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THE PRACTICE OF DAM SAFETY RISK ASSESSMENT AND MANAGEMENT: ITS ROOTS, ITS BRANCHES, AND ITS FRUIT

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ABSTRACT

This paper provides an overview and introduction to the current practice of dam safety risk assessment and management. It includes a summary of the history and development (“roots”); various facets and roles (“branches”); and benefits, limitations, and future growth ("fruit”) of risk assessment and management. A broad role for risk assessment at the core of a comprehensive dam safety management program is proposed. In this role, the results of risk assessment are used to feed business and management processes such as, capital project evaluation and budgeting, loss financing and insurance, legal liability and due diligence assessment, and emergency preparedness and contingency planning. Contrasts are made with traditional dam engineering practice and the standards approach. The paper draws on the experience of the authors in conducting risk assessments on more than 130 dams for government and private owners and regulators in the U.S. and Australia.

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INTRODUCTION

The "sapling" of dam safety risk assessment and risk management is growing in the risk environment in which dams exist. Bowles et al. (1997) state that, "*Practical dam safety management is intrinsically risk management.*" The recent report, Whither Civil Engineering?, from the U.K. Institution of Civil Engineers (1996) states that, "*Risk cannot be eliminated; therefore it must be managed.*" While few would deny that dam engineering and dam safety management deal intrinsically with risk, opinions differ as to how explicitly and how quantitatively risk should be addressed in practice. In this paper, which was written to introduce a one-day session on Dam Safety Risk Management at the Eighteenth USCOLD Annual Lecture, we seek to provide an overview and introduction to the current practice of dam safety risk assessment and management. The paper summarizes its history and development ("roots"); its various facets and roles ("branches"); and its benefits, limitations, and future growth ("fruit").

The scope of this paper is broader than making decisions about whether or not to proceed with structural works to improve the safety of an individual dam. It takes the perspective that risk assessment outcomes have an important role to play in all aspects of dam safety management. Risk assessment for individual dams and portfolios of dams are viewed as a valuable core activity in a dam safety program. When properly applied, risk assessment can play a vital role in the integration of other dam safety activities, such as operations and maintenance, routine inspections, monitoring and surveillance, periodic safety reviews, staff training and awareness, and emergency planning. Unlike the extreme loading conditions which have become a focus of traditional dam safety practice, these other activities affect the management of dam safety risks on a day-to-day basis.

ITS ROOTS—HISTORY AND DEVELOPMENT

The "roots" of dam safety risk assessment and management can be traced from the "seeds" of the technical procedures and philosophies of dam engineering and risk assessment which have germinated and grown in the "soil" of a demand for the approach. In the first subsection, we review engineering, societal, business, and public policy drivers which are leading private and governmental dam owners to use risk-based approaches. In the second subsection, we focus on the technical basis for the risk-based approach.

Drivers

The following is a summary of some of the important drivers which have led dam owners to take the risk-based approach:

Engineering considerations

- Existing dams which do not satisfy current flood and earthquake loading criteria.
- Existing dams which were not built to meet the current state-of-the-practice.
- The aging and deterioration process in dams.

- The significant cost of complying with standards.

Societal considerations

- Increased downstream development below dams.
- Increased risk aversity and societal expectations for greater protection from natural and man-made hazards.
- Growing expectations that the community will be involved in decisions which affect its safety.
- Difficulty in relating to low probability risks which are associated with dams.

Business and public policy considerations

- "Reinvention of Government" which has resulted in a greater emphasis on performance-based budget justification, the "user pays" principle, and diminished governmental funding.
- A shift away from prescriptive regulation to "lighter regulation," including the sunsetting of manuals.
- A governmental emphasis on risk-benefit justifications for health, safety, and environmental regulations.
- Deregulation of the electrical utility industry and other pressures on corporations to improve business performance of all assets, including dams, as indicated by the growing emphasis on asset management approaches.
- Corporatization and privatization of dams which were previously owned and operated by governmental agencies, and removal of the shield of governmental immunity leaving directors and management personally liable for dam safety decisions and practices.

Ironically, the increased severity of design flood and earthquake standards has not always led to safer dams. Where a regulator, such as the FERC, has the power to require dam safety improvements, they have taken place. However, state regulators do not always have similar powers. In one state, its legislature has instructed the dam safety regulator not to require dam safety improvements, except in an emergency, or if the state contributes 80% of the cost from a limited fund. This state has dam safety standards which are as severe as most states, but has made little progress towards achieving them. So merely having severe standards is not a sufficient condition for achieving them.

In many cases, decision-makers are not convinced of the justification for engineering standards that are cited as the basis for costly dam safety works at their dams. As a result, priority has not been given to these works, unless a powerful regulator has required it. Some private dam owners, such as irrigation districts, simply cannot afford to meet these standards. In the public sector, the available funds for dam safety improvements fall significantly short of those that are needed to achieve compliance with engineering standards.

In contrast to the state in which the legislature has “tied the hands” of its dam safety regulator, there is another state in which the regulator has aggressively pursued partial dam safety fixes. This has been done through a consideration of the risks associated with each dam, and by negotiating dam safety fixes to a point at which they can be afforded by the dam owner. As a result, some level of risk reduction, albeit in many cases to less than a full standards level, has been achieved at the overwhelming majority of dams in this state. Although the first state has adopted standards level criteria, little if any risk reduction has been achieved, whereas the second state has achieved significant risk reduction, in a generally cost effective manner through using a risk-based approach.

Those who favor a “hard” regulatory approach may suggest that all that is needed is to give regulators the power to require that owners implement dam safety fixes. However, this would likely result in less than an optimal rate of risk reduction (Bowles et al., 1995, and Bowles et al., 1998), and would be inconsistent with the trend towards requiring that regulations be justified using a “risk-benefit” rationale. This trend is driven by a concern that we can no longer justify or afford compliance with many health, safety, and environmental regulations (Howard, 1994), and that many of these regulations have been neither cost effective, consistent, nor “sensible” in their risk reduction (OMB, 1992). An example of these concerns in dam safety is in cases where risk reduction for extreme event fixes is negligibly small, but very costly when compared with risk reduction opportunities at other dams or in other fields.

A risk-based approach to dam safety management offers an alternative to the “broad brush” and often cost ineffective character of an engineering standards approach, and to the “stalemate” which sometimes exists in jurisdictions in which a regulator lacks the power to enforce dam safety regulations. If properly applied, risk-based approaches can provide the justification for a responsible dam owner to take action to reduce significant dam safety risks. To make a convincing case for a costly dam safety measure to a private board of directors typically requires more than a statement that a dam does not meet an engineering standard. In our experience, the case for or against risk reduction measures can be made clearly by presenting the results of a risk assessment in business terms such as cost effectiveness of risk reduction, legal and insurance implications, and risk-based benchmarking against safety practice in dam safety and other fields. This approach has worked even in cases where no dam safety regulator exists.

Some have suggested that the underlying motivation for the risk-based approach is to save money by either not fixing dams or by fixing them to a lower standard of safety. Although this motivation does exist in some cases, our experience is that dam owners are prepared to proceed with justifiable works when a convincing case is made based on risk assessment outcomes. Thus, when properly applied, the risk-based approach can result in a more rapid reduction in dam safety risks than may occur using the traditional approach. This is particularly true when portfolio risk assessment is used to prioritize risk reduction measure across a group of dams (Bowles et al., 1998). When a risk-based approach is used, the owner may still choose a standards-based safety level. In some cases, we have seen that the risk-based approach leads to justification of safety levels which are more stringent than a standards level (Bowles et al., 1998). In addition, by relating risk identification information to day-to-day dam safety practice, significant reduction of risks, which are much more likely to be realized than extreme loading condition, can be achieved.

Technical Origins

Early interest in applying risk-based approaches to spillway sizing dates back to the ASCE Task Committee on the "Reevaluation of the Adequacy of Spillways of Existing Dams" (ASCE, 1973). The efforts of this group were controversial because they advocated placing a value on human life and then basing spillway sizing on a purely economic analysis to determine the least total economic cost based on summing risk costs and annualized costs of a dam safety fix.

In the USA, the 1976 failure of Teton Dam and the later failure of Taccoa Falls Dam, led to an Executive Order being issued by President Jimmy Carter which instructed federal government agencies to explore *"the degree to which probabilities or risk based analysis is incorporated into the process of site selection, design, construction, and operation."* This led to several research projects funded by federal agencies (e.g., Howell et al., 1980 and McCann et al., 1985) and some in-house efforts by the U.S. Bureau of Reclamation (1989) and the U.S. Army Corps of Engineers (1987). These efforts did little to address the issue of how to incorporate loss of life considerations into dam safety decision making. FERC (1986) regulatory guidelines were modified to include the possibility of the economic risk analysis in cases where no loss of life was expected. ASCE (1988) published another report on "Evaluation Procedures for Hydrologic Safety of Dams." Although this report did not resolve how to consider loss of life, it did propose a loss financing approach using indemnity costs.

In the 1980's, several risk assessment applications were conducted by the authors for dam owners in the western U.S. (Bowles, 1990). Two of these applications utilized cost-per-(statistical) life-saved as a measure of the cost effectiveness of reducing life safety risks to address loss of life considerations (Bowles et al., 1998).

In the early 90's, B.C. Hydro (1993) and the Australian Committee on Large Dams (ANCOLD, 1994) developed interim life loss tolerable risk criteria based on practices in other fields, such as industrial facility siting and nuclear power. Although interim, by explicitly addressing loss of life considerations, these criteria proved to be a turning point in the application of dam safety risk assessment. In 1995, the U.S. Bureau of Reclamation began to develop risk assessment procedures and interim Public Protection Guidelines (USBR, 1997). Since then, the USBR has performed dozens of risk assessments and is currently the largest user of the approach for making dam safety decisions. The USBR is also integrating risk assessment outcomes into other aspects of its dam safety management program.

In 1997, an International Workshop on Risk-Based Dam Safety Evaluations was held in Trondheim, Norway. The workshop participants were drawn from about 20 countries. Although research and development efforts were presented by most of these countries, applications of risk analysis were limited to only a few countries such as Australia, Canada, South Africa, and the USA.

From a philosophical perspective, some roots of dam safety risk assessment can be traced to concepts which were developed in the fields of "decision analysis under uncertainty" and probabilistic risk assessment in the nuclear and aerospace industries. However, there are some significant differences between these fields and dam safety. For example, decision analysis under uncertainty, which is built on an expected value decision criterion, may be suitable for business risk problems involving relatively high frequency-low consequence events in which an averaging process can be realized. However, this criterion has been widely questioned for application to fields such as dam safety, which involve low probability-high consequence events, because the averaging process which justifies the expected value approach may not exist in practice. Also, dam safety engineering deals with very extreme loading conditions, the severity of which, have rarely been approached. It also deals with foundation and other material properties which are not as well defined as in mechanical and electrical systems.

Although it is true that the paradigm for a risk-based approach to dam safety is distinctly different from the traditional standards-based approach (Bowles et al., 1997), there is much that we have learned in the traditional approach which must be part of a risk-based approach. Thus it is not surprising that traditional dam engineering analysis has been "grafted" into the current practice in dam safety risk assessment. That is, since new analysis techniques, which explicitly account for reliability and uncertainty in the performance of dams are not generally available for practical application, traditional analysis procedures are currently adapted for analyses that support dam safety risk analysis.

ITS BRANCHES—FACETS AND ROLES

The major "branches" of dam safety risk management include risk analysis, risk evaluation, and risk treatment (reduction). Risk assessment combines the first two branches and risk management combines all three. Various levels of effort have been proposed for performing risk assessments (McCann and Castro, 1998), but underlying these is the concept that risk assessments should be staged, with greater detail being justified by the value expected to be added for decision making (Bowles et al., 1978). This is referred to as a "decision-driven" approach (NRC, 1996).

A framework for dam safety risk assessment is presented in Figure 1. As shown by the "column" structure in this figure, the risk assessment process follows a five-step sequence from initiating events to system responses, outcomes, exposure factors, and consequences. Both external (e.g., floods, earthquakes, and upstream dam failures) and internal (e.g., the initiation of piping in an embankment dam under static loading) initiating events are considered. Each external initiating event is described by a number of loading ranges. Several steps may be necessary to fully describe the system response to a given initiating event leading to an outcome of dam failure or no failure. Various types of consequences of dam failure may be considered, including loss of life, economic damages, environmental damages, and societal effects.

There are four major steps in a risk assessment as illustrated by the "row" structure of Figure 1. These steps are as follows: 1) risk identification, 2) risk estimation, 3) risk evaluation, and 4) risk treatment. In Figure 1, the term, risk treatment, refers to the consideration of risk treatment (reduction) alternatives using risk analysis and risk assessment. Implementation of risk treatment is part of risk management.

Risk Analysis

Risk analysis involves both risk identification and risk estimation (first two rows in Figure 1). Risk identification is the process of recognizing the plausible failure modes if the dam were subjected to each type of initiating event. Typically, failure modes are represented in an event tree, which becomes the risk analysis model.

Risk estimation consists of determining loading, system response and outcome probabilities, and the consequences of various dam failure scenarios and no-failure scenarios, so that incremental consequences can be estimated. Probability and consequence estimates are then applied to the various branches of the event tree model. Consequences are a function of many factors including, the extent and character of flooding, the season of the year, the warning time and effectiveness of evacuation, and the effectiveness of contingency plans. Risk reduction alternatives are developed and analyzed in a similar manner to the existing dam, by changing various inputs (e.g., system response probabilities and consequences) to represent the improved performance of each alternative.

Risk Evaluation

Once risks have been identified and quantified for an existing dam and risk reduction alternatives, they are evaluated against risk-based criteria. Some considerations in applying these criteria, including ALARP (as low as reasonably practicable) and de minimis risk considerations, are summarized in the section on Risk-Based Criteria in Bowles et al. (1998).

Risk Treatment

From a business or management perspective, risk treatment options can be grouped into the following categories, although they are "not necessarily mutually exclusive or appropriate in all circumstances" (AS/NZS, 1995):

- "Avoid the risk" - this is choice which can be made before a dam is built or perhaps through decommissioning an existing dam.
- "Reduce (prevent) the probability of occurrence" – typically through structural measures, or dam safety management activities such as monitoring and surveillance, and periodic inspections.

- “Reduce (mitigate) the consequences” – for example by effective early warning systems of relocating exposed populations at risk.
- “Transfer the risk” – for example by contractual arrangements or transfer of an asset.
- “Retain (accept) the risk” - “after risks have been reduced or transferred, … residual risks … are retained and … may require risk financing.”

While the first three options reduce the risk to which third parties are exposed, the fourth and fifth options only affect the risk that the owner is responsible for and not the risk to which third parties are exposed.

ITS FRUIT—BENEFITS, LIMITATIONS, AND FUTURE GROWTH

Benefits

Just as good fruit is the product of good husbandry, valid and useful results from risk assessment and risk management are produced by a valid process that is conducted by qualified professionals. Examples of the benefits (“fruit”) which have been experienced by both the practitioners and customers of dam safety risk management are summarized below:

Risk Analysis including Risk Identification

- Systematic identification of potential failure modes including some which may have gone unrecognized using traditional approaches.
- Improved understanding of dam performance by the responsible engineers, including the event sequences which could lead to failure.
- More comprehensive engineering analysis than is typical using traditional approaches.
- Facilitates effective technical review and quality assurance.
- Facilitates ranking of failure modes and directing analysis effort to important issues which are not necessarily those which are amenable to analysis, such as seepage and piping.
- Provides basis for identification of effective structural and non-structural risk reduction measures.

Risk Assessment including Risk Evaluation

- Accounts for site-specific aspects.
- Justification for the extent and timing of risk reduction measures.
- Facilitates (benchmarking) comparison with risks at other dams or other types of facilities.
- Provides inputs to the decision process but does not prescribe the decision.

Risk Management including Risk Treatment/Reduction

- Facilitates transparency in the decision process.
- Facilitates effective communication between all parties.
- Provides managers and decision-makers an improved understanding of the significance of dam safety issues (e.g., criticality of gate operations and emergency preparedness planning).
- Provides a basis for deciding on additional investigations, analyses, monitoring, and surveillance.
- Provides inputs to assessing legal liability, due diligence, business risks, and loss financing positions.
- Facilitates a systematic and cost effective approach to justification of risk reduction measures.
- Provides a basis for prioritization of risk reduction measures across dams to maximize the rate of risk reduction (Bowles et al., 1998).

Limitations and Future Growth

To a large degree, the limitations of the current state-of-the-practice in dam safety risk assessment are also the limitations of the current state-of-the-practice in dam engineering. Our analysis tools are imperfect and available information on material properties (including foundation conditions) is often far less than would be the normal practice in other branches of engineering.

Just as judgment is a key element in dam engineering it is a key factor in dam safety risk assessment. In performing a risk assessment, the engineer and others are expected to quantify their judgments and the associated uncertainties in probabilistic terms.

Improved techniques are needed for developing technical inputs to risk analysis. These procedures should represent both reliability and uncertainty considerations. Also improved procedures for eliciting professional judgments and minimizing biases which might exist in these judgments should be developed. The efficiency of risk analysis calculations and procedures for consequence estimation are undergoing continuous improvement. Also several efforts are underway to develop dam safety risk analysis and risk assessment guidelines (e.g., ASCE, CEA, ICOLD, USBR).

However, it is important to remember that the underlying purpose of risk assessment is to assist decision-makers to make better decisions. We are not dealing with the pursuit of scientific inquiry, although we obviously desire as firm a scientific foundation for dam safety risk assessment as can be provided at any point in time. The following quotation from a recent essay on Uncertainties in Global Climate Change Estimate by Pate-Cornell (1996) is pertinent here:

> *When science can progress quietly, independently from the pressures of public policy making, the scientific community has ample time to fight its internal battles and to prove or disprove each element of the problem. There is no need to*

synthesize the state of knowledge until the problem is considered resolved by most. … When decisions need to be made along the way, based on partial and incomplete information for private purposes or pubic sector regulations, one does not have the luxury of taking the time to reach a complete, unquestioned consensus. In that case, the available information, imperfect as it is, must be synthesized at a particular stage to represent as closely as possible the state of knowledge at that time.

One of the most beneficial ways of adding to our capability in this developing field is through the performance of risk assessments for actual dams involving their engineers and decision-makers. There is an urgent need for benchmarking information on the risk profiles of existing dams and even more importantly on the risk reduction characteristics of implemented measures. This information will be invaluable to decision-makers for interpreting risk assessment results, including ALARP and de minimis risk considerations (Bowles et al., 1998).

SUMMARY AND CONCLUSIONS

Risk assessment and risk management can be an important enhancement to traditional dam engineering approaches. Whilst their successful application requires a paradigm shift, it is essential that qualified and experienced dam engineers be responsible for their execution.

While engineering standards have served a valuable role in enhancing dam safety, there are many cases around the world in which they have also served as a deterrent to the achievement of any significant risk reduction. If the goal is avoidance of dam failure and reducing risk as soon and as cost effectively as possible, then dam safety risk assessment and risk management have a key role to play as core activities in modern dam safety programs.

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Risk Assessment Framework