a commonly accepted level of conservatism. Traditional standards are mostly intended to establish a level of confidence that a design will result in a successful, load-tested structure, given uncertainties in the loading conditions and capacity of the structure to resist load. However, these standards fall short of providing a systematic mechanism to help evaluate and answer dam safety questions in a way that helps the agency identify reasonable corrective actions.

Extensive use of engineering judgement is required to answer these questions. Decisions based on engineering judgements have always been fundamental to dam safety assessments. This is due primarily to the many material properties and model uncertainties inherent in the investigative methods currently available to assess the performance of existing dams. Existing dams are typically plagued with uncertainties, because they often lack many state-of-the-art features. For new dams, many of these uncertainties are addressed in the design and construction stage, such as removing foundation materials subject to liquefaction, incorporating embankment zoning and filtering to control and filter seepage, and providing structure geometry that ensures linear behavior.

Risk assessment approaches provide a mechanism to quantify this judgement. Quantified judgement not only helps assess the question of how safe, but also permits the probabilities of being wrong or right to be considered in the decision-making process. Quantified judgement also provides a means to prioritize program efforts on the basis of risk between dams as well as failure modes, in order to achieve the most effective risk reduction with available resources and a more balanced approach to dam safety.

Some examples help illustrate this discussion:

> *Case 1a*: After completing traditional analyses to assess the ability of an embankment dam to withstand the maximum credible earthquake, a typical judgement-based conclusion might be that the crest of the dam is not expected to deform more than available freeboard and therefore failure is unlikely. This conclusion provides the decision makers with little information concerning our confidence in the conclusion. It also provides little or no information regarding uncertainties regarding the understanding of loading conditions, dam behavior, or the potential consequences. Combining a low probability

of failure with a potentially high load probability and high consequences may lead decision makers to believe that they are overexposed and that the chances of being wrong about the dam response are too great.

Case 1b: Another typical response to this example could also be that crest deformations are likely to exceed available freeboard and cause dam failure. A standards-based conclusion that the dam is unsafe provides the decision maker with little information concerning risk in comparison to other dams in the inventory. Reclamation typically has several dams with issues to address at any given time. An effective dam safety program should provide the information required for prioritizing the needs for corrective action on the basis of overall improvements to public safety.

Case 2: The conclusion of another analysis might be that seepage, although unfiltered, is not likely to cause piping. Such a conclusion does little to help the decision makers understand the level of risk that is being accepted. It also fails to evaluate whether or not the accepted risk is comparable to the risks associated with other potential failure modes. Merely meeting accepted design standards may not portray the importance of particular failure modes when the loads leading to these failure modes have very different probabilities of exceedance.

Traditional standards-based approaches often place substantial emphasis on maximum credible earthquake (MCE) or probable maximum flood (PMF) issues without facilitating, and often concealing, a comprehensive look at all contributing load levels and risk factors. Risk assessment approaches allow all factors that contribute to risk to be considered, which can lead to a better understanding of risk and consequently more effective risk management. Reviewing the components of the risk equation helps to establish a better appreciation for this understanding:

Loading:

Standards-based approaches typically use MCE, PMF, and normal water surface (NWS) for load evaluations. These standards do little to inform the decision maker about exposure to the highest risk events. To effectively manage risks, decisions need to be made with knowledge of the lowest level of loads and associated probabilities that can cause dam failure to initiate. These loads could be very different from the MCE, PMF, or NWS. In addition, large earthquakes and floods in some regions of the west are usually more probable than similar events in other regions. Standards-based approaches do not provide a way to assess these regional impacts on risk to facilitate effective program prioritization.

Structural Response:

Structural response probability under a full range of loads for a given load category (e.g. earthquake, flood, static) is comparable to the safety factor in a standards-based approach. Required safety factors are frequently established somewhat arbitrarily such that a design is adequately conservative. Using an assigned factor of safety criteria does not recognize different levels of data and model uncertainty from site to site and tends to assume that the influencing factors are uniformly understood. Is a 1.0 factor of safety for seismic stability adequate for each site and the range of potential uncertainties that may exist? Could failure still occur? Is the requirement for a 4.0 factor of safety for foundation stability under normal loads unreasonable for a load-tested structure? Would it be more effective to direct resources to higher-risk issues on another dam?

Exposure:

Reservoir levels that create unsafe conditions under various loading scenarios commonly may occur during certain periods each year. This is especially true for Reclamation irrigation storage facilities that typically fill during the spring but are drawn down by the end of the irrigation season. Seismic stability, flood overtopping, or other issues evaluated only under full reservoir conditions would overstate risk. Likewise, it may be common for some reservoirs to operate in flood surcharge, in which case evaluation at normal reservoir levels could understate risk for various issues and possibly even conceal certain safety concerns that arise between normal reservoir elevation and crest of the dam. In addition, exposure to consequences can have seasonal variations that may elevate or reduce risks. Standards-based dam safety assessments do not accommodate variations in risk-exposure factors in a meaningful way and do not facilitate an identification of these factors. The consideration of risk-exposure factors is a natural outcome of risk assessment approaches.

Consequences:

A few individuals at risk 20 miles downstream represents a different level of risk from that of a few individuals who reside at the toe of the dam. A large metropolitan area at the toe of the dam represents an even greater level of risk. Flood-wave travel time affects warning time and time available to evacuate the population at risk, which directly influences the number of fatalities expected during a dam failure. Standards-based dam safety assessments focus only on the structure. This not only ignores the consequence contribution to risk, it also tends to distract the analysis and decision processes from the fact that managing/minimizing adverse consequences is the essence of dam safety. Risk assessment approaches illuminate factors that keep objectives focused on methods to effectively and efficiently minimize consequences.

Traditional analysis and investigation techniques remain an essential component of dam safety assessments. When combined with risk assessment approaches, a better understanding of risks is achieved, which facilitates good decision making. Traditional techniques are essential for providing an understanding of structural behavior and the potential limitations of model uncertainties and material property variability. The traditional analysis results become a significant source for structure-response probability estimates in the framework of a risk assessment.

Public Protection Guidelines

Interim guidelines for achieving dam safety public protection (USBR 1997) have been established so that estimated risks can be measured against the justification for risk-reduction actions. "Public protection" terminology is used instead of "acceptable risk", because the program emphasis is on achieving public protection. "Acceptable risk" criteria tends to establish a mindset that no risk-reduction actions should be considered if risks are below the criteria. However, prudent program practices should thoroughly understand the nature of risks and always look for opportunities to efficiently reduce them in a cost-effective manner. "Acceptable risk" terminology also creates an attitude of callous insensitivity to public safety; it does not recognize the fact that all dams have some risk of failure no matter how well designed or constructed. Guidelines are used, in lieu of specific criteria, so that site-specific influences and conditions not easily or reliably represented in a risk assessment framework can be considered in the decision. These guidelines do allow deviations, but require an understanding of the basis for the deviation.

Figure 1 represents *Tier I Guidelines* and focuses on potential loss-of-life considerations. This figure is used to plot the estimated expected annualized loss of life for each load case, evaluated as follows:

A. Estimated Average Annual Loss of Life > .01:

Risk is typically considered elevated to the level that there is strong justification to take actions to reduce risk for continued long-term operations. In addition, risk-reduction actions should be considered during the interim until the permanent modifications can be designed and implemented. Interim actions could consist of operating under reduced reservoir levels, enhanced monitoring, enhanced emergency preparedness, and/or various structural measures that reduce estimated risks below .01.

B. Estimated Average Annual Loss of Life between .001 and .01:

Strong justification to reduce risk for continued long-term operations. There is not strong justification for interim risk reduction actions provided modifications could be implemented within approximately five years. However, easy opportunities to better manage risks during the interim should not be overlooked.

C. Estimated Average Annual Loss of Life < .001

The justification to implement risk-reduction action diminishes as estimated risks are increasingly smaller than .001. Corrective action costs and the associated amount of risk reduction that could be achieved are factors that influence decisions. Opportunity costs for

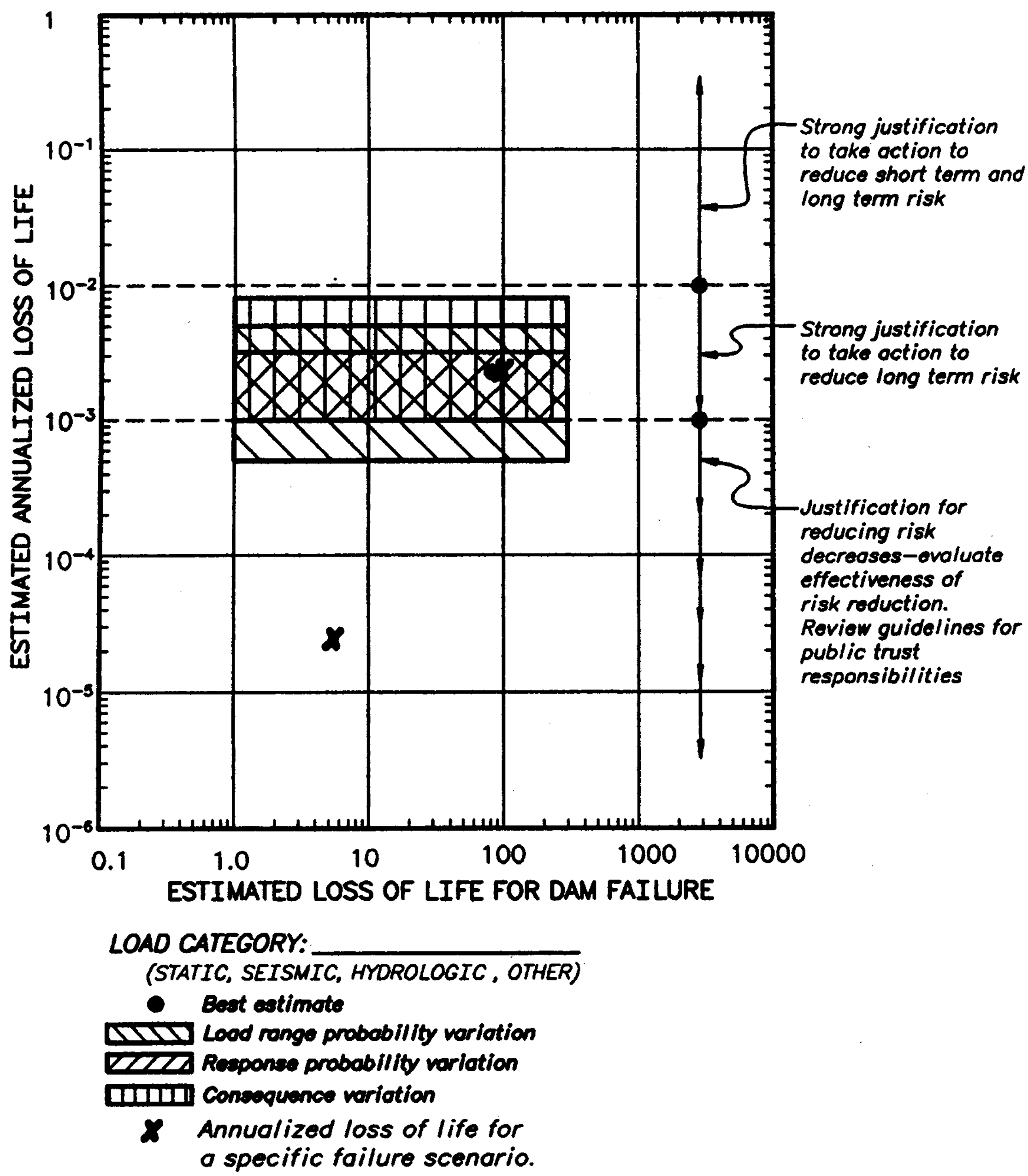

Figure 1. Tier 1 Guidelines (Loss of Life)

taking actions in this range are also considered in terms of available agency resources that would be forgone for efforts on higher-risk facilities or failure modes. In addition, other water-resource management issues begin to play a more significant role in the decision. Decisions to take no risk-reduction actions are not considered permanent. Issues and associated risks are revisited on a minimum six-year recurring basis, recognizing that risk factors and agency priorities are subject to change.

Establishing .001 as the zone of differentiation between strong and reduced justification for taking risk-reduction actions creates a sliding level of protection that is proportional to consequences. This is best illustrated by examining the risk equation in the following simplified expression:

Annual Life Loss = Annual Event Probability x Loss of Life

.001 = 1/1,000 x 1 lost life

} 10 times safer design

.001 = 1/10,000 x 10 lost lives

} 10 times safer design

.001 = 1/100,000 x 100 lost lives

This relationship shows that with greater consequences, a more remote design event is required to achieve an adequate level of public protection. This is consistent with societal values which view single events that cause high numbers of lost lives as long-remembered national tragedies. There is significant public aversion to single, high-consequence events, and the public expects a high degree of protection from such events. With low-consequence events, several other factors need to enter into the decision-making process:

1. When loss of life is low, a small population can be exposed to events having relatively high probabilities. Risks become similar to other societal risks such as auto accidents and disease. However, introducing dam-failure risks could significantly contribute to the overall life risks to these individuals.

2. The greater the inventory of dams and the time of exposure, the more likely it becomes that the agency will experience a dam failure as shown in Figure 2. For example, assuming a binomial distribution and allowing 10 dams within the Reclamation inventory of 382 dams to have an average annual failure probability of 1/1,000 yields a 40 percent chance of failure within the next 50 years from just these 10 dams. For 50 dams, the chance of experiencing a dam failure increases to greater than 90 percent. Once a dam failure occurs, public trust is compromised and the public will expect more severe and potentially

more costly protection. In addition, a high level of national safety and stewardship of public assets is expected of an agency entrusted to manage a large inventory of dams.

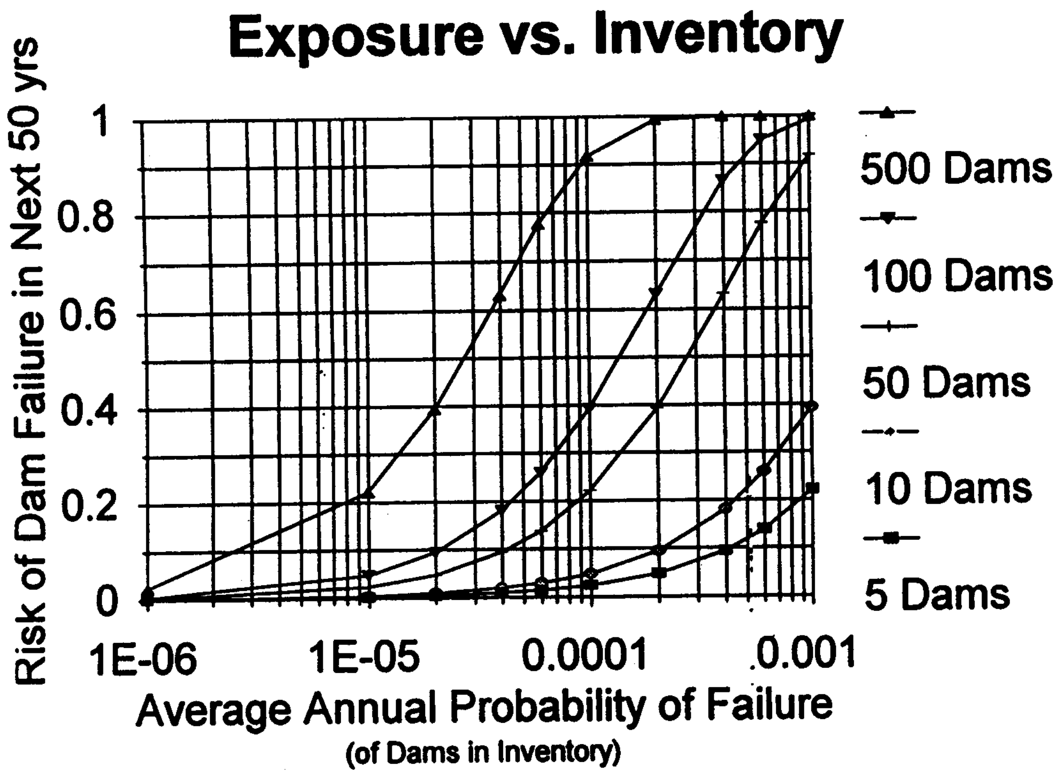

Figure 2. Risk Exposure at Multiple Dams

3. The estimated expected average annual loss of life is based on the overall average risk exposure of the population in question. This does not consider that some individuals within the dam failure inundation zone have a greater exposure to the dam failure than others.

Figure 3 represents the *Tier 2 Guideline*, which is intended to help balance these concerns. Tier 2 establishes the justification for making structural modifications to limit annual failure probabilities to 1/10,000. This ensures a higher degree of protection to small populations and critically exposed individuals than would be potentially provided under Tier 1 Guidelines. It also enhances public trust by being proactive in maintaining the developed water resources in the western states. Taking actions to improve dams that are not equipped with state-of-the-art features to improve their safety is prudent in maintaining our aging infrastructure and public investments. The chance of experiencing a dam failure within 50 years from 10 dams each having an annual failure probability of 1/10,000 is reduced to 5 percent

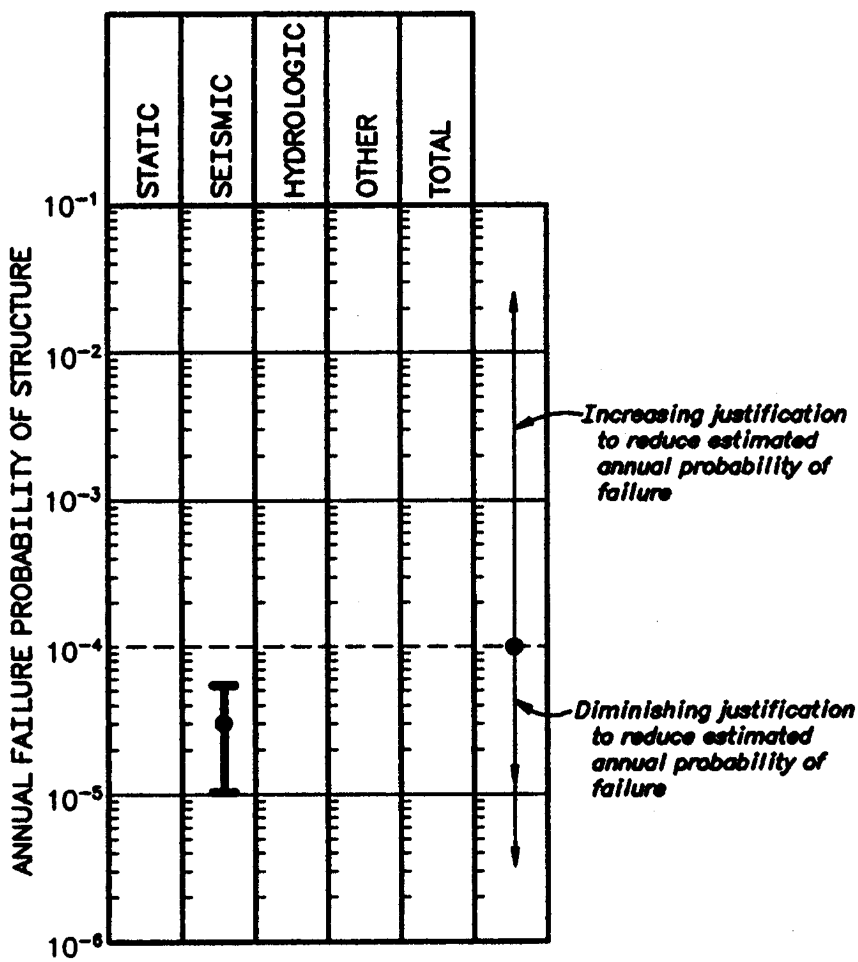

Figure 3. Tier 2 Guidelines (Failure Event Probability)

from the 40 percent chance in the previous discussion. The 50-dam example is reduced from a greater than 90 percent chance of failure down to a 21 percent chance.

Risk Assessment Methodology

In order to apply risk assessment methods to the Reclamation inventory of dams for the purpose of dam safety decision making, it is important that there be a degree of consistency in the methods used for assessing risk. Following two years of applying such risk assessment methods within Reclamation, a document (USBR 1997) is currently being prepared to identify general methods to be used in performing risk assessments. The objective of the document is to gain consistency in number of failures, it is difficult to develop meaningful frequency relationships for the failure rates of dams due to specific failure modes. As a result, Reclamation's experience in the past two years is that the probability estimates developed by the risk assessment team can most realistically be thought of as a degree of belief in the annual probability of failure for a given dam under the given conditions. By accepting probabilities based on this "degree of belief" philosophy, risk assessment teams have been able to consider information from a wide variety of sources when developing probability estimates. They can combine the knowledge gained from data collection and analysis, historical failure rates, failure case studies, understanding of physical processes, and understanding of structural behavior. With this approach, the team can make a judgement regarding the expected failure probability of a dam for a given failure mode. Considering data from these multiple sources provides the team members with an understanding of the load conditions that would be required to allow a failure mode to develop. Reclamation recognizes that these probability estimates are not perfectly accurate and may change as additional knowledge becomes available. However, these estimates represent the best risk-based information available for a given dam at a given time.

From a decision-making perspective, risk-based information provides a means for dealing with the uncertainties of managing a water storage facility. When presenting risk-based information to decision makers, it is important to provide a measure of the uncertainties associated with the estimated risk so that the risks can be considered in light of other factors having a bearing on the decision (cost, environmental, social, etc.). While uncertainty can be addressed in a variety of ways, Reclamation has chosen to address it through sensitivity analysis of the estimated risk results.

Application to Dam Safety Decisions

The objective of implementing risk assessment methods in the Reclamation Dam Safety Program has been to improve organizational effectiveness in achieving risk reduction in the existing inventory of dams. The traditional means of achieving this objective has been to determine which dams are unsafe and then implement modifications at those dams. Implementation of risk assessment has allowed Reclamation to go beyond the question of whether or not a dam is safe to incorporate the concept of risk assessment into all phases of the Reclamation dam safety process. Following dam inspections, which occur every three years for each dam, a brief assessment of risks is conducted to determine if any need to be addressed in more detail. Through the use of risk assessment, it is possible to determine if the risk at a particular dam is significant and its relative priority with respect to risks at other Reclamation dams. When additional investigations are required, risk assessment results assist in developing an investigation program focused on the data and analysis with the greatest potential for risk reduction. When corrective actions are determined to be necessary, risk assessment results can be used to guide the development of alternatives that most effectively reduce the risk at a dam. In these ways, risk applying risk assessment methods with an appropriate level of effort, so that meaningful risk-based information can be incorporated into dam safety decisions.

Some of the issues considered in selecting risk assessment methods included scalability, flexibility, and reliability. With the Reclamation inventory of 382 storage dams, the risk assessment methods must be applicable to a wide variety of dam types, heights, reservoir sizes, and conditions. The same methods that are used to analyze Grand Coulee and Hoover Dams should also be applicable to small diversion dams when the levels of effort are scaled appropriately. The methods should also be flexible enough to allow unique and site-specific conditions to be evaluated within a risk context. Flexibility is also required to allow new developments to be incorporated as Reclamation continues to learn about the use of risk-based information in decision-making processes. In order to achieve maximum risk reduction throughout the Reclamation inventory, the results from each risk assessment should be evaluated against a common basis. Reclamation considers the risk estimates to be reasonably reliable if an internal peer review shows that loading conditions, structural responses, and consequences have been adequately addressed. While no two risk assessment teams would arrive at exactly the same values of risk, the goal is to present sufficient information such that any differences in estimates do not alter the decisions to be made.

Much of the methodology document focuses on recommendations for applying basic principles of probability and statistics to the case of a particular dam. However, there have been three areas in which Reclamation has needed to select approaches which fit the overall purpose of risk assessment in the decision-making process. These areas include selecting the risk assessment team members, estimating load and structural response probabilities, and dealing with uncertainty.

There are many good arguments for a variety of risk assessment team compositions. Many people believe that the credibility of the values determined in the risk assessment is enhanced by the use of world-renowned consultants on the team. Others believe that risk assessments should be performed by teams of individuals who are already familiar with the dam and can directly contribute to the understanding of its behavior. At Reclamation, the core of the risk assessment team is the group of technicians, engineers, and geologists who have an ongoing responsibility for following the behavior and condition of the dam. Since these individuals are generally not trained risk assessment professionals, the team is provided with a facilitator to guide them through the risk assessment process. When there are very sensitive issues involved, it is common practice to involve independent industry consultants either as members of the team or by presenting results to them for review. This approach helps ensure that the risk information provided to decision makers is based on the best collective information available.

From a public protection perspective, the water resources industry has been fortunate that dam failures are unusual events. However, with a relatively limited assessment has become a valuable tool for evaluating and correcting dam safety concerns as an integral part of the Bureau of Reclamation's mission to manage water resources in the western states.

References

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