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RISK ANALYSIS IN GEOTECHNICAL AND EARTHQUAKE ENGINEERING STATE-OF-THE-ART AND PRACTICE FOR EMBANKMENT DAMS

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ABSTRACT

Despite a proliferation of papers on quantitative risk analysis for dams during the past twenty years, risk analysis has not found widespread application in dam safety practice. Recent experience suggests that, despite a great deal of enthusiasm in the 1990's, the professional opinion concerning the usefulness of risk analysis in dam safety practice is almost as divided now as it was in the early 1980's. This paper presents an account of the history and development of risk analysis in dam safety practice in the field of geotechnical earthquake engineering since its inception in the early 1960's to September 2000.

Against this background, and with regard to the discussion of the State-of-the-Art/Practice, the paper describes the latest attempts to quantify risk associated with earth dams for two failure modes, seismically induced liquefaction and a proposed procedure for seismically induced non-liquefaction deformation failure. To overcome the difficulties in reporting a complete risk analysis, the case study in Part II is presented in a way that will enable the profession to obtain an initial appreciation of what is involved in quantified risk analysis for dams. Concerning the State-of-the-Art/Practice, the paper presents background to what are essentially proposed practices as there is as yet no broadly accepted standard of practice for defensible analysis of risk associated with large dams.

PART I –EVOLUTION OF QUANTITATIVE RISK ANALYSIS IN DAM SAFETY PRACTICE

INTRODUCTION

The term "risk" implies some form of action in the face of uncertainty; it is a term of universal significance with several interpretations. Risk assessment provides a basis for making decisions concerning the need for, and extent of, risk control measures. Risk analysis is an integral part of the risk assessment process.

Recent improvements in understanding of what dam risk assessment involves have revealed that the decision-making process concerning the risk issue in question governs the form and extent of the risk analysis method adopted. Therefore, any discussion on the use of risk analysis to support dam safety decisions and management must be carried out within the context of the decision-making and management processes that apply. These processes will generally be different from one application to the next, from one owner to the next and from one jurisdiction to the next, with the result that there is no universal and concise approach to risk assessment.

This said, the methods used to analyse risk should follow the same general engineering and scientific principles in all jurisdictions recognising that the extent to which these principles are applied will be dependent on the risk assessment processes that are adopted.

The discussion is set against a background where, despite a burgeoning, but usually not independently peer-reviewed literature on risk assessment in dam safety practice, dam safety regulators have remained generally silent. This poses a significant obstacle to informed debate on risk analysis because "technically well-informed" regulators are essential participants in any debate concerning the role of risk analysis in dam safety decision-making. The regulatory authorities must ultimately be satisfied that the analysis methods are appropriate for use in decision-making concerning matters of public safety. The absence of stated regulatory positions concerning the acceptability of risk analysis methods in dam safety decision-making practice means that much of the debate surrounding its potential uses are carried out in somewhat of an intellectual vacuum and without societal consent which is often represented by regulation.

This paper reflects the view that prior to discussion on applications of risk analysis in dam safety practice, the dam engineering profession should first develop an agreed understanding of:

1. What risk is and in particular what dam risk is?
2. How risks posed by dams can be analysed?
3. What are the experience and qualification requirements for participants in the risk analysis process?
4. What are the strengths and weaknesses of proposed

approaches?
5. What do the outputs of a risk analysis for a dam mean?
6. How can methods and results of risk analyses be validated?
7. How can the results of a risk analysis be used in dam safety decision-making?
8. What are the roles and responsibilities of all participants in the overall process?

Addressing these issues does not impose conditions on risk analysis that are any different than those imposed on other methods of analysis used for important decision making concerning matters of public safety.

In its most complete sense, risk analysis characterises the uncertainty that is inherent in the answer to the question *How safe is the dam?* Risk analysis does have other uses but these are necessarily less than complete to the extent that different forms of risk analysis can be applied to varying degrees across an entire spectrum that ranges from an initial subjective sense of the risk to a complete characterisation of the risk. Therefore, it is important that the risk analysis identifies precisely where it lies in this very broad spectrum. Further, it is important to make a distinction between formal risk assessment used to develop safety cases and safety reports for licensing purposes, and informal risk assessments. The latter have varying degrees of usefulness ranging from an initial perception of what might be an appropriate course of action, to detailed characterisation of the risk to justify further risk control measures. However, they fall short of being suitable to reach a conclusion that the risks are being adequately controlled. To date, all dam risk assessments have, by default, been of the informal type as there are no regulatory structures to complete the societal and licensing component of the assessment anywhere in the world to my knowledge. Risk analyses, especially quantitative risk analyses, which result in actions to reduce dam risk may be quite different to those required to reach agreement with a regulator that a dam is *safe enough*. A risk analysis conducted to achieve the former purpose may not be adequate for the latter. In general, a risk analysis that is deemed appropriate for one application may be deemed to be unsuitable for another application.

It is also important to recognise that risk analysis is not a decision-making process in itself, but rather an integral part of a risk assessment. Risk analysis and risk assessment add new dimensions to dam safety decision-making as they involve, amongst other things, explicit characterisation of the uncertainty that pervades all aspects of dam safety decision-making as well as the complex concept of societal risk. Societal risk is regulated by society as a whole through its political processes and regulatory mechanisms. Typically, societal risks are unevenly distributed, as are their attendant benefits. The distribution of such major costs and benefits is a classic function of Government, subject to public discussion and debate (Health and Safety Executive (HSE), 1999). Therefore, the notion of the dam engineering profession and/or individual dam owners or agencies establishing so-called 'tolerable criteria' for societal risk, when viewed in this context, becomes untenable.

At the outset, it is important to note that, with one or two notable exceptions including flood protection dykes in the Netherlands, risk assessment aimed at determining if a dam is *safe enough,* is generally not being carried out. Further, and despite the proliferation of papers on the subject of risk analysis during the past ten years, there is no formal regulatory acceptance of proposed risk analysis and risk assessment methods. This can be attributed in part to the lack of an appropriate regulatory framework to address the issue of risks posed by dams. Therefore, opportunities to fully utilise risk analysis in dam safety practice are limited at this time.

This paper discusses the role of risk analysis in dam safety decision-making and management from this broad perspective. It is based on the experiences of a regulated owner, which has formally embraced the concepts of risk management in dam safety as a matter of corporate policy. Further, it is based on almost ten years of experience in experimenting with the various proposed approaches, subjecting them to critical review, rejecting some and improving others, and ultimately subjecting the most satisfactory approach to a simulated test of (risk) regulatory acceptability.

TERMINOLOGY

Clear and consistent definition, interpretation and use of risk management terms are essential. In this regard, the definitions and interpretations presented in the *Guide to Dam Risk Management* (Dam Safety Interest Group (DSIG), 1999) and the draft ICOLD bulletin on Risk Assessment (International Commission of Large Dams (ICOLD), 2000) are an important step in this direction. The terminology and interpretations used here are consistent with these documents. A useful discussion on risk assessment terminology was prepared by the UK Health and Safety Executive (HSE, 1995) which serves as an authoritative source. The following focuses on the key definitions and interpretations

Risk: A measure of the probability and severity of an adverse effect to life, health, property or the environment. One interpretation holds that risk may be estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e. the product of the probability of occurrence and the consequence) or, alternatively, by the triplet of scenario, probability of occurrence and the consequence.

Risk Assessment: whose essential features are illustrated in Fig. I-1 is central to dam risk management. In risk assessment, the results of the risk analysis and risk evaluation processes are integrated and recommendations are made concerning the need to reduce risk.

Risk Analysis: Risk analysis provides an understanding of the nature and extent of the uncertainty concerning the conditions under which the dam will be required to perform and the uncertainty in the response of the dam to these conditions. Risk analysis for dam safety is a structured process aimed at identifying both the extent and likelihood of consequences associated with dam or dam component failures (uncontrolled release of the reservoir). Risk analysis processes, when applied by appropriately experienced and knowledgeable individuals or groups, assist in revealing uncertainty in the

fundamental performance characteristics of the dam and its components. The process generates information about the risk in the system and the contributors to that risk.
Risk analysis processes can assist in all aspects of dam safety management that involve the collection of data and generation of information and which lead to the conclusion (in the face of uncertainty) that, given certain performance requirements are met, the dam can be operated safely.

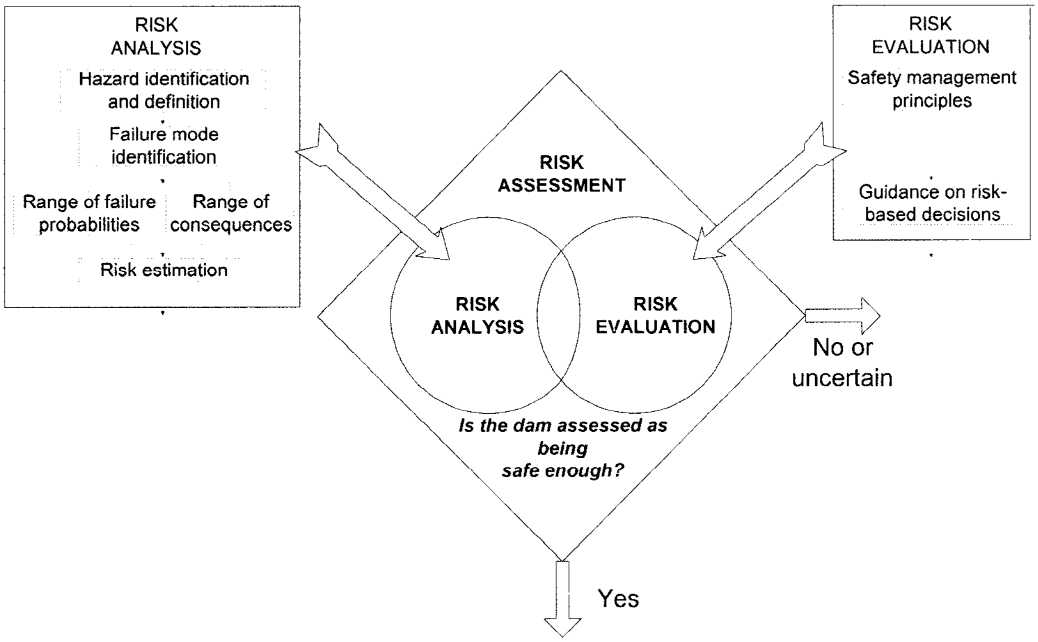

Fig. I-1. Risk Assessment and its components - Risk Analysis and Risk Evaluation

Risk analysis for dam safety requires a multidisciplinary approach as it covers areas of science, engineering and social science expertise ranging from hazard analysis, dam response analysis to consequence analysis involving consideration of economics, sociology and psychology. Therefore, when used as an input to the decision-making process, risk analysis may not be solely a matter of engineering.

In principle, the process must be able to identify and analyse all possible failure modes in the same way as forensic engineering identifies the causes of failures and accidents.

Risk Evaluation: the process of understanding and judging the significance of risk is fundamental to risk assessment and risk-based decision making. The principal role of risk evaluation in risk assessment is the generation of decision guidance against which the results of a risk analysis can be assessed. The process of generating risk-based decision guidance requires a statement of the owner's safety management principles, values and preferences as well as those of the public, including consideration of the prevailing financial, legal and regulatory conditions.

Definitive statements concerning the significance of a particular risk require definition of the background against which the significance of the risk is being described. In order to do this, there must be a general understanding of all risks within the system under consideration. In some cases the system will be limited to the dam itself. In others, the system could include local downstream, state wide, national and even international elements.

Risk evaluation involves policy analysis and policy development and therefore is not an engineering discipline. Engineers may be involved in risk evaluation to explain the insights that risk analysis can reveal and how it might be best interpreted. In this regard, engineering provides input to and support for the policy-making activities that constitute risk evaluation.

Whereas regulatory authorities may provide or rule on tolerable risk levels, public acceptance will require good communication and transparency of process. It may well be that, as risk assessment becomes established on a firm scientifically valid base, risk communication could become as important as risk reduction in determining public tolerance of risks posed by dams.

HISTORICAL PERSPECTIVE

The following historical perspective is not intended to be a complete chronological account of all stages of the evolution of risk analysis in dam safety practice, but rather to focus on the principal stages in the development of this branch of engineering as applied to dams. The pre-1990's material is based on the literature and on discussions with some of the key players who were involved in the various initiatives. The 1990's account reflects my own first hand knowledge and involvement. In presenting the account of the development of risk analysis in dam safety in this way, I recognise that this 'abridged history' cannot also provide a view of the history of the development of theories and models in the field of general geotechnical earthquake engineering during the same period.

Origins - The 60's. Consideration of risk is implicit in engineering practice and techniques to control risks, based on empirical evidence, have been absorbed into engineering practice over the years. The first formal published treatment of risk estimation can be traced back to Casagrande's Terzaghi lecture in 1964 (Casagrande, 1965). The significance of Casagrande's work, which is rarely quoted in contemporary literature, should not be overlooked as it forms a cornerstone of contemporary applications of risk analysis in geotechnical engineering practice.

Casagrande's contribution is remarkably insightful not just in relation to risk analysis but also in relation to ignorance, uncertainty and admitting to their extent in engineering practice. Casagrande's definition of 'Calculated Risk' goes beyond what nowadays would be called risk analysis (the process of estimating risk) to include risk assessment and risk control. Casagrande observed that *"the term 'calculated risk' is widely used in engineering, if not somewhat loosely; and that usage and most suggested definitions have in common a meaning that includes the following two distinct steps:*

(a) The use of imperfect knowledge, guided by judgement and experience, to estimate the probable ranges of all pertinent quantities that enter into the solution of a problem.

(b) The decision on an appropriate margin of safety, or degree of risk, taking into consideration economic factors and the magnitude of losses that would result from failure.

Casagrande outlined a philosophy by means of a fictitious example, which if risk analysis is used in design and construction (considerations (a) and (b) together) remains valid to this day. Casagrande did not extend his philosophy to the assessment of the risk associated with existing geotechnical structures, but his description of consideration (a) above provides a sound basis for extending his approach to such an application.

Casagrande's Terzaghi lecture prompted several written responses, and probably many unwritten thoughts, several of which remain relevant today. However, most of the debate centred on experience and practical implications with little discussion of the underlying philosophy of risk analysis (consideration (a) above). This does not detract from the philosophical content of Casagrande's contribution, rather that the philosophical dimension requires expansion.

Interestingly, in his discussion on Casagrande's Terzaghi lecture, J. H. Stratton (Stratton, 1965) commented as follows: *"Experience and judgement come with maturity, but maturity does not necessarily breed either. The pattern of thought followed by the author [Casagrande] in resolving solutions to the problems described in his examples represent an orderly and analytical process – one far beyond the capabilities of most in the profession."*

Therefore, and despite differences in terminology and application, Casagrande's insightful treatment of this complex subject can be considered to be the basis of subsequent developments in risk analysis in geotechnical and earthquake engineering practice - developments that were slow in coming.

Investigations - The 70's. Subsequently in the 1970's, there were several attempts to perform risk analyses for geotechnical structures, and theoretical approaches were proposed. For dams, most investigations related to hydrologic hazards and the use of economic risk analysis concepts in sizing spillways, with little emphasis on the response of earth dams to seismic loading. It is not clear why seismic considerations were not a significant part of the 'risk debate' for dams in the 1970's, as Casagrande had clearly identified its importance. It may be due to the historical good performance of dams during earthquakes, as a review of the statistics of dam failures and incidents reveals, despite the seismically induced damage caused to the San Fernando Dams by the earthquake in February 1971. It also may be due to the complexities of the problem and the general ability to deal with the problem analytically at that time.

Importantly, applications of economic risk analysis to dams were restricted to situations where there was no threat to life, a trend that continues today, although somewhat differently. The issue of threat to life and its incorporation in economic risk analysis for spillway adequacy was introduced in 1973 and quickly dismissed by the profession. The idea of assigning a monetary value to life was deemed unacceptable by the profession at large with the result that risk analysis for dams as proposed then, was not taken seriously.

The 1970's and also the 1960's provided significant advances in the discipline of *'Prediction in Geotechnical Engineering'* (e.g. Lambe, 1973). Lambe classified predictions in terms of three general types, *before event*, *during event* and *after event*, with further subdivision of the latter two types depending on whether or not the results are known at the time as, illustrated in Table I-1.

Prediction Type	When prediction made	Results at time prediction made
A	Before event	-
B	During event	Not known
B1	During event	Known
C	After event	Not known
C1	After event	Known

Table I-1. Classification of prediction (after Lambe, 1973)

Lambe noted "*the Profession is in great need of simple techniques to make type A predictions. Even though type B predictions might be helpful, they are normally not nearly as useful as type A predictions. Type C predictions are autopsies. Our professional literature contains the results of more type C1 predictions than of any other type. Autopsies can of course be very helpful in contributing to our knowledge. However, one must be suspicious when an author uses type C1 predictions to 'prove' that any prediction technique is correct.*" (Lambe, 1973). In his conclusions, Lambe remarked, *"We have many powerful tools for solving difficult problems. Even so, I have become increasingly aware* *of our limitations. There are many situations where we cannot predict the performance of facilities with known reliability. We need to continue our experimental and theoretical work to improve our understanding of mechanisms and to generate simple prediction techniques for the practising engineer"* (Lambe, 1973).

The lack of emphasis on the investigative work of the 70's in this review does not detract from its importance in present day applications of risk analysis concepts in geotechnical earthquake engineering. The MIT Trial Embankment study (Lambe, 1973, Hynes and Vanmarcke, 1976) illustrates the challenge in predicting failure for static loading conditions for geotechnical structures in terms of conditions which are close to 'controlled'.

The MIT Trial Embankment revealed the difficulties in performing what can be considered to be amongst the most straightforward applications of risk analysis alluded to in Casagrande's original work. Clearly, if static loading conditions present such analytical difficulties, dynamic loading must present even greater challenges.

INITIAL APPLICATIONS – THE 80'S

Risk-Based Decision Analysis. The 1980's saw a drive towards more formalised risk-based decision analysis in dam safety practice which incorporated benefit-cost analysis and which included consideration of seismic issues. Application of these economic risk analysis techniques began to receive more detailed treatment in the literature in the early 1980's. The term 'Risk-Based Decision Analysis', which accurately describes what they were, is the term that was used when risk-based concepts were applied in (limited) practice. Here, it is important to note that what was termed a Risk Assessment in Dam Safety Practice in the 1980's (National Research Council, 1983) is what would now be termed a risk estimate. They were not risk analyses or risk assessments in terms of currently accepted terminology, but they did represent first steps in developing the risk analysis framework which emerged in the 1990's.

This Risk-Based Decision Analysis concept correctly identified the basic components of a modern day risk analysis as follows:

- *"Identification of the events or sequences of events that can lead to dam failure and evaluation of their (relative) likelihood of occurrence.*
- *Identification of the potential modes of failure that might result from the adverse initiating events.*
- *Evaluation of the likelihood that a particular mode of dam failure will occur given a particular level of loading.*
- *Determination of the consequences of failure for each potential failure mode."*

The methodology had an additional step to calculate the risk cost, but this has not been presented here as risk cost is only one representation of risk, and it was the representation of choice for its intended application. The term (relative) is also important as the approach was used for comparison of options as opposed to deciding if a dam was safe enough.

Whitman's Proposed Approach. Whitman's Terzaghi lecture (Whitman, 1984), which provided the first insights into what was to come in the 90's, built on the original ideas proposed by Casagrande almost twenty years earlier. The lecture presented all of the elements of what is now known as quantitative risk assessment for dams:

- Probabilistic hazard analysis
- Event tree based analysis of dam response
- Consequence analysis, and
- Risk evaluation criteria (based on suggestions by G.B. Baecher).

Whitman's paper included a number of important observations, not the least of which is the fact that the overall theory is complex. Whitman, recognised Casagrande's concern that while *"he [Casagrande] envisioned that it might be possible to develop a subjective rating system for dams, he worried whether there were enough experienced engineers who could be expected to apply such a system in a reliable manner"*. In response to this concern, Whitman proposed *"in very preliminary form, a rating system cast in the format of a risk to failure. This approach has two facets:*

1. *An event tree to give structure to the rating process.*
2. *A set of criteria to guide choice of probabilities at each branch of the event tree."*

Whitman put forward this approach "*not as the answer to the very real problem of recognising the riskiness of various dams, but to stimulate further discussion on the topic."*

Whitman's ideas did not find practical application in risk-based dam safety decision-making in the 1980's. The use of risk-based approaches relied on the US Bureau of Reclamation's (USBR) procedures as outlined in the Guidelines to Decision Analysis (USBR, 1986). Event trees remained extremely general in form with no detailed decomposition of the failure mechanism. Practical applications of risk-based analysis of dams in the 1980's did not adopt the 'de-compositional' approach to engineering analysis referred to by Baecher et al. (1980) and for which Whitman proposed an operational structure.

Whitman's *General Comments Concerning Risk Evaluation* was also insightful as it introduced the concept of engineered structures being *'safe enough'* which is now central to goal setting types of risk regulation (Bacon, 1998). Whitman also rightly observed that engineers should not be solely responsible for the evaluation of societal risks from engineered structures, rather that they should be participants in a societal process. Time has shown the validity of this observation, which was not heeded by all at the time or subsequently.

Applications Of Risk-Based Concepts In Dam Safety. Risk-based procedures for prioritisation (McCann et al., 1983) also emerged as did risk-benefit analyses for the construction of new dams (Pate, 1981).

The Tongue River Risk Assessment (PRC, 1986) was an important development as it represented the first attempt to present dam risk, for discussion purposes, to the Montana legislature. The engineering analysis (risk analysis) was carried out using the USBR's procedures, which were described as *"the only documented procedures at design level."* Probability estimation was in terms of a combination of historical/empirical and judgmental approaches, although the process for combining objective and subjective probabilities was not described. The Tongue River Risk Assessment captured the basic essence of a modern day risk assessment without application of the detailed analysis and evaluation procedures of the form suggested by Whitman (this did not emerge until the 1990's).

Interest appeared to be growing outside the water resources industry with an application in the mining industry, presented by Vick and Bromwell (1989). This case study provided a description of how probabilistic risk analysis was used in decision-making concerning the design of a dam on Karst in Florida. The probability of failure was estimated using the fault tree analysis technique and included an estimate of the monetary consequences associated with loss-of-life. Typical of risk-based analyses of the 1980's, the results of the study were used to inform the owner's decision-making process. In particular, the paper noted: *"The geotechnical engineer need not be intimidated by lack of expert knowledge or detailed information in assigning probabilities that accurately reflect his or her engineering judgement, provided that the failure scenario can be decomposed into tractable events amenable to evaluation by experience and to investigation by sensitivity analyses."* This view appeared to suggest that the analytical and de-compositional difficulties alluded to by Casagrande, Whitman, Baecher et al., and others had been overcome.

Tolerable And Unacceptable Risk In The 1980's. During the 1980's, publications on risk assessment of dams generally avoided the issue of 'acceptable' or 'tolerable' risk criteria. This does not mean that the need for some sort of decision criterion was not recognised; it was. However, risk to life was not formally addressed by dam safety regulatory authorities, as it was generally felt that major dams whose failure would result in loss-of-life should be capable of withstanding the Maximum Credible Earthquake (MCE). The *'myth of absolute safety'* embodied in the concept of the Probable Maximum Flood (PMF) introduced to assure the body politic that the level of flood for which a dam is designed is reasonable had and still has its seismic counterpart in the MCE.

Outside the dams industry, the United Kingdom Health and Safety Executive published "Tolerability of Risks from Nuclear Power Stations" and an accompanying "Comments" document (HSE, 1988). This presented regulatory recognition of the notion of tolerable risk from hazardous facilities and the formal description of risk evaluation criteria. The ALARP principle, which forms the basis of consideration of what constitutes *'safe enough'*, was stated in regulatory terms and provided a framework within which risk analysis might be carried out. The Tolerability of Risk Document provided the basis for life safety criteria proposed for dams in the 1990's.
The last part of the 'pre-1990's risk analysis historical jigsaw puzzle' was put in place when USBR published its *Policies and Procedures for Dam Safety Modification Decision-making* which defined a *'Safe Dam'* as *"one which performs its intended functions without imposing unacceptable risks to the public by its presence"* (USBR, 1989).

It later transpired that the view of tolerability of risk for dams that prevailed at that time was overly simplistic, and that regulatory involvement would be required to establish the principles of Tolerability of Risk for dam safety.

Impressions from Within the 'Dam Risk Analysis Community'. Overall, a review of the 1980's dam risk literature could give the impression that risk-based dam safety decision-making was well established. It appeared that the principles of, and framework for, risk assessment, which had been developed outside the dams industry, could now be broadly applied to dams. The structure of the process was well defined, and it required only modification for dam safety purposes Bowles (1989). Interest in risk-based decision making for dams became so widespread that entire conferences on *Risk-Based Decision-Making in Water Resources*, sponsored by the Engineering Foundation and supported by several cosponsors were held. The introduction to the proceedings of the fourth conference, held in 1989, referred to the *'growing popularity of risk-based decision-making"*.

Thus, at the end of the 1980's, while none of the numerous initiatives in risk-based decision-making for dams addressed the question *Is the dam safe enough?*, it appeared that all of the components necessary to take this next step were in place, at least in principle. In other words, if valid comparisons between risk reduction measures could be made and relied on, it was thought possible to compare the risk associated with any individual option with some objective value of risk which quantifies 'safe enough'.

A Broader View – Impressions from the 'Edge and Outside'. One might reasonably conclude that conceptually, the elements of risk analysis in dam safety assessment, including seismic safety assessment had been identified. However, certain difficulties with the analytical detail remained. This was nothing new. Concerns about the practicality of all aspects of risk analysis had been raised since Casagrande first introduced the concept of calculated risk, and many remain today. Importantly, the enormous difficulties in determining probabilities of dam failure through analysis were clearly identified. Baecher et al. (1980) provide a useful account of the difficulties as follows: *"Engineering analysis is de-compositional. It proceeds by separating the engineering design into the mechanisms of failure, analyzing or estimating each component of the failure mechanism in isolation, and recombining the components according to basic physical principles and natural laws. Thus any analytical approach to estimating probabilities of failure requires full enumeration of failure mechanisms, complete identification of natural events, processes or properties affecting those failure mechanisms, and detailed specification of the engineering relationships within and among mechanisms.*
The difficulties of analytically estimating probabilities of dam failure are that (1) dams can fail through an essentially infinite number of mechanisms or modes which cannot be fully enumerated, (2) detailed decomposition of dam performance may lead to events and types of physical behaviour that are even more difficult to analyse than aggregate performance, and (3) even for those mechanisms commonly analysed by

engineers, the present models are deterministic. To date, no comprehensive attempt at analytical assessment of the probability of failure for particular dams has been made. Even if such analyses were possible, because both the modeling and the assignment of probabilities are necessarily subjective, the results might not be repeatable.

Perhaps the most severe limitation of analytical approaches is due to the fact that most failures of constructed facilities occur in ways that cannot be analyzed. Recent studies of the historical occurrence of structural failures seem to indicate that possibly as few as 10% are attributable to mechanisms within the scope of present or prospective methods of engineering analysis [quoting Flint et al., 1976]. Most failures occur due to accident, inadequate construction control, or poorly understood physical processes. There is every reason to think that this situation also applied to dams. Therefore, any analytically derived probability of failure is only likely to be a lower bound.

Analytical predictions of probabilities of failure leading to more accurate estimates than that obtained from the historical record do not seem possible at present. Fundamentally, analytical procedures suffer from requiring explicit identification of failure mechanisms, which cannot be completely enumerated. Analytical predictions also suffer by the inadequacy of engineering science to explain fully all aspects of dam behavior. While future development may broaden the applicability of reliability modeling of dams, and while certain naturally recurring hazards can be analyzed, overall reliance on analytical procedures to obtain probabilities of failure seems premature, at best, and may actually be logically impossible."

These and other technical difficulties inhibited the application of risk analysis in dam safety in the 1980's. There was significant research interest in risk-based decision analysis, and a so-called 'judgmental technique' aimed at overcoming the technical difficulties mentioned above emerged (NRC, 1983). In terms of the judgmental approach, *"the investigator attempts to quantify his judgment based on all available information. The judgmental statement may be made directly in terms of annual probability of failure of the dam due to a particular condition (e.g. probability of failure due to internal erosion = 1×10^{-3} annually), in terms of the chance of failure over a specified remaining operational life of the dam, or as a fraction of the probability associated with other modes (e.g., about twice the risk attributable to flooding and overtopping).*

However, when the literature on risk-based methods is reviewed in the context of dam safety in general, a different picture emerges. With the exception of the large self-regulating US Federal dam agencies (Bureau of Reclamation and Corps of Engineers), involvement of dam owners and dam safety regulators in the development of risk-based methods was almost non-existent with few actual applications in practice. In fact, the wider dam engineering community remained highly suspicious, even critical of, risk-based approaches to dam safety decision-making.

Dr. Ralph Peck, widely recognised as having unparalleled knowledge and experience in the field of dam design and dam safety was clearly not convinced by the arguments in favour of risk-based dam safety. Dr. Peck eloquently and effectively expressed his concerns (Peck, 1980, 1982); but he was not alone, as similar views were held (and remain held) by the majority of dam engineers. In fact, Peck's 1980 paper "*Where has all the Judgment Gone*?" includes, as a reference, the paper by Baecher et al. and the question '"Where has all the Judgement Gone?" follows a discussion on the use of the base rate of dam failures of 10^{-4} as a 'default value'.

In his "Comments on Risk Analysis for Dams" where he provided strong arguments against proposals to quantify risks posed by dams, Dr. Peck made the following remarks:

- *"A risk analysis of a dam having the potential for failing by piping would be meaningless if it did not consider these* [previously discussed] *factors, because these are the factors that decide the safety of the dam. When the state of the art of risk analysis is capable of doing this, I shall become an enthusiastic supporter. I think this may be possible, and I endorse efforts to that end. I don't believe the time is now. I don't believe the implication of all these factors can be quantified by asking the most qualified experts to choose a number between 1 and 10.*

- *In its present state, risk analysis provides powerful insights into the relative importance of various factors affecting the safety of dams, especially with respect to hydrology, reservoir operation, and seismic events. Its contribution in assessment of stability seems, if my former colleagues will forgive me, somewhat academic. Its application to assessment of the risk of subsurface erosion and piping, especially if it diminishes design for defense in depth, could be dangerous. The experience that leads to the art of design for defense in depth is not experience that develops an expert in risk analysis; an enormous amount of interaction will be needed before I should want to see so fundamental a change in design philosophy."* (Peck, 1982)

In 1983, Dr. Rasmussen (of nuclear power plant fame), when invited to speak at a joint Stanford-MIT conference on the issue of how risk analysis might be applied to dams, is reputed to have expressed the view that not enough is known about dams to make a risk analysis of dam failures (Jones, 1999).

The International Commission on Large Dams (ICOLD) view was as follows: *"In most cases, computation of the overall probability of failure of a given dam would require so many assumptions, affected by such a high degree of uncertainty, that the final figure would not be of any practical value for project design and a judgement of its safety."* With regard to statistics, the ICOLD position was that *"a statistical figure derived from historical records of failure and the number of existing dams has no relevance to an individual dam and would do injustice to a dam carefully designed, constructed, operated and maintained by competent engineers"* (ICOLD, 1987).

The Utah Power and Light study (Waite, 1989, a) provides valuable insights into the regulatory acceptance of Risk-Based Decision Analysis (termed a risk assessment) and some of the difficulties faced by dam owners. It also provides insight into what would become contentious issues for debate in the 1990's – costs of retrofitting dams to ever-increasing deterministic safety standards and costs of risk analyses! Waite's open and frank description of the discomfort of the Federal Energy Regulatory Commission (FERC) is as follows:

"FERC staff was uncomfortable with our decision, and they have our sympathy in this regard. We think they visualized the result, could be a whitewash of genuine safety problems, inadvertently or intentionally superficial, politically controversial, and not result in a truly balanced evaluation or solution. They seemed particularly concerned that the technical and economic review would have insufficient depth to provide an effective information base and that insufficient information was generally available to make reliable risk judgments. They said such a "risk assessment" would miss too many factors and details, currently handled as intangible factor-of-safety components, and result in a risky model. Even if we did a proper job on the evaluation, we think that FERC was concerned about a possible precedent that would allow later, less well founded work by others jeopardize industry safety standards. The decision to go ahead with the risk assessment was executed with mixed feelings within our own organization too." (Waite, 1989, a).

Waite also provided some useful insights into lessons learned from the study. Two valuable insights, one posed as a question were:

- *"Procedurally, did the study go as anticipated? No, not entirely. Personally, if I had to do it again, I would insist on physical evaluation of the facilities condition being given greater emphasis. If you don't examine existing conditions closely, you will probably learn your lesson later.*
- *Don't short change the development of the details in a risk assessment."* (Waite 1989, b).

<u>The State-of-the-Art/Practice in the 1980's.</u> The literature on risk analysis for dams presents a broad spectrum of views ranging from creating the impression that there were no difficulties to be resolved at one end of the spectrum to insurmountable problems at the other. A balanced and informed view can only be obtained from a broad, in-depth examination of all of the issues involved. Clearly, while such a treatment is beyond the scope of this paper, the review suggests that, at the end of the 1980's, fundamental theoretical and practical difficulties existed which would have to be resolved before risk analysis could become an established and accepted process for analysing the safety of dams. The unique nature of dams, the poor understanding of the causes of failure, the complex nature of risk and the general problem of experience referred to by Casagrande, clearly posed enormous problems. The task that existed at the start of the 1990's of resolving these difficulties in a generally acceptable, mathematically correct and scientifically valid way to permit risk analysis for dams to become an accepted practice was not a trivial one.

The difficulties that have been identified do not mean that the activities of the 1970's and 1980's were not of considerable value; they were, but they did not meet the overall objective of determining if a dam is safe enough. I hold the view that significant advances in understanding of risk analysis of dams were achieved during the first twenty-five year period since Casagrande proposed the concept. The research and development work carried out at MIT, Stanford and other centres of learning, together with that carried out by the Bureau of Reclamation and the Corps of Engineers provided a conceptual base from which to work. The pioneering applications of the concepts embodied in the USBR's Guidelines to Decision Analysis provided the basis of future applications of risk analysis in formal assessment of risk posed by dams.

This said, the 'State-of-the-Art/Practice of risk analysis of dams at the end of the 1980's had not progressed to formal risk assessment, although the Tongue River Dam Risk Assessment had captured most of the essential features, without the benefit of the vitally important detailed analytical probability estimation processes and the risk evaluation component. An interesting feature of the 'State-of-the-Art/Practice' at the end of the 1980's was that, for practical purposes, the analytical procedures had not really evolved during the decade. Of the three basic approaches to estimating dam response probabilities:

1. *The analytical (probability) approach,*
2. *The empirical (historical frequency) approach, and,*
3. *The judgmental approach*

a combination of the latter two were used throughout the decade (e.g. Bowles, 1989).

Although not stated explicitly, the three approaches to probability estimation were treated as equivalent with NRC (NRC, 1983) clearly stating that *"a combination of empirical and judgmental approaches appears to be most practical at the present time.* However, the validity of this assertion was not demonstrated, and it does require the questionable mixing of the objective and subjective philosophies of probability theory.

The procedure was as follows (NRC, 1983):

- *"Historical failure probabilities can be obtained for specific conditions and types of structures, but they need to be adjusted based on the conditions at a particular dam.*
- *This adjustment is based on the inspection, analysis, and judgment of the engineers performing the safety evaluation of the dam.*
- *The two estimates may be combined by means of a Bayesian updating procedure in which a weight is assigned to the relative confidence in each of the estimates (historical and engineer's judgment)."*

Of course, such a procedure cannot be applied in the absence of historical data on dam failures, something that is extremely sparse for seismically induced failures. Further and probably even more importantly, the procedure overlooks the simple fact that none of the dams in the database have the "historical failure probability". Historical failure probability (frequency) is a mathematical property of the population of failed dams as a proportion of the total (a small number of 1's and a larger number of 0's). The weighting procedure (step 3) also raises questions concerning how the engineer makes the estimate as it is already a weighted version (site-specific adjustments up or down) of the historical frequency (step 1). Of course, the procedure breaks down completely if the historical failure frequency for a particular class of dam and hazard is zero because judgment is based on knowledge, and knowledge is familiarity gained by actual experience, directly or indirectly through others (DiBiagio and Høeg, 1989). Another difficulty relates to the non-intuitive nature of probability and the numerous examples of 'judgments' of probability being spectacularly wrong!

The risk estimation procedure was generally represented by a three-step process, which towards the end of the 1980's was often illustrated in a simplified three-step event tree where the system response was modelled in two steps as illustrated in Fig. I-2. Event trees of this nature, and this particular example, are simply graphical illustrations of the tabular representation of the example presented in Appendix A of the USBR's 1986 Embankment Dams Design Standard No. 13, Chapter 14, Guidelines on Decision Analysis (USBR, 1984), as previously described by NRC (NRC, 1983).

Considering all of the above, the process whereby reliable estimates of response probabilities for individual, unique dams, concerning events that are beyond experience and not readily analysed, using statistics from a sparse and heterogeneous database can be 'judged' was not at all clear. What was also not clear was the meaning of these 'blended probabilities'.

Probabilities of system response were typically assigned using the 'judgmental' approach with sensitivity studies carried out to determine the sensitivity of the outcome to these variations in inputs. The accounts of how these judgmental probabilities are arrived at generally refer to probabilities being estimated based on engineering analysis, experience and judgement (NRC, 1983, and Bowles, 1989) without applying a procedure of the type suggested by Whitman. Importantly, applications of risk analysis in dam safety in the 1980's did not employ the *'type A'* predictive models referred to by Lambe (Lambe, 1973).

Further and importantly, the significant advances in geotechnical earthquake engineering, and in particular the advances in liquefaction, were not employed in risk analyses for dams even though liquefaction risk was amenable, in principle at any rate, to quantification (NRC, 1985, a, Liao et al, 1988). In many respects, advances in geotechnical and earthquake engineering were not finding widespread application in risk analysis for dams.

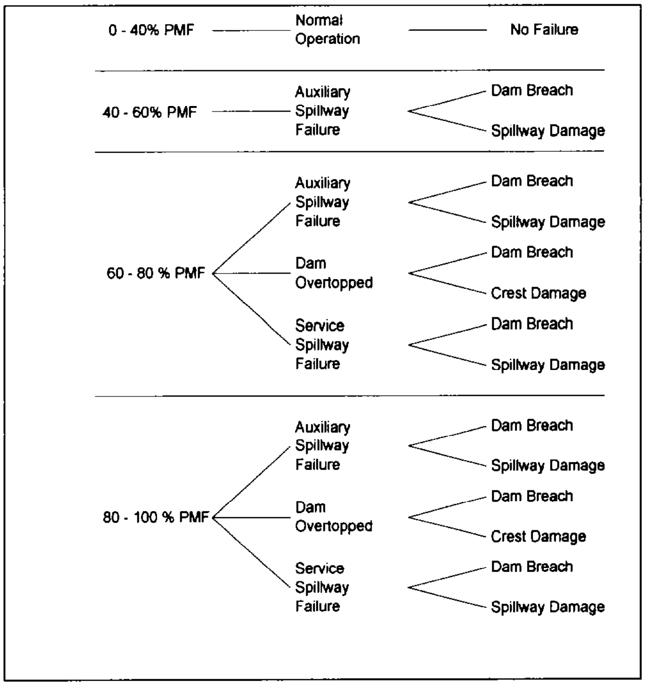

Fig. I-2 Simplified Event Tree for Hypothetical Dam Considering Hydrologic Loading (after Bowles et al. 1987)

In summary, interest in risk-based decision-making did not translate into action in any significant way in the 1980's. What was termed 'risk assessment' in the dam industry was actually what had become generally known as a grossly simplified form of risk estimation in other hazardous industries. This 'generally loose' use of terminology was a source of considerable confusion. The State-of-the-Art/Practice of risk analysis in the 1980's was essentially established prior to 1983and applied by the USBR (NRC, 1983). The NRC view (NRC, 1985, b) was that *"the quantitative risk-cost analysis approach has been applied to very few dams and is such a recent development that it can be barely called "current practice".*

In general, proponents of risk-based methods were generally unsuccessful in providing convincing, scientifically based arguments to advance the concept to routine practice. The profession was clearly divided, and there was no regulatory acceptance of risk assessment in dam safety practice. Applications of risk-based methods were the exception rather than the norm, the scientific and theoretical basis for the analysis methods had not been established in an engineering sense, and none of the applications answered the question *"Is the dam safe enough?"*

Level Of Interest In Risk-Based Dam Safety Decision-Making. Towards the late 1980's dam owners, faced with ever increasing design standards for dams, began to show an interest in risk-based decision-making. Many owners were faced with the prospect of ever increasing costs associated with retrofitting their dams to meet new design standards. The cost of retrofitting old dams to new standards tends to be enormous, with benefit-cost ratios generally substantially less than 1.0. The economics of dam safety simply did not add up, and it was not possible to develop business cases for dam safety improvements in the normal way. The situation faced by Utah Power and Light (Waite, 1989, a) was not unique.

FIRST STEPS IN FORMAL RISK ANALYSIS AND RISK ASSESSMENT – THE EARLY 1990'S

BC Hydro, the Provincially owned hydroelectric utility of British Columbia, was the first major dam owner to seriously attempt to answer the questions *How Safe is the Dam?...Is it Safe Enough?* using risk assessment techniques. G.M. Salmon, BC Hydro's Director of Dam Safety initially sought assistance from the USBR's Mr. J. L. Von Thun who had been heavily involved in developing the USBR's Risk-Based Guidelines on Decision Analysis. Early on (1991), Salmon suggested that it might be possible to measure the safety of a dam in terms of the expected value of the loss. Recognising the immense difficulties associated with monetising the value of human life, Salmon proposed that life safety be considered separately from monetary losses. He suggested that an expected value for loss of life $E_{\text{life loss}} > 0.001$ lives/dam/year would constitute a level of risk to the public that would be unacceptable (BC Hydro, 1991). The commencement of BC Hydro's initiative coincided with the publication of the Canadian Standards Association's National Standard on *Risk Analysis Requirements and Guidelines* (Canadian Standards Association (CSA), 1991).

Salmon recognised that analytical procedures would be necessary to make reasonable estimates of the risk posed by a dam, and he instituted a major development initiative aimed at determining the risk posed by dams by means of analytical techniques. BC Hydro took on the challenge of advancing the state of knowledge beyond the grossly simplified approaches of risk estimation used in the existing risk-based decision analysis technique by moving to de-compositional analysis.

A number of projects were initiated to investigate how to estimate probabilities of:

- Extreme loads on dams (large earthquakes and floods)
- Dam responses and failure mechanisms, and
- Dam failure consequences.

A separate project was initiated to provide a framework for the risk assessment process to integrate the various analytical components, to establish potential risk-based decision criteria through a risk evaluation process, and to assess the risk posed by the dam to determine if it is safe enough.

In keeping with BC Hydro's tradition of bringing an appropriate level of expertise to bear on difficult dam engineering problems, BC Hydro engaged advisory panels of internationally recognised experts in the various disciplines involved to guide the investigations. The projects were led by BC Hydro senior engineering staff supplemented by consultants. Originally, it was not intended to develop new theoretical models and analytical techniques, but rather to build on existing techniques by adapting them to suit the types of problems in hand. In this regard, the probabilistic seismic hazard analysis studies were relatively straightforward as analytical techniques had been introduced over twenty years previously and subsequently refined. By 1992, BC Hydro had performed 'basic' probabilistic hazard analyses, as depicted in (Fig. I-3), for all of its dam sites.

The 'basic' approach to characterising the seismic hazard at a dam site was the principal method used in dam risk analyses in the 1990's. While useful for providing an initial estimate of the seismic hazard, the technique falls short of full probabilistic characterisation of the risk. 1995 saw a move towards more comprehensive characterisation of the seismic hazard by including explicit treatment of the aleatory and epistemic uncertainties, as shown in Fig. I-4.

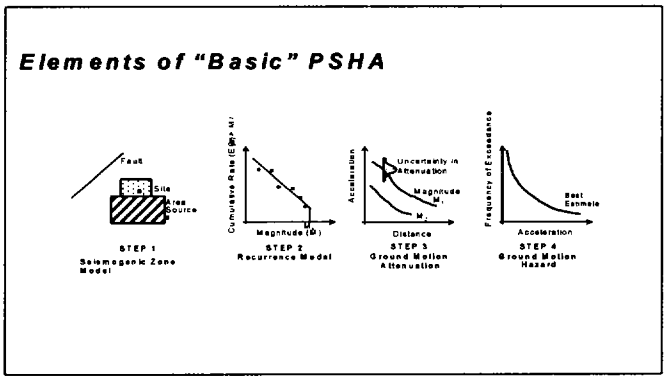

Fig. I-3. Basic Probabilistic Seismic Hazard Analysis (1992)

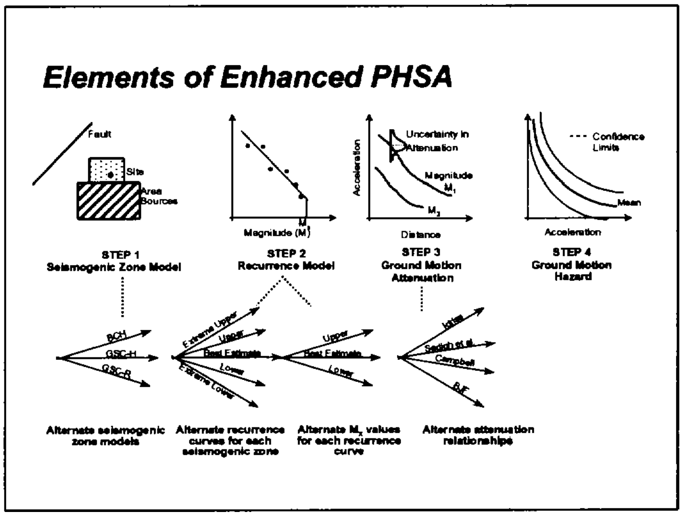

Fig. I-4 'Enhanced' Probabilistic Seismic Hazard Analysis (since 1995 at BC Hydro)

The first 'experiment' using the de-compositional event tree approach was carried out on BC Hydro's Terzaghi Dam. However, the study raised more questions than it provided answers, and it was terminated without being brought to a conclusion. Therefore it was not possible to draw any conclusions about the validity of the analysis method or to make any inferences concerning the safety of the dam on the basis of this study. BC Hydro consented to the publication of brief accounts of the principles involved in this analysis (e.g. Vick and Stewart, 1996) with the view to gauging the reaction of the profession. This consent does not constitute endorsement of either the method of analysis or any inferences that might be made concerning the safety status of the dam.

In early 1993, the general feeling in BC Hydro's engineering group was that estimation of risk through analytical means was easier said than done. Analysis of risk through *decomposition* of the various aspects of the physical phenomena involved into their fundamental components was recognised as being extremely difficult and required very significant effort and expertise. This realisation cast serious doubts as to the validity of existing 'judgmental' estimation of dam response probabilities. In summary, the question "*If the problem is difficult to analyse, then how can one make reasonable judgements of the probable response of the dam to extreme loads?*" arose and was one of the most vexing questions raised by these pilot studies as it called into question the methods used to estimate probabilities in existing risk-based decision analysis methodologies.

BC Hydro's engineers understood that to succeed it would be necessary to develop robust 'de-compositional' models of dam failure mechanisms. This required that they address issues deemed by others (e.g. Peck, 1980, Baecher et al, 1980) to be *'nigh on impossible'*. With the added complication that, even if general theories of dam failure could be developed, they would necessarily require refinement to account for the unique features of each dam and dam site. Although these pilot studies did not provide scientifically based analytical techniques that could be applied with confidence, they did suggest that it might be possible to estimate risks posed by dams along the lines suggested by Whitman. The 'apparent alternative' was to fix fundamental mathematical and philosophical problems with the *'empirical/judgmental'* approach to estimating dam response probabilities. This course of action was ruled out, not just because of the intractability of the mathematical problems but also because it was clearly understood that the event tree model of the failure process and the probabilities assigned at nodes in the tree were inextricably linked (Hartford and Salmon, 1995). This problem here being that the 'probability' is an artefact of the model and the manner in which epistemic and aleatory uncertainty are represented.

BC Hydro's framework for risk assessment was established in September 1993 in the form of *'Interim Guidelines'*, which included a trial example of an event tree analysis for extreme floods and earthquakes (BC Hydro, 1993). The *Interim Guidelines* were presented for discussion within the profession, and summary papers were issued over the next two years. Shortly thereafter in January 1994 and entirely independently, the Australian National Committee on Large Dams (ANCOLD) issued *Guidelines on Risk Assessment for Dams* (ANCOLD, 1994). The ANCOLD guidelines and the BC Hydro *Interim Guidelines* were conceptually very similar. According to ANCOLD, *"the immediate objective of many of those advocating risk assessment in current practice is to provide defensible design solutions as economic optima that are likely to be of lower cost than those that result from a traditional engineering standards approach to design."*

At the time, this analysis work did not meet with any serious objections, and this created the impression that all of the problems of analysing risk posed by dams had been resolved. In other words, it appeared that the concerns of Casagrande, Peck and others as well as the issues outlined by Baecher et al. might have been adequately addressed. This is not to say that there was not scepticism; there was (e.g. Fanelli, 1991, Lafitte, 1992, 1993, Lombardi, 1993, Ruggeri et al., 1993), but the written objections were not specific to the method of analysis. Further, risk assessment, which includes the use of risk analysis to address life safety issues for dams, did generate significant critical comment. However discussion of these broader policy issues is beyond the scope of this paper.

This lack of adverse comment on the analytical procedures was of concern to me and other BC Hydro staff, as initiatives of this nature are inevitably controversial. Given the divisions in the profession, the almost unquestioned acceptance of the approach by sections of the dam engineering community was disconcerting. This lack of adverse comment concerning the analytical procedures could not be interpreted as general acceptance of risk assessment. Absence of evidence cannot be interpreted as evidence of absence!

One section of the dam safety profession appeared to accept that dam failure processes could be described by a relatively small number of failure modes: two extreme-event failure mode initiators, earthquake and flood, and one general 'static' failure mode. Further, there was little or no debate concerning the difference between this 'de-compositional' approach and the 'empirical/judgmental' approach. The de-compositional models of failure mechanisms for each failure mode appeared to be accepted at face value; partly it seems because the models depicted generally accepted descriptions of failure mechanisms. The question as to whether or not the failure mechanism was fully decomposed into its fundamental parts required attention.

In BC Hydro's early risk analysis 'experiments', probabilities were assigned using the scheme proposed by Vick (1992) for transforming verbal descriptions of the 'degree-of-belief' of the study team to numerical values. Successful application of this mapping scheme depends on Bernoulli's Principle of Indifference being valid.

Verbal descriptor	*Probability*
Event is virtually certain	*0.99*
Event is very likely	*0.9*
Completely and totally uncertain[1, 2]	*0.5*
Event is very unlikely	*0.1*
Event is virtually impossible but cannot be physically ruled out	*0.01*

Table I-2. Mapping scheme suggested by Vick (1992)

Although not known at the time, this was the 'Kent Chart' approach to quantifying verbal descriptions of probability which had previously been tried and subsequently abandoned by US military intelligence (Cooke, 1991). Further, the approach did not find much in the way of acceptance in Australia where investigations into risk analysis were also being carried out. The issue of assigning a probability P = 0.5 as representing uncertainty raised the most serious concerns

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[1] Vick subsequently revised the descriptor adding that the condition that there was no preference for either outcome.

[2] The US Bureau of Reclamation uses the term 'neutral' to describe *'no preference for either outcome'*.

P = 0.5 occurs in many problems of probability, the most well known one being flipping coins. However, hidden in much literature discussion of the meaning of **P** = 0.5 is Bernoulli's **"Principle of Insufficient Reason"** (the name is due to Von Kries –(Howson and Urbach, 1991)). Keynes (Keynes, 1931) described it, the **"Principle of Indifference"**, a description also preferred by modern philosophers (Howson and Urbach, 1991).
According to Keynes; *"The principle of indifference asserts that if there is no* ***known*** *reason for predicating of our subject one rather than another of several alternatives, then relative to such knowledge the assertion of each of these alternatives have an* ***equal*** *probability. Thus* ***equal*** *probabilities must be assigned to each of several arguments, if there is an absence of positive grounds for assigning* ***unequal*** *ones".*

Keynes was highly critical of Bernoulli's principle, largely because it leads to paradoxical and contradictory conclusions. He quoted several, but the engineering/scientific example attributed to Von Kries presented by Keynes and reproduced below provides a useful insight into one of the many difficulties.

"Consider the specific volume of a given substance. Let us suppose that we know the specific volume to lie between 1 and 3, but we have no information as to whereabouts in this interval its exact value is to be found. The principle of indifference would allow us to assume that it is as likely to lie between 1 and 2 as between 2 and 3; for there is no reason for supposing that it lies in one interval rather than in the other. But now consider the specific density. The specific density is the reciprocal of the specific volume, so that if the latter is ***v****, the former is 1/v. Our data remaining as before, we know that the specific density must lie between 1 and 1/3, and, by the same use of the principle of indifference as before, that it is as likely to be between 1 and 2/3 and 2/3 and 1/3. But the specific volume being a determinate function of the specific density, if the latter lies between 1 and 2/3, the former lies between 1 and 1½, and if the latter lies between 2/3 and 1/3, the former lies between 1½ and 3. It follows, therefore, that the specific volume is as likely to lie between 1 and 1½ as between 1½ and 3; whereas we have already proved, relatively to precisely the same data, that it is as likely to lie between 1 and 2 as between 2 and 3."*

Von Kries' complete treatment was not left uncriticised but according to Keynes, the criticism could not "restore the credit of the principle of indifference". Keynes continued,

"Moreover, any other function of the specific volume would have suited our purpose equally well, and by a suitable choice of this function we might have proved in a similar manner that any division whatever of the interval 1 to 3 yields sub-intervals of equal probability. Specific volume and specific density are simply alternative methods of measuring the ***same*** *objective quantity; and there are many methods which might be adopted, each yielding on the application of the principle of indifference a different probability for a given objective variation in the quantity."*

The specific volume/density example is just one of a great many instances where the principle of indifference produces untenable outcomes, and this example illustrates just one of the many issues that one needs to be cognisant of when assigning **P** = 0.5.

Ironically, Keynes, in an attempt to overcome the problem of inconsistency inherent in the Principle of Indifference, developed his own version; however, he did not succeed in overcoming the fundamental problems with the concept.
One of the dilemmas that all of this poses for risk analysts is as follows:

Compare the case where all of the evidence shows that 50% of the evidence supports a proposition and 50% supports its antithesis with that of the case where there is no evidence to support the hypothesis or its antithesis and therefore no reason to prefer one hypothesis over the other. Perfect knowledge and complete ignorance are represented by the same 'Probability'.

Some challenges associated with the above discussion on probability is that dam risk analysts need to clearly explain and communicate:

- What they mean by probability
- How they assemble the evidence
- What they mean by **P = 0.5**, and
- How they translate the evidence into numerical values of probability.

*"Before the ascendance of the modern theory, the notion of equal probabilities was often used as synonymous for "****no advanced knowledge****."* (Feller, 1968). There is no place for Bernoulli's Principle of Indifference in the modern theory of probability, although an analogous principle holds in the probability of gambling. This is an important distinction as 'indifference' concerning the outcome of a gamble and 'equal weights of evidence'.

In addition to the problem with P = 0.5, the mapping scheme did not clearly outline that the probability was a measure of the degree of confidence that the individuals had in their belief in the outcome at each node in the event tree.

By 1994, the 'trial' approach to dam risk analysis that BC Hydro was experimenting with became a 'commodity engineering' service. It was possible for owners to issue requests for proposals for what appeared to be the BC Hydro type of risk analysis service and to receive offers to perform the work. In-house engineering staff in other utilities also began to implement the approach. However, BC Hydro's *Interim Guidelines*, which for many was a principal source of reference, contained the results of only one pilot study and importantly, the procedures for conducting the analysis were not included as they had not been developed. However the situation was rather more complex and any impression that quantitative risk analysis could be treated as a routine engineering service was clearly without foundation.

At the early stages, BC Hydro's strategy was to apply existing or proposed methods of analysis to a wide range of dam safety issues. One objective of this strategy was to use the insights generated to enhance on-going dam safety decision-making.

A second objective was to identify through experience of application, the strengths and weaknesses of existing or proposed risk analysis methodologies. The 'practice' that emerged in 1994 had been established in the absence of the necessary investigations into the strengths and weaknesses of the proposed method. Further, the 'practice' was not necessarily delivering the proposed 'BC Hydro' approach. The approach that emerged in the State of Victoria in Australia for portfolios of dams was a hybrid of the USBR's risk-based decision analysis and the BC Hydro decision criteria. (e.g. SMEC/RAC, 1995, Watson et al., 2000). Although termed risk assessments, these approaches are not risk assessments in the accepted sense, and no analytical procedures were used to estimate the risk.

Because its dam safety program was quite mature and most of the obvious issues had been identified through the use of traditional methods of analysis, BC Hydro also had an interest in the many aspects of dam safety decision-making not readily addressed by conventional analytical methods. Risk analysis was seen as having the potential to extend conventional dam safety analysis to consider the dam as a system and to consider all aspects of behaviour in a consistent manner.

The successful application of risk analysis in any dam safety program requires the development of a robust and fully integrated general set of theories of dam failure processes. It also requires the development of a database of experience and evidence to validate the theories, and to make possible the exercise of judgement by suitably experienced dam engineers for application in specific cases.

In 1994, as part of its strategy, in response to concerns expressed by some of BC Hydro's engineering staff, and in the absence of significant criticism of the proposed analytical procedures, BC Hydro's risk analysis project staff began to investigate the validity of various aspects of the analysis procedures.

Some of the reasons for the concerns were:

1. Pilot analyses of concrete dams tended to produce much shorter event trees and much higher failure probabilities than earthfill dams, especially under earthquake and flood loading conditions. This led to the inference that concrete dams were much more vulnerable than earthfill dams, an inference that is not supported by the historic evidence of the generally better performance of concrete dams!
2. The estimate of risk was found to be highly dependent on how the failure process was modelled.
3. In some cases, the estimate of risk was found to be highly dependent on the individuals estimating the probabilities, with no means of discriminating between estimators.
4. In other cases, the estimate of risk was not sensitive to the probabilities assigned if complementary paths at certain nodes in the event tree model led to failure.
5. In most cases, the pilot analyses indicated that the risk associated with combinations of conditions associated with less than the most extreme earthquakes and floods constituted the highest proportion of the risk. Here again, it was not clear if this phenomenon was an artefact of the model and the people making the estimate.
6. There was concern that the estimate of risk was an artefact of:
   - The event tree.
   - The scheme for assigning probabilities.
   - The knowledge and biases of the person assigning the probabilities and not a 'measure' of the safety of the dam.

Other issues included:

- The need to demonstrably and effectively address the concerns of the various eminent experts who had previously cast doubts as to the feasibility of risk analysis.
- The clearly identified difference in level of effort between analytically derived probabilities and 'judgmental' probabilities.
- The compatibility of estimates of failure probabilities made using analytical techniques and the 'judgmental' estimates made in terms of the procedures outlined by NRC (NRC, 1983) and still used in practice (SMEC/RAC, 1995).

An underlying concern can be summarised as: "Is this too good to be true?" It appeared that teams of dam safety engineers could assign 'subjective probabilities' based on their 'degree-of-belief' in a hypothesis and be able to quantify the risk due to all dam failure modes in about a week! This was achieved in the absence of:

- Expertise or training in probabilistic reasoning.
- A statistically valid empirical database of failure modes mechanisms and frequencies.
- Robust theories of dam failures.
- Demonstrably fully decomposed models of the failure processes.

Another concern of mine was that "the grossly simplified 'judgmental' approach could be applied with even less effort even though probability is notoriously complex with numerous examples of probability playing tricks with ones intuition and 'judgement'".

Questions to be addressed included but were not restricted to:

1. The scientific validity of the de-compositional models of the failure mechanisms.
2. The mathematical and philosophical basis of the interpretation of 'subjective probability' as applied in the analyses.
3. The scientific validity of the process for estimating 'judgmental probabilities' as assigned by analysis teams.
4. The interaction between the extent of decomposition of the failure mechanism and the estimate of risk.
5. Expertise, experience and knowledge requirements of analysis teams.
6. Site specific information needs for input to analysis models.
7. Could anything be done to make the probability estimates 'tamper-proof' and not open to manipulation?
8. The validity of comparing subjective estimates of risk with objective decision criteria.
9. Was the process of estimating 'judgmental' probabilities really the exercise of judgement or was it something less and if so how much less?
10. What did the subjective estimates of probability and

resulting risk estimates actually mean and what can they be used for?

11. Did the risk analysis process, as implemented, actually lead to a better understanding of the performance of the dam under all possible conditions or was the claimed 'improved understanding' simply a perception of those involved?
12. Could dam owners rely on risk analysis as a component of a dam safety decision-making process?

Clearly, given the broad range of issues to be addressed and questions to be answered, it would have been inappropriate not to address them to the fullest possible extent. At the same time, BC Hydro felt that the appropriate approach was to continue performing a limited number of risk analyses, while gradually addressing the issues of concern.

In 1993/94, BC Hydro performed a risk analysis for seismically induced liquefaction of the foundation soils of its Murrin 2 Substation. The method of estimating the probability of liquefaction proposed by Liao et al. (Liao et al., 1988) provided the basis for the analysis, and Professor Whitman was engaged to review the work. The geotechnical properties of the site had been extensively investigated, and there was a considerable amount of information about the performance of similar substation structures and equipment during earthquakes.

Prior to the risk analysis, a Failure Modes and Effects Analysis (FMEA), facilitated by consultant Steven G. Vick, was conducted. All of the technical disciplines involved in determining the effects of earthquakes on the electric system was represented as were the field staff who operate the system and managers who would plan the response. The FMEA provided the necessary precursory collection and formatting of information necessary to proceed to the risk analysis phase. This exercise led to BC Hydro adopting the position that FMEA should be considered as an essential precursor to more detailed risk analysis studies rather than the more subjective, unstructured 'failure mode screening' typically carried out in dam safety risk analyses.

In conducting the risk analysis phase, BC Hydro's engineering staff departed from the 'workshop' approach to constructing event trees and assigning subjective probabilities as attempted for dam safety risk analyses. Instead, the engineers responsible for the project developed a framework to analyse the risk and implemented the 'de-compositional' approach to engineering analysis from the top down. The seismic risk problem for the substation as a whole was 'decomposed' into discipline-based tasks. The discipline-based tasks provided the sub-frameworks for the 'de-compositional' engineering analysis of each aspect of the problem to be carried out. The discipline-based tasks were:

1. Probabilistic seismic hazard analysis
2. Probability of liquefaction analysis
3. Ground deformation analysis given liquefaction
4. Ground shaking analysis given no liquefaction
5. Structural response analysis given deformation and shaking
6. Structural response analysis given shaking
7. Damage states analysis
8. Times to repair analysis

Owing to the nature of the problem, and experience obtained from California and Japan, the necessary theories and models were available to perform the analysis (Garner et al., 1998). The probability of liquefaction of the foundation fills is illustrated in Fig. I-5.

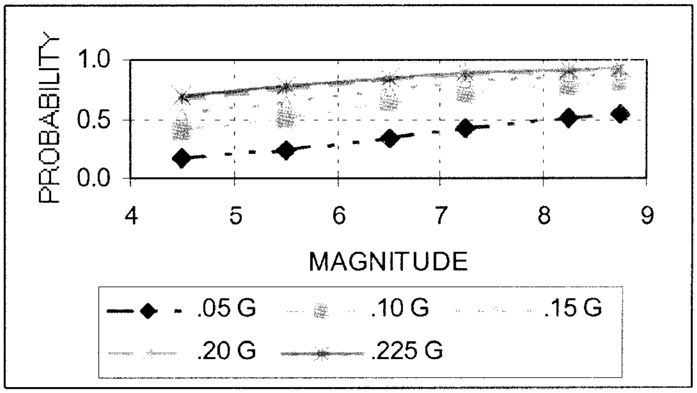


Fig. I-5. Probability of liquefaction of foundation fills (after Garner et al., 1998)

Ground failure phenomena resulting from liquefaction were expected to have several forms-flow slides, settlement and lateral spreading. Lateral spreading occurring in near-liquefied soils is considered the most important ground failure mechanism for this site.

Three deterministic methods and one linear regression method were evaluated to establish the most appropriate method for determining the potential ground movements. The Bartlett and Youd method (Bartlett and Youd, 1992) for computing lateral spreading was chosen as the preferred method of analysis. Bartlett and Youd's process requires estimation of the ground surface PGA which includes amplification effects (Garner et al., 1988).

The results were presented as F-N curves of probability of substation outages greater than 'N' hours. It quickly became obvious that risk represented in this way was as much an artefact of the way the data is presented as it is the risk analysis.

Discussion of this issue is unfortunately beyond the scope of this paper but is mentioned here as F-N curves for life safety considerations for dams began to appear around this time (ANCOLD, 1994). Despite clear problems with the F-N representation of risk and warnings that it may not be suitable for situations such as dam failures (HSE, 1999), it remains a preferred representation of risk to life by some proponents.

The Murrin Substation Risk Analysis demonstrated that, in principle, the analytical techniques were available to permit the probability of failure of earth dams to be determined by analytical means. The next stage in the development of analytical methods of quantifying the risk posed by dams was to perform a feasibility study by applying these techniques to a dam. This feasibility study led to the Keenleyside Dam risk analysis, which (as far as I am aware) is the only analytically based risk analysis of a dam to be completed to date. Details are presented in Part II of this paper.

In 1995, the USBR joined BC Hydro in its quest for the answer to the question *How Safe Is The Dam?... Is it Safe Enough?* In order to get started in risk assessment and build on the concepts embodied in their 1989 Policies and Procedures for Dam Safety Decision-making, the USBR invited Dr. M.G. Schaefer, Mr. G. Salmon and myself to present a workshop on risk assessment in dam safety practice. Dr. Schaefer had led the development of the State of Washington's Risk-Based approach to dam safety decision-making and was and still is active in the field of quantifying probabilities of extreme precipitation events.

Towards the end of 1995, BC Hydro published (Hartford and Salmon, 1995) some of its concerns about the difficulties associated with de-compositional risk analysis and simplified 'degree of belief' approaches to probability estimation. At the same time, a feasibility study of the probability of liquefaction failure of Keenleyside Dam was carried out using the method of analysis pioneered in the Murrin Substation risk analysis. Investigations into simplified approaches to specific problems continued. Also, a firm of consultants was commissioned to perform a comprehensive quantitative risk analysis of a concrete dam for all possible failure modes. Despite an unprecedented level of effort, it was not possible to bring the risk analysis of the concrete dam to a robust conclusion. Further, all of the investigations into simplified approaches failed to provide a satisfactory means of quantifying risk.

THE WATERSHED YEARS: 1995 – 1998

In recognition of the difficulties described above, BC Hydro adopted a dual strategy (simplified and detailed) of research and development. This involved continued investigations into simplified (practical) approaches with parallel investigations into rigorous methods for estimating risks posed by concrete and earthfill dams. The most unusual feature of the early 1990's effort was the concerted attempt to develop a 'practice' without first establishing its theoretical foundations. We recognised that we were essentially trying to develop guidelines for risk analysis in dam safety practice in advance of the usual period of 'trial and error'. What transpired was the 'Achilles heel' of the early 1990's attempts to introduce risk analysis as a professional dam safety service.

The 'simplified path' recognised the need for pragmatic approaches to risk management to be applied generally in practice in an efficient and effective way. The 'detailed path' was based on the principle that 'you only genuinely know if you have taken a short cut if you have previously reached the same destination by a longer route'. Essentially we had gone back to the fundamental philosophies of geotechnical engineering practice as espoused by Terzaghi in his *Theoretical Soil Mechanics* and repeated in *Soil Mechanics in Engineering Practice.*

The strategy required several simultaneous studies, and it also presented an opportunity to examine how different professional groups addressed the difficult issues involved. Most investigations were carried out by BC Hydro staff supported by consultants ranging from a highly specialised team focusing on one hazard and one failure mode, to teams of generalists using simplified approaches carrying out multidisciplinary studies. The concrete dam study, which was the largest and most comprehensive, was awarded to a firm of consultants.

This strategy differed from the general trend adopted by most other investigators who favoured simplified approaches to failure mechanism modelling, empirical formulae and 'empirical/judgmental approaches. At the same time (1996), the Hume Dam incident prompted a detailed risk analysis in Australia, which, by default, resulted in an unplanned dual experience base in Australia.

This development was most unexpected although it was in fact a case of history repeating itself as ANCOLD and BC Hydro had, in 1994, come to coincident conclusions concerning the general principles of risk assessment in dam safety practice.

In adopting the dual strategy, BC Hydro had an unparalleled experience base to evaluate the success of its investigations. By 1998, BC Hydro carefully examined the success of the various initiatives and concluded that 'simplified approaches', while desirable in concept, were not achievable given the analytical techniques available. BC Hydro also concluded that detailed analytical estimates of risk could only be made under very special circumstances because, for the most part, the necessary analytical procedures were either overly crude or non-existent. In particular, BC Hydro concluded that fundamental philosophical and scientific problems with simplified de-compositional approaches to failure mechanism analysis and probability estimation using 'Kent Charts' rendered the approach unsuitable for decision-making concerning the safety of dams. In reality, BC Hydro had produced empirical evidence supporting the hypotheses of earlier years mentioned previously (Casagrande, Baecher et al., Whitman) that reliable quantification of risk would be difficult and beyond the capability of most engineers. Further, it was perfectly clear that Lambe's observation that there was a need for Type A predictive models was correct.

These were profound developments from an engineering perspective, because, in principle, Casagrande's proposal, as developed by Whitman, was feasible provided Lambe's Type A predictive models were available. Importantly these huge advances in engineering were accompanied by even greater changes in risk management in general.

In 1997, BC Hydro concluded that the 'engineering' approach to risk assessment, i.e. estimate the risk and compare against 'arbitrarily selected decision criteria' for use in decision—making was fundamentally flawed. BC Hydro also recognised that risk analysis was of limited value if it was not carried out within a risk management and risk control framework that is legally defensible and acceptable to knowledgeable regulators and the public. This led to the development of BC Hydro's dam risk management system, the architecture of which is gaining increasing acceptance in international practice (Fig. I-6).

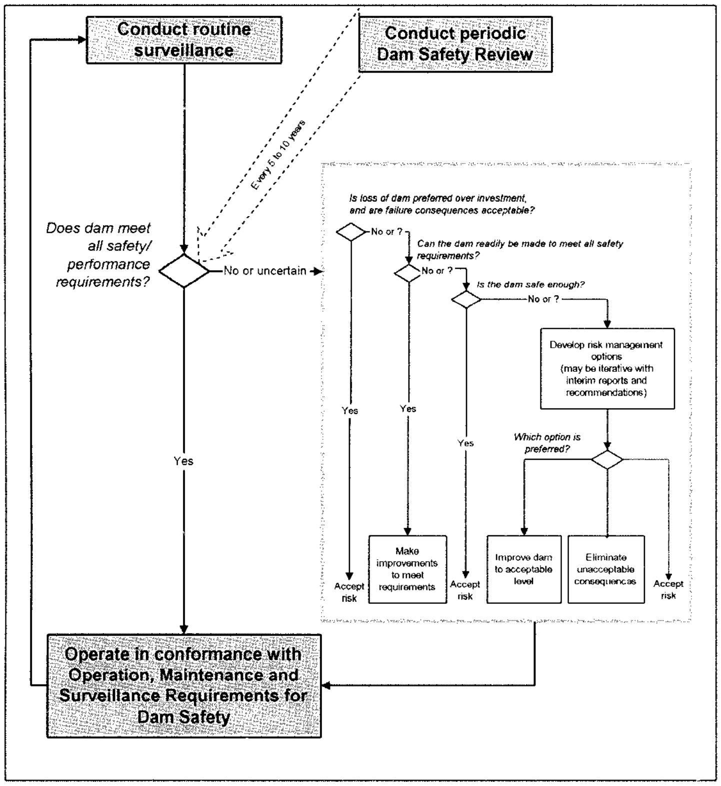


Fig. I-6. BC Hydro's Dam Risk Management System

By the end of 1998, BC Hydro's position concerning the role of risk analysis in dam safety practice was distinctly different to contemporary trends, which continued to be based on simplified approaches. In some respects, we were mistakenly perceived as having unrealistically high standards employing 'impractical' (from the perspective of lowest cost to the owner and 'commodity' engineering experience) analytical procedures. However, we remained undeterred as history (including our own extensive experience) indicated that quantitative risk analysis in dam safety practice was difficult and possibly even impossible for some cases, especially if not practised within a structured risk management procedure.

THE EVE OF Y2K

As Y2K approached, it became clear that society expected owners of 'risky' facilities to be much more accountable for the safety management of their operations. The end of the 1990's saw a paradigm shift in risk regulation with increased requirements for owners of hazardous facilities to obtain and maintain public trust. Decisions concerning risk to the public from engineered facilities no longer rest with owners and their engineers with the result that decision-making procedures concerning risk posed by dams would never be the same again. The most comprehensive treatment of the role of risk assessment in the management of catastrophic risks (e.g. dam failures) was produced by the UK Health and Safety Executive in 1999.

On the eve of Y2K, all of the procedures and requirements for scientifically valid and legally defensible assessment of risk posed by dams were, in principle, in place. The analytical engineering procedures are outlined in Part II.

Y2K AND BEYOND

At the time of writing, Y2K is not over and the outlook for risk analysis in geotechnical earthquake engineering beyond Y2K is somewhat, but not completely, unclear, as evidenced by Vol. I of the Proceedings of the 20th ICOLD Congress held in Beijing in September 2000. The 'dual path' that emerged in Australia resulted in two apparently diametrically opposite points of view. At one extreme there is the view that *"methodologies for estimating the chance of dam failure are poorly developed and, at the present time, do not provide a defensible basis for the conclusive sign off on the safety status of a dam"* (McDonald et al., 2000). At the other extreme, there is the view that *"methods are available for estimating the probability of failure of dams for use in Quantitative Risk Assessment for all failure modes"* (Fell et al., 2000).

Importantly, the conclusions reached by McDonald et al, who had explored the detailed analytical approach, also coincided with those of BC Hydro. These observations are further investigated in Part II of this paper.

PART II
QUANTIFICATION OF SEISMIC RISK FOR EARTH DAMS

CASE STUDY 1 – HUGH KEENLEYSIDE DAM

The purpose of presenting this section in this format of a "slide presentation" is to illustrate most effectively and concisely the essential features of one half of a detailed quantitative risk analysis, recognising that any detailed account would require an entire volume. This problem was well recognised by Terzaghi (Terzaghi, 1942) and, because scientifically-based quantitative risk analysis for dams requires an enormous amount of effort, it is not amenable to publication and peer review in the academic journals unless special arrangements can be made. To date, the necessary arrangements for publication of peer reviewed papers on quantitative risk analysis of a scientific nature in the established engineering and scientific literature has not occurred.

A very abridged account of one part of the Hugh Keenleyside Dam quantitative risk analysis is described. The risk analysis has been restricted to:

- one section of the earthfill dam system (the centre section),
- one hazard (seismic) and,
- one failure mode (seismically-induced liquefaction).

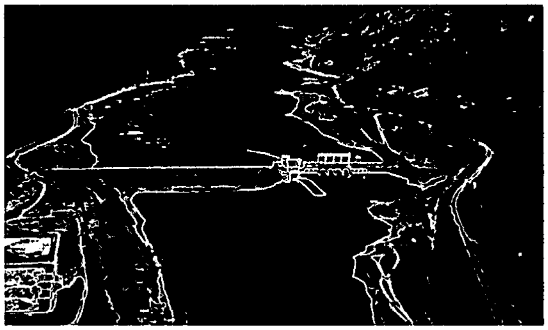
I have deliberately omitted one half of the risk analysis, the consequence analysis.

The Hugh Keenleyside Dam (formerly Arrow Dam) is located on the Columbia River about 8 km upstream of Castlegar, British Columbia. The dam impounds the Arrow Lakes Reservoir, which has a storage volume of 8.8 x 10^9 m^3 and extends 233 km north to the city of Revelstoke. The regulation of this reservoir, under the terms of the Columbia River Treaty, provides both flood control and increased hydroelectric generation at plants located further downstream in the United States. There are currently no power generation facilities at this dam.

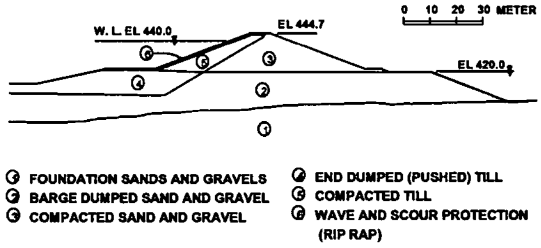
The dam, which has a total length of 810 m, comprises a 58 m high concrete gravity structure, 360 m in length, a navigation lock, concrete bulkhead sections and a 52 m high earthfill dam 450 m in length. The impervious barrier comprises an upstream till core connected to an impervious blanket that extends 670 m upstream.

In 1990, BC Hydro's seismic hazard studies indicated that updated seismic design parameters were significantly higher than those used for the original design of the project over 25 years ago. Consequently, seismic stability studies of the concrete dam and earthfill dam were initiated in 1990 and 1991 respectively. The seismic study of the earthfill dam was initiated to assess the liquefaction potential and seismic stability of the earthfill dam and foundation materials. Screening level studies, which included field investigations and simplified analyses, indicated that extensive liquefaction could be triggered during the Maximum Design Earthquake (MDE) in the lower 20± m of the earthfill dam. Subsequently, additional field and laboratory investigations and more detailed analyses were carried out.

Keenleyside Dam



Middle Cross-section of the Earthfill Dam



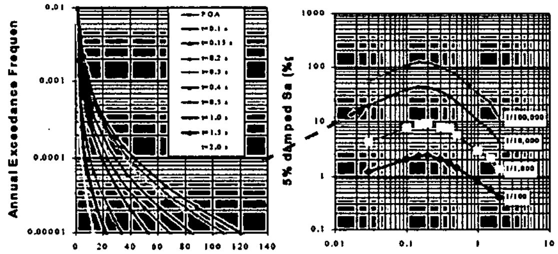
Probabilistic Seismic Hazard Analysis

A state-of-the-art probabilistic seismic hazard analysis (PSHA) was carried out by BC Hydro, which permitted probabilistic description of:

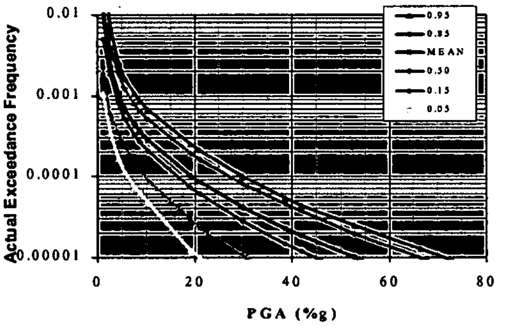
- Peak Ground Acceleration (PGA),
- Peak Ground Velocity (PGV),
- Spectral Acceleration (S_a),
- Magnitude,
- Epicentral distance, and
- Response spectrum.

The enhanced PSHA considered both aleatory and epistemic uncertainties, with the "mean" seismic hazard expressed as annual exceedance frequency of the peak ground acceleration, together with confidence bands (expressed as fractiles). Owing to the general lack of defined faults, the average potential hazard across the region was used as the basis for characterising the seismic hazard. The outputs of the PSHA were expressed in the various forms required for the dam response analysis.

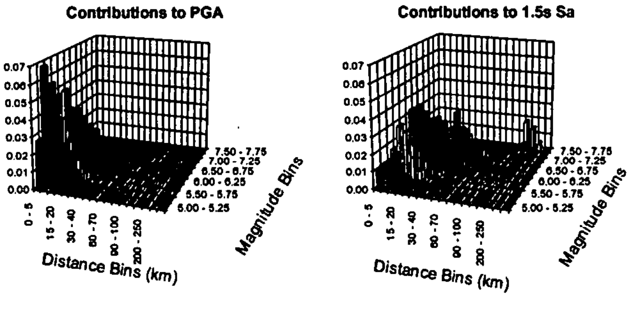
Uniform Hazard Response Spectra



Uncertainty in PGA Hazard



Magnitude-Distance De-Aggregation



Typical seismic parameters required as input to assess the dam response were:

- PGA and S_a hazards, complete with mean values and the uncertainties,
- De-aggregation of the seismic hazard by magnitude and distance,
- Uniform hazard response spectra, and,
- Parameters for assisting in time history selection.

Dam Response Analysis

The first stage of the dam response analysis involved a dynamic analysis of the main section of the earthfill dam. The inputs to the analysis comprised the outputs of the PSHA and the geotechnical parameters of the soil materials comprising the dam and the foundation as obtained from field and laboratory investigations.. Focus for the dam response analysis was obtained by first performing a simplified screening analysis using basic calculations and empirical charts. This was followed by detailed analysis generally involving dynamic response analyses using up to six earthquake records as inputs. The outputs of the PSHA were treated "deterministically" by selecting appropriate values of peak ground acceleration (PGA) and the currently accepted maximum magnitude of the design earthquake (MDE) (e.g. PGA with an annual exceedance frequency (AEF) of 10^{-4}, coupled with a magnitide of = 6.5). The matter of deterministic definition of the MDE on the basis of PSHA is controversial and is further complicated by enormous inconsistencies between deterministic performance goals for earthquake and flood hazards. Treatment of the problem of seismic performance goals is beyond the scope of this lecture, but it is worth noting that these problems are restricted to deterministic performance goals, problems that are overcome in the risk assessment approach. Design spectrum were based on the 1991 work of Idriss, supplemented with the later update presented by Idriss (1998).

Detailed original site investigation and construction records were available. In addition, the results of detailed investigations of the dam carried out in the 1990's using state-of the-art investigative techniques were collected. Exploration methods included standard and cone penetration tests with appropriate consideration of the method of penetration and energy calibration. For the more gravelly soils, the Becker penetration test, with appropriate corrections, was used. The gravely nature of the soils, which were barge dumped through flowing water at the time of construction, posed significant challenges both for investigation and subsequent analysis.

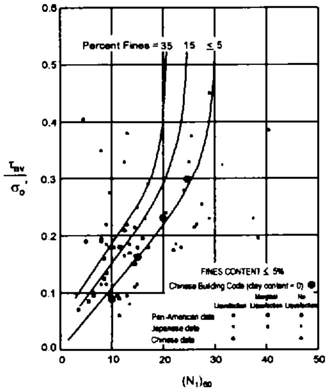
For the purpose of modelling liquefaction, it was assumed that the established model for seismically induced liquefaction of granular soils applied, although there was some uncertainty concerning the validity of this assumption. This assumption was subsequently investigated further. The fundamental features of the model were:

- When loose granular soil is subjected to vibration or cyclic shear loading, the soil skeleton tends to compact to a smaller volume.
- If the soil is saturated and the water within the pore is prevented from draining, the load originally carried by the soil skeleton is gradually transferred from the intergranular stress to the pore water.
- With the reduction in the intergranular stress, the stiffness and the shear strength of the soil become smaller and smaller.

- The consequence is that the deformation becomes larger and larger. When the strength becomes less than the static shear load, FLOW SLIDE becomes likely

The Lower San Fernando Dam case history of seismically induced liquefaction and slumping provides empirical evidence supporting the modelling assumptions. Soil liquefaction triggering was based on the work of Seed et al. (1984-1985)

Soil Liquefaction Triggering



based on Field Performance

Relationship between stress ratios causing liquefaction and $(N_1)_{60}$-values for clean sands and silty sands for M = 7.5 Earthquakes

(After Seed et al., 1985)

Typical Screening Analysis for Liquefaction

Chart for Liquefaction Assessment is due to Seed et al (1987)

CSR is Cyclic Stress Ratio

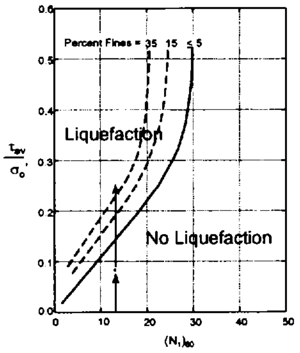
$$CSR = 0.65 \cdot \frac{\gamma_{sat}}{\gamma_w} \cdot A \cdot r_d$$

γ_{sat} is the saturated unit weight

γ_w is the unit weight of water

A is peak ground acceleration

r_d is a reduction factor dependent on the depth of soil element under consideration

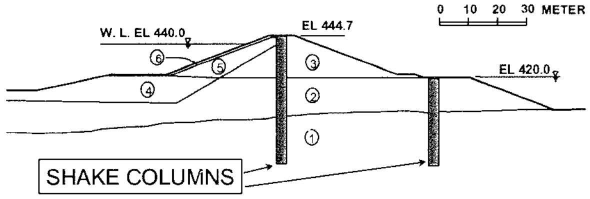


For the purposes of obtaining the cyclic stress ratio (CSR) from 1-Dimensional (SHAKE) (Schnabel et. al, 1972) and 2-Dimensional (FLUSH) (Lysmer et. al, 1975, 1979) time history dynamic response analyses, three to five earthquake records were selected for the deterministic analyses based on the peak ground acceleration, magnitude and the shape of the design spectrum. The calculated CSR was then used to determine the zones of liquefaction and high excess pore pressure. This provided the ability to determine the post earthquake stability using limit equilibrium analysis, or post earthquake deformation (crest slumping) using finite element deformation analysis.

The selected earthquake record, expressed in terms of acceleration time history, served as the input to the dynamic analysis (SHAKE model), which utilised a non-linear strain dependent stress-strain relationship. The dynamic response analysis involved an 'equivalent linear analysis' where, through iteration, the shear moduli in different layers were compatible with the average strains developed.

1D Shake Analysis

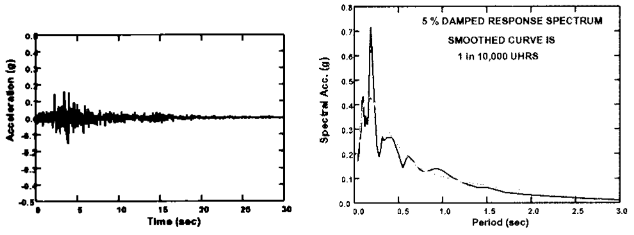
Middle Cross-section of the Earthfill Dam



1 FOUNDATION SANDS AND GRAVELS
2 BARGE DUMPED SAND AND GRAVEL
3 COMPACTED SAND AND GRAVEL
4 END DUMPED (PUSHED) TILL
5 COMPACTED TILL
6 WAVE AND SCOUR PROTECTION (RIP RAP)

Selection of Acceleration Time Histories

Selected PGA was 0.22 g, M6.5



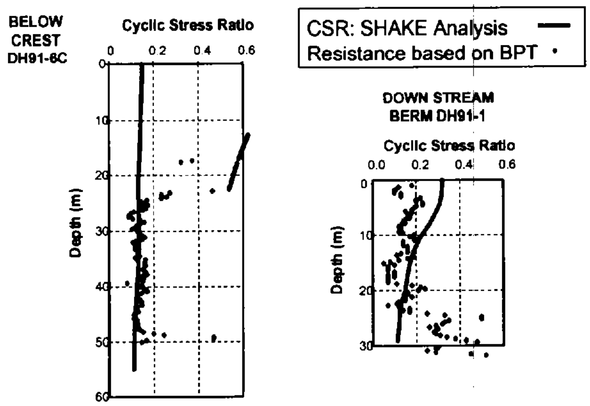
SAN FERNANDO, CALIFORNIA EARTHQUAKE, FEBRUARY 9, 1971

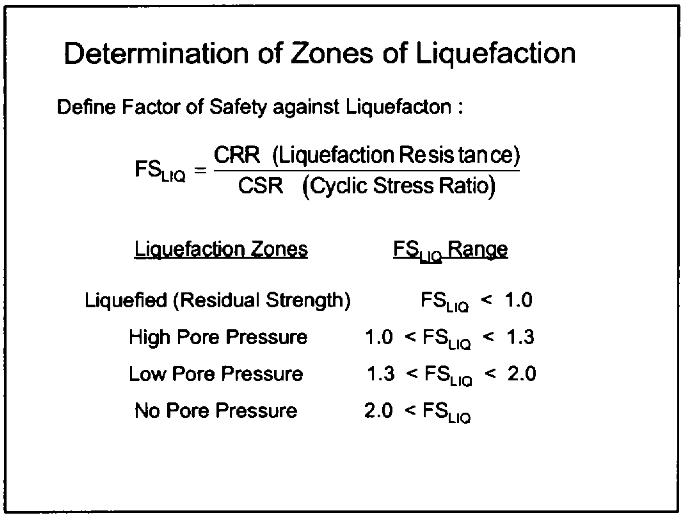
Stn.: LAKE HUGHES, STATION #4

CHAN 1 ; N21W ; Scale Factor = 1.100

The output of the SHAKE analysis for the two representative columns provided the calculated variation of CSR with depth at the specified locations. Zones of liquefaction were defined in terms of Factor of Safety against Liquefaction

Liquefaction Analysis using SHAKE Results





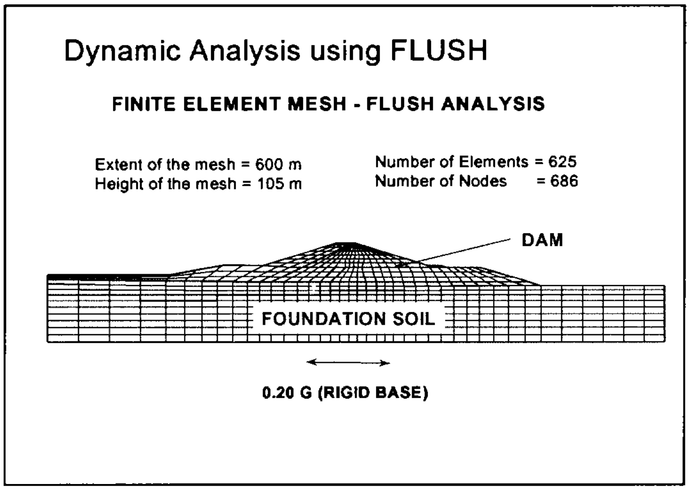
Determination of Zones of Liquefaction

Define Factor of Safety against Liquefacton :

$$FS_{LIQ} = \frac{\text{CRR (Liquefaction Resistance)}}{\text{CSR (Cyclic Stress Ratio)}}$$

Liquefaction Zones	FS_{LIQ} Range
Liquefied (Residual Strength)	$FS_{LIQ} < 1.0$
High Pore Pressure	$1.0 < FS_{LIQ} < 1.3$
Low Pore Pressure	$1.3 < FS_{LIQ} < 2.0$
No Pore Pressure	$2.0 < FS_{LIQ}$

The more refined 2-dimensional finite element FLUSH analysis also utilised the frequency domain analysis method, a non-linear strain dependent stress-strain relationship, and the 'equivalent linear analysis' technique.

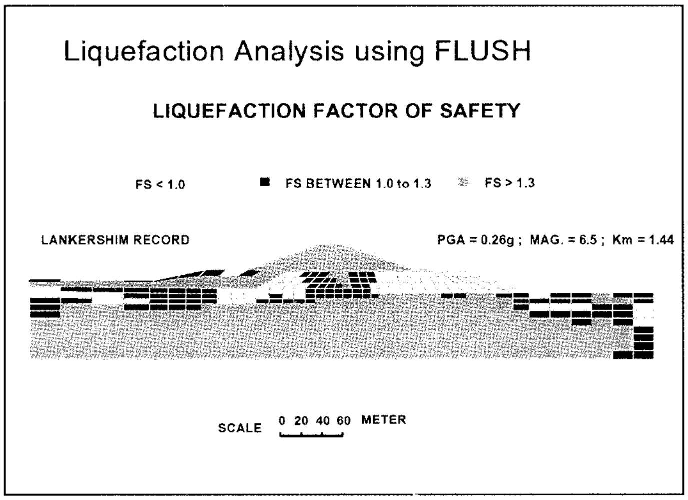


Dynamic Analysis using FLUSH

FINITE ELEMENT MESH - FLUSH ANALYSIS

Extent of the mesh = 600 m
Height of the mesh = 105 m

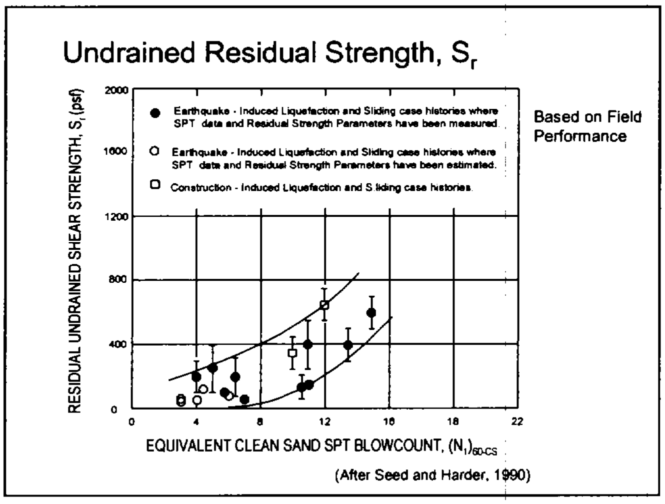
Number of Elements = 625
Number of Nodes = 686



Liquefaction Analysis using FLUSH

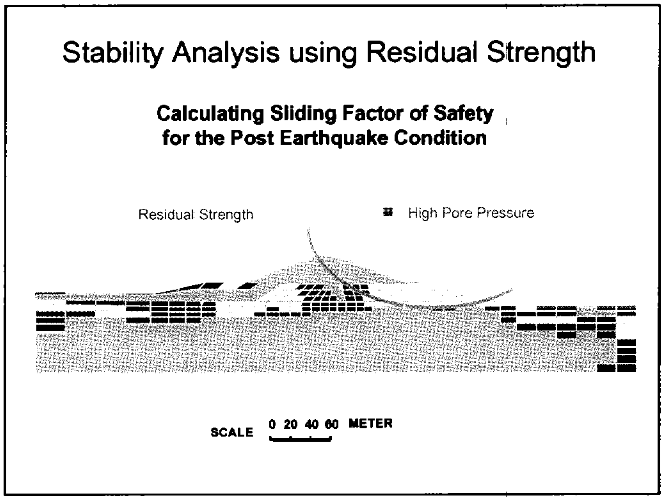
LIQUEFACTION FACTOR OF SAFETY

While selection of the post-liquefaction value of the residual strength is vitally important because of its influence on the post-liquefaction stability of the dam, there is no straightforward means of estimating what the probability distribution of the residual strength might be. Laboratory measurements, based on post-cyclic monotonic loading is not particularly satisfactory as the results are 'point data' that tend to be on the high side. Empirical data can be used as a basis, but this too is not particularly satisfactory owing to differences between existing empirical relationships. The issue is further complicated by the fact that the material in the dam and foundation is gravelly.



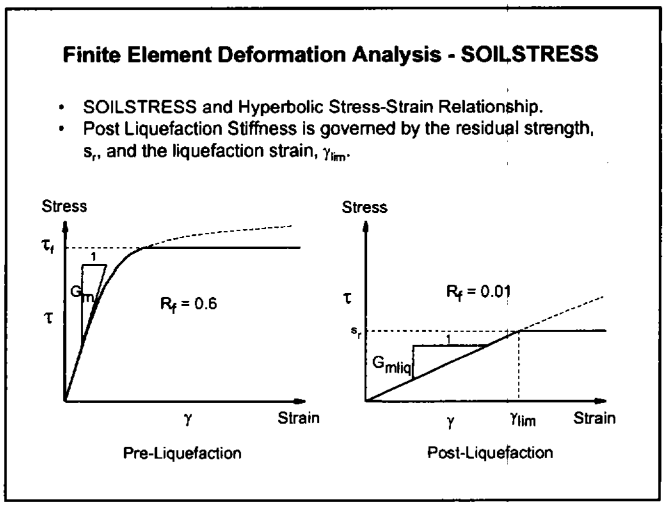
Undrained Residual Strength, S_r

(After Seed and Harder, 1990)



Stability Analysis using Residual Strength

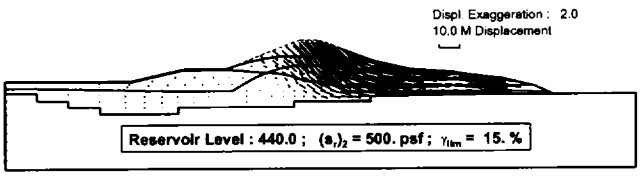
Calculating Sliding Factor of Safety for the Post Earthquake Condition



Finite Element Deformation Analysis - SOILSTRESS

- SOILSTRESS and Hyperbolic Stress-Strain Relationship.
- Post Liquefaction Stiffness is governed by the residual strength, s_r, and the liquefaction strain, γ_{lim}.

Finite Element Deformation Analysis - Results



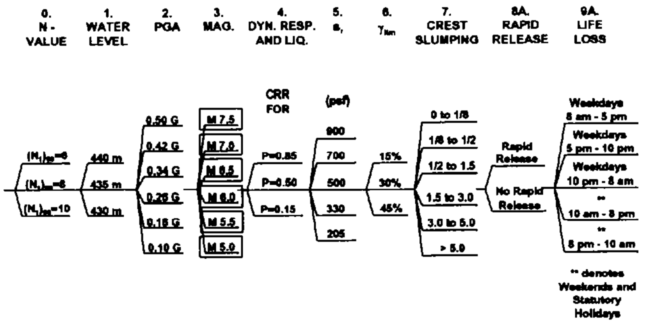
Keenleyside Earthfill Dam - Middle Cross-section

The phased approach to the dam response analysis, beginning with screening analyses and culminating in detailed finite element deformation analysis, proved to be very successful. However, it is important to recognise that there are enormous differences in time and resource requirements between these two approaches.

Procedure For Calculating The Probability Of Failure

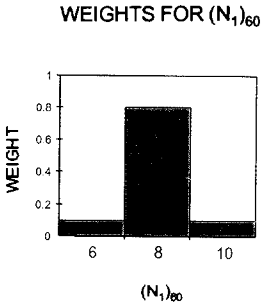
The procedure for calculating the probability of failure of the dam recognised the uncertainties in the deterministic analyses of the dynamic response as described in the previous section. While the procedure described here is restricted to the seismic hazard and the associated performance of the dam, this account is structured to illustrate how the geotechnical earthquake engineering component of the analysis was interfaced with the dam breach and failure consequences analyses. The essential features of dam failure mechanism were modelled in event tree format where the term 'event tree' is used in its most general form.

Event Tree - Life Safety



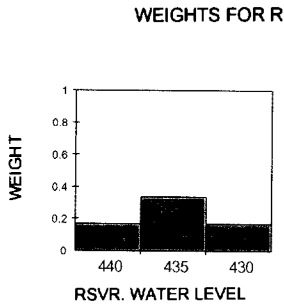
For instance, the distribution of in-situ soil strength (i.e. N-value) is a pre-earthquake state of nature and not an 'event' per se, as is the reservoir level at the time of the earthquake.

$(N_1)_{60}$ distribution



- These are subjective estimates and the values were selected based on the results of field investigaion and other geotechnical data.
- The N values shown on the chart are the nominal values, e.g. N=10 refers to 10 blows for downstream berm, 11 blows for mid-slope and 12 blows for the material below the crest.

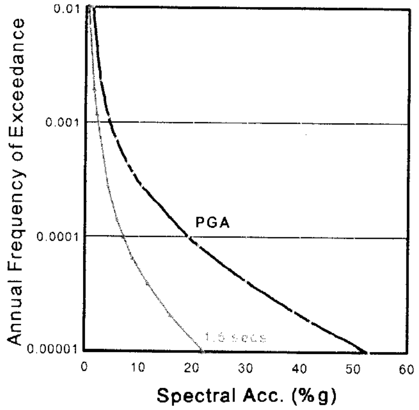
Reservoir Level Weights



- These probabilities are based on the historical record of the water levels.
- It is judged that when the water level is below EL 430.0, the consequence of overtopping given failure is negligible.

The seismic hazard was introduced at the third and fourth nodes in the tree

Probabilities - Ground acceleration

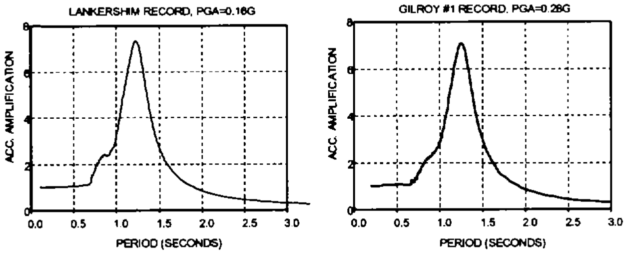


Two-dimensional analysis was carried out using two earthquake records to obtain the acceleration response. While spectral acceleration (S_a) were used in the analysis, the associated PGA values were used for labelling the amplitude of the earthquake in the analysis for convenience.

Conditional Probabilities - Acceleration Response

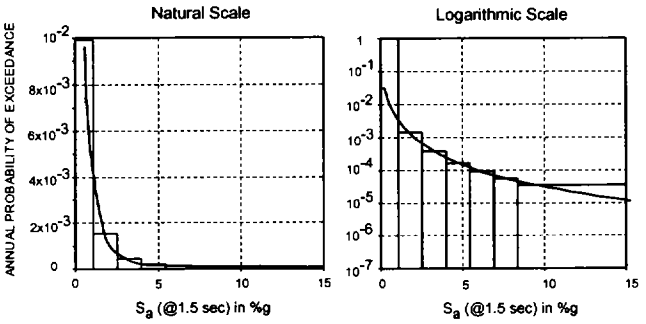
FOURIER AMPLIFICATION FUNCTION

2D Analysis using 2 EQ Records
Typical Point within the Dumped Sand and Gravel



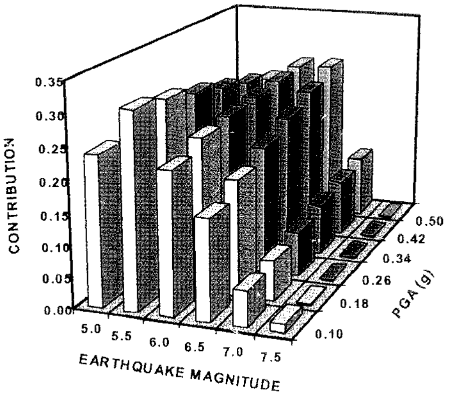
Selected 6 Acceleration Intervals,

the probabilities are based on S_a.



The seismic hazard was characterised by six acceleration levels, and for each acceleration level, the contributions from different earthquakes were de-aggregated into six magnitude intervals, leading to thirty-six PGA – Magnitude pair combinations for input into the subsequent liquefaction analysis.

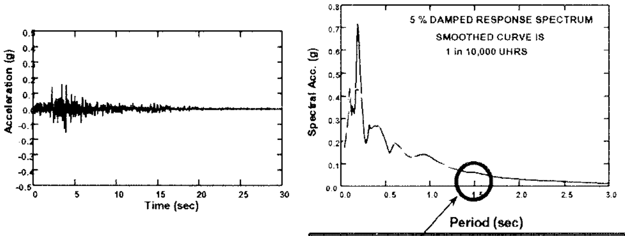
Magnitude Contributions



Time histories were scaled to the selected PGA; however, the appropriate uniform hazard response spectrum, matched at the 1.5-second spectral ordinate, was used to derive the probabilities.

Acceleration Time Histories

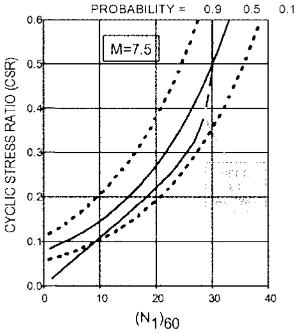
Scaling Factors and Probability



Stn.: LAKE HUGHES, STATION #4
CHAN 1 ; N21W ; Scale Factor = 1.100

The Conditional Probability for the scaled time history is obtained matching the appropriate UHRS at 1.5 seconds Sa.

Probability of Liquefaction - Deterministic Triggering

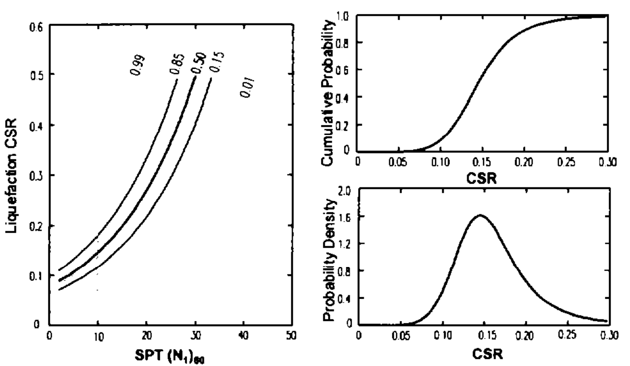


The determination of the **Probability of Liquefaction**, $\mathbf{P_{LIQ}}$, given the value of CSR is based on the data compiled by Liao, Veneziano and Whitman, 1988 :

$$P_{LIQ} = \frac{1}{1+e^{-Q}}$$

$$Q = \beta 1 + \beta 2 \times \ln(CSRN) - \beta 3 \times \left((N_1)_{60}\right)$$

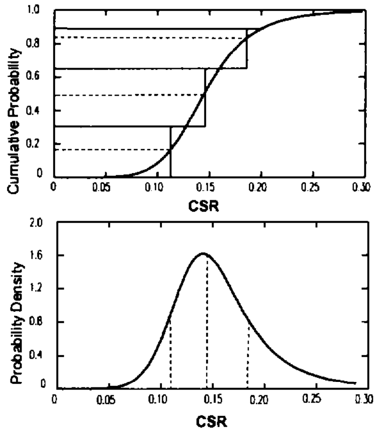
Probability of Liquefaction



(After Liao, Veneziano and Whitman, 1988)

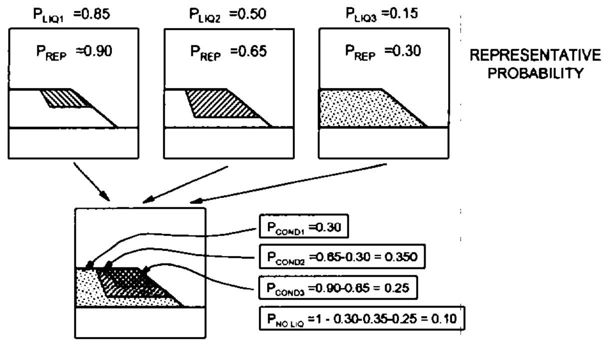
Rather than using a single value of probability of liquefaction (PLIQ) to determine the liquefaction resistance (CRR), three different values were used. That is, for a given $(N_1)_{60}$ value, there are three different CRR values, corresponding to different confidence levels, that are used to determine the liquefaction zone. For instance, for the case of $(N_1)_{60}$ = 10 blows/ft, CRR values of 0.11, 0.14 and 0.18 correspond to 15%, 50% and 85% probability. These three values of probability of liquefaction, together with the thirty six PGA-Magnitude pairs (6 sets of CSR's x 6 magnitude correction factor intervals and 3 associated values of P_{LIQ}) resulted in a total of 108 liquefaction cases to be considered. In other words, there were 108 end branches at the liquefaction node of the event tree. To make the analysis tractable, the 108 liquefaction states were reduced to six representative "liquefaction states".

Realization of Liquefaction Resistance from P_{LIQ}



Conditional Probabilities of the Liquefaction Maps

ZONES OF LIQUEFACTION FOR DIFFERENT P-LIQ.

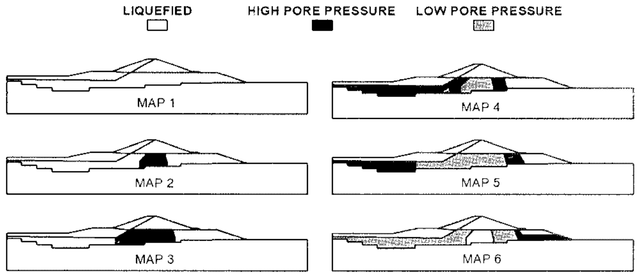


Probabilistic Description of Liquefaction Zones

Representative Liquefaction Zone Maps (Total=108)

PLIQ	PGA (g)	M 7.5	M 7.0	M 6.5	M 6.0	M 5.5	M 5.0
0.15	0.50	1	1	1	2	2	2
	0.42	1	1	2	2	2	4
	0.34	1	2	2	2	4	4
	0.26	2	2	3	4	4	5
	0.18	2	3	4	5	5	5
	0.10	4	4	5	6	6	6
0.50	0.50	2	2	3	4	4	4
	0.42	2	3	4	4	5	5
	0.34	3	4	4	5	5	6
	0.26	4	4	5	5	6	6
	0.18	4	5	5	6	6	6
	0.10	6	6	6	6	6	6
0.65	0.50	4	4	4	5	5	6
	0.42	4	4	5	5	6	6
	0.34	4	5	5	6	6	6
	0.26	5	5	6	6	6	6
	0.18	5	5	6	6	6	6
	0.10	6	5	6	6	6	6

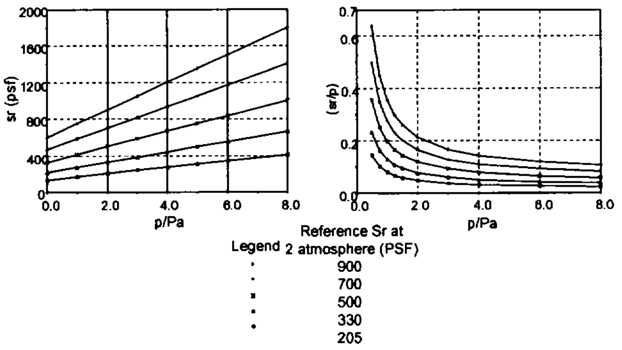
Representative Liquefaction Zone Maps



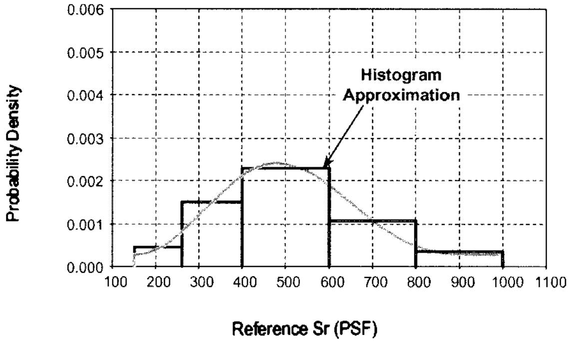
The next stage of the analysis was to determine the probability distribution of crest slumping given the liquefied state (as described by one of the representative maps). The range of crest slumping was divided into increments; 0m, 0.1m, 0.5m, 1.5m, 3m, 5 m and >5m. The steps in the process were as follows:

1. Using the 'gravity turn-on' finite element method, the magnitude of crest slumping (Dcr) for a given liquefaction map was calculated, with an appropriate range of values for the strength and stress-strain parameters, s_r and γ_{lim} selected to reflect the uncertainty of these parameters in the probabilistic analysis.
2. Using a subjective transformation of the computed crest slumping to predicted actual crest slumping, the conditional probability of the crest slumping falling within one of the intervals mentioned above was estimated.
3. Steps 1 and 2 were repeated for each combination of s_r and γ_{lim}.
4. Step 3 was repeated for each liquefaction zone map.

5 Sr Values with Different Probabilities



Subjective Probability Distribution for Sr Values

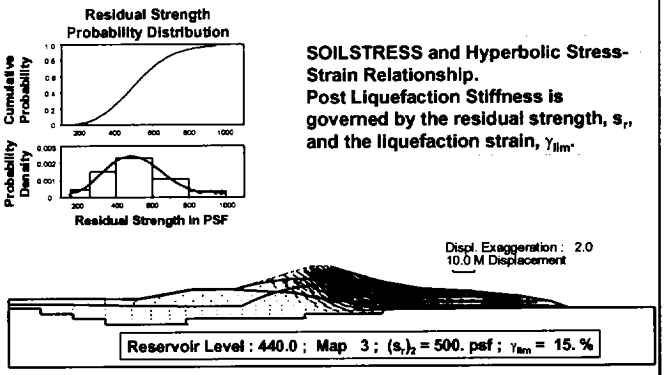


Subjective Probability Distribution for γ_{lim}

Probability Values for γ_{lim}

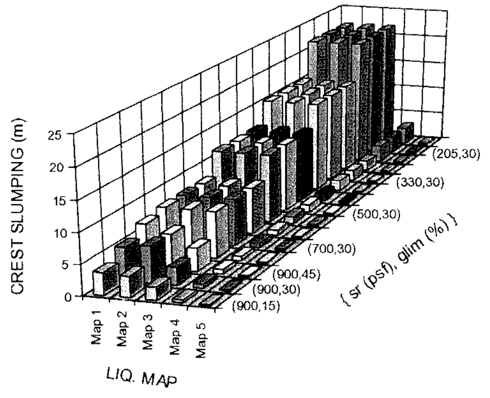
γ_{lim} (%)	Probability
15	0.3
30	0.4
45	0.3

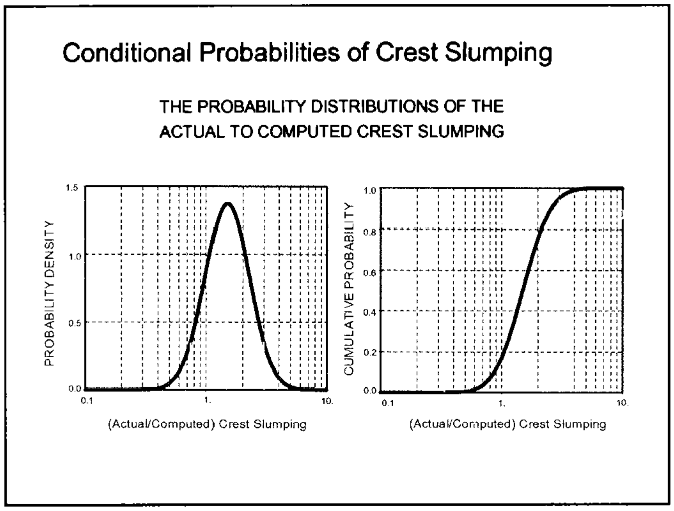
Finite Element Deformation Analysis



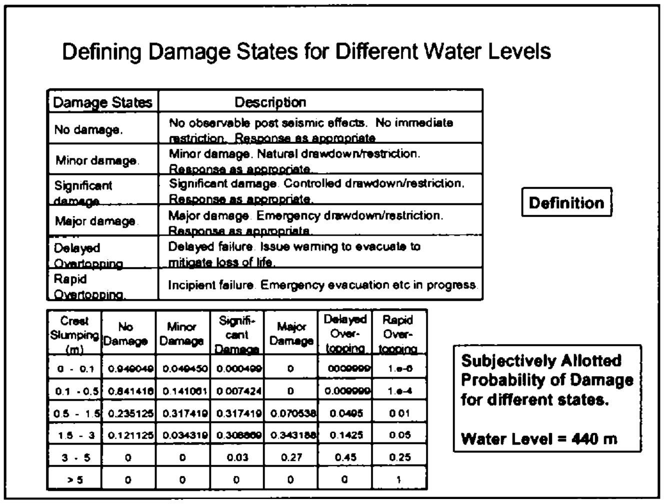
SOILSTRESS and Hyperbolic Stress-Strain Relationship.
Post Liquefaction Stiffness is governed by the residual strength, s_r, and the liquefaction strain, γ_{lim}.

Computed Crest Settlements





Finally, damage states for the range of original reservoir levels were defined to link the dam breach with the inundation consequences component of the analysis (not described here). The damage states ranged from 'No Damage' through 'Rapid Release'.



Defining Damage States for Different Water Levels

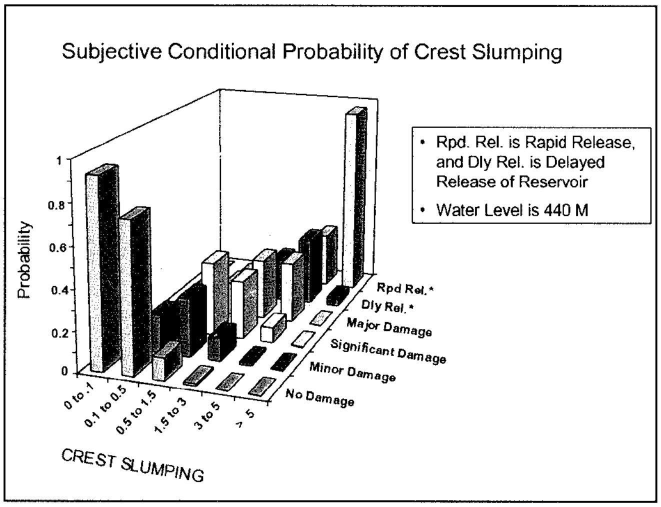
Damage States	Description
No damage.	No observable post seismic effects. No immediate restriction. Response as appropriate
Minor damage.	Minor damage. Natural drawdown/restriction. Response as appropriate.
Significant damage	Significant damage. Controlled drawdown/restriction. Response as appropriate.
Major damage.	Major damage. Emergency drawdown/restriction. Response as appropriate.
Delayed Overtopping	Delayed failure. Issue warning to evacuate to mitigate loss of life.
Rapid Overtopping.	Incipient failure. Emergency evacuation etc in progress.

Definition

Crest Slumping (m)	No Damage	Minor Damage	Significant Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
0 - 0.1	0.949049	0.049450	0.000499	0	0009999	1.e-6
0.1 - 0.5	0.841416	0.141061	0.007424	0	0.009999	1.e-4
0.5 - 1.5	0.235125	0.317419	0.317419	0.070538	0.0495	0.01
1.5 - 3	0.121125	0.034319	0.308869	0.343188	0.1425	0.05
3 - 5	0	0	0.03	0.27	0.45	0.25
> 5	0	0	0	0	0	1

Subjectively Allotted Probability of Damage for different states.

Water Level = 440 m



- Rpd. Rel. is Rapid Release, and Dly Rel. is Delayed Release of Reservoir
- Water Level is 440 M

Here ends the geotechnical earthquake-engineering component of the Keenleyside Dam Risk Analysis. The consequences of failure analyses being the 'other side' or the risk equation is not presented in this paper. Both components, however, are required to advance from the engineering analysis to the wider policy/societal risk evaluation and assessment processes.

The analysis of the probability of failure of the Keenleyside Earthfill Dam due to seismically induced liquefaction has been subjected to extensive independent peer review by recognised experts in all of the required engineering disciplines. This peer review is necessary to establish the validity of the analytical procedure used to compute the probability of failure. Here it is important to note that, even this extensive analytical estimate of the risk is incomplete as a formal analysis of the uncertainties in the estimate of risk has yet to be carried out. However, the procedures to perform this uncertainty analysis are known and are essentially of the form used in the probabilistic seismic hazard analysis. However, this does not detract from the analysis that has been completed thus far, as it was sufficiently complete to permit BC Hydro to advance to the next stage of the dam safety decision-making process.

The entire analysis and assessment process is presently being documented. Therefore, it would be inappropriate for anyone to reach any conclusions concerning the underlying philosophy, the level of effort and resource requirements and the status of the analytical procedures for use in dam safety practice in general. This said, the geotechnical earthquake-engineering component of the analysis used to estimate the probability of failure, with the exception of the uncertainty analysis, has become established as a scientifically valid engineering procedure through the recognised professional and learned procedures.

Professor A. Casagrande, who introduced the concept of risk analysis for dams, was the consultant for the original design of Keenleyside Dam. Professor R.V. Whitman, who extended the work of Professor Casagrande and developed the procedure for analysing the probability of failure, provided participatory peer review for the Keenleyside Dam Risk analysis, along with Professor C.A. Cornell and Professor N.C. Lind. Professor P.M. Byrne, Dr. W. F. Marcusson III and Professor R.B. Seed provided subject matter expertise in the various aspects of the analysis of the performance of the dam. Together with the BC Hydro team members, Casagrande's vision of the future was successfully created, for one of his own designs. This 'giant step' forward was made during the Watershed Years from 1995 to 1998, and it provides a basis for further advances in risk analysis for dams, especially in the field of geotechnical earthquake engineering.

RECENT DEVELOPMENT INITIATIVES IN DETAILED QUANTITATIVE RISK ANALYSIS

A review of the literature quickly reveals that, for the most part approaches to risk analysis range from applications which involve little de-composition and rely extensively on 'judgmental' probabilities. The 'watershed period' represents an important stage in the development of risk analysis in dam safety practice. It can be traced back to the first serious attempts to use risk analysis to decide *if a dam is safe enough* when the issues of scientific validity and legal defensibility came to the fore in international practice. The following two examples presented in this paper, the Hume Dam case study and the second a procedure proposed by Lin and Hung (Lin and Hung, 1999) for non-liquefaction seismic risk analysis, serve to illustrate the form and status of 'post watershed' risk analysis for dams.

Professor H.B. Seed observed that embankment dams may fail because of excessive settlement and deformation, or due to a significant build-up of pore water pressure, or as a result of sliding of embankment slopes (Seed, 1979). This raised the question as to whether or not the 'settlement' and 'deformation', and/or the embankment slope sliding failure modes could be. Information on the seismic component of the Hume Dam risk analysis, which focuses on liquefaction, is presented to illustrate some of the many issues that must be considered by the analysis team. The dam response analysis procedure is not presented, but was similar to an earlier, but unsatisfactory iteration of the Keenleyside risk analysis. The work of Lin and Hung, (Lin et al. 1999) suggests that, in principle, it might be possible, to assess the risk for embankment slope sliding at any rate. Interestingly, the groundwork for this analysis was developed in the 1980's and involved some of those working in this field at that time. There are significant parallels between the proposal of Lin and Hung and the Keenleyside Dam risk analysis. This is due in part because they both rely on the pioneering work carried out at MIT during the 1980's.

The question of 'equivalence' of methods and decisions made on the basis of the risk analyses that present different various level of analytical detail (essentially none through to mathematically and scientifically rigorous) is one of the most difficult questions requiring resolution at this time.

HUME DAM RISK ANALYSIS – SEISMIC RISK COMPONENT FOR THE EARTH DAM

The Hume Dam risk analysis represents one of the most ambitious attempts to perform a comprehensive risk analysis of a large dam comprising earth and concrete structures for all failure modes. The sheer breadth and complexity of the problem to be analysed are such that an in-depth analysis of the risk could not be carried out. This brief summary, based on McDonald and Wan, 1998 and McDonald, Cooper and Wan, 2000 (which in no way could ever reflect the enormous amount of work involved) outlines some of the complexities in the analytical procedures that should be accounted for in a seismic risk analysis. The Hume Dam risk analysis does not constitute an alternative to the Keenleyside Dam risk analysis as it does not include the vitally important deformation analysis, and it includes procedures subsequently found to be unsuitable to the task of quantifying risk. However, it is worthy of recognition because it led to the conclusion concerning inadequacy of analytical procedures for 'signing off' on the safety status of dams.

From the perspective of geotechnical earthquake engineering, the study represents a significant advance in Australian practice as it was the first time that the effects of earthquake magnitude were considered in a risk analysis in that country (McDonald and Wan, 1998). The account does refer to protocols for assigning probabilities (these are not presented here) but the validity (in an absolute sense) remains to be demonstrated. This is an issue for debate in the profession, something which has not received adequate attention thus far.

The approach used at Hume Dam included consideration of:

- five dams, three training walls and a system of 29 spillway gates,
- 81 failure modes,
- up to 32 branches in event trees,
- 8 flood loading states,
- 48 earthquake loading scenarios, and
- 6 prior storage levels.

This resulted in a requirement to assign and keep track of some 15,000 conditional probabilities. It was felt that without a systematic approach, analysts and reviewers could become confused in attempting to assess such a large number of figures. It was also recognised that there was a need to maintain logical consistency throughout the analysis. Double counting also had to be avoided. It was considered that the most practical approach for handling the large number of probabilities was to enter them onto spreadsheets, and to use the event trees simply to illustrate the logic of the failure process. Whilst the spreadsheets reduce the computation load and avoid arithmetic errors, there was no practical way of assessing logical consistency and checking against double counting. The solution that was adopted for the Hume study was the concept of the "Probability Assignment Protocol". This was a concise instruction for assigning probabilities as a function of loading condition.

The obvious requirement to write down the reasons for assigning probabilities (see BC Hydro, 1993) was found by the analysis team to clarify their thinking and was extremely beneficial to the analysis. It also provided a permanent record of the rationale, which allows those not associated with the study to understand the basis for the probability values. The analysis team went as far as to recommend *"that such documentation should be regarded as mandatory for a risk assessment study"*. The analysis team also felt that documentation of sound reasoning would be an aid to legal defensibility, especially where review panels might pass judgement on the reasoning.

Seismic response considerations and analysis method

The procedure of Liao and Whitman was followed for the Hume risk assessment study. The Hume embankments were not susceptible to liquefaction but the alluvial soils of the foundation were. However, spatial considerations were considered to be important, as the analysis was based on information gained from drill holes that had been put down at various sections along the length of the embankments. This issue poses several interesting philosophical questions about the meaning of 'probability of failure' for long linear structures. While these issues remain to be resolved, the account of how it was examined in the Hume Dam risk analysis is summarised here because it illustrates a way of thinking, and it was the first time that the matter had been addressed in contemporary practice. The matter was considered during the Keenleyside Dam analysis, but not followed through for various reasons (Keenleyside Dam is not as long, and there are other unique features that made it appropriate to consider the dam in sections).

At regular depth intervals, SPT values had been obtained and samples had been recovered for particle size analysis. A spreadsheet was prepared, with fields for information such as location, borehole number, depth, soil type (percent fines), groundwater level and N value from the CPT and SPT tests. Each row represented one test level in one borehole. There was an entry for every test location over all of the embankments. On another spreadsheet, every row of the test data spreadsheet was run through the Liao et al regression equations to find the probability of liquefaction for that test location. It was observed that the Liao et al. equations yielded a probability of liquefaction for low magnitude events. However, it was felt that, in reality, such events would not cause liquefaction because the duration of shaking would be too short and the number of stress reversals too few. It was decided that this problem would be handled by setting the probability of liquefaction to 'zero' for event magnitudes of M5.0 or less. This initial stage was consistent with the magnitude 'cut-off' approach followed for Keenleyside Dam.

The highest probability of liquefaction in a borehole was taken as the representative probability for that location. At sections where there were three boreholes, some interesting questions arose:

1. What is the probability that liquefaction will occur at all three boreholes; that is, over a sufficiently large area that a large scale slide could occur?
2. Would liquefaction at only one borehole location give rise to a threat to the dam?
3. What is the probability that the boreholes have found the zone that is most susceptible to liquefaction?

Concerning question 1, it is reported that after considerable reflection, it was concluded that the first question should be addressed using the uni-modal bounds theorem described as follows: The upper bound probability of liquefaction occurring over the whole area is the lowest of the three representative probabilities for each location, whereas the lower bound probability would be the intersection of the liquefaction events at each location. The lower bound would be the product of the three representative probabilities and was generally considered to be a vanishingly small value. The next problem encountered when addressing this question related to embankment length issues and concerned the fact that the more boreholes that are available, the lower the lower bound probability. The only possible conclusion is that the probability of liquefaction at a borehole is a function of the area represented by the borehole such that the lower bound probability becomes independent of the number of boreholes. This thought process gave rise to a related question: "What is the area to which the Liao et al probabilities apply?" The complexity of these issues was clearly recognised by the analysis team, and they deserve credit for putting their approach forward for debate. For reasons of practicality, the analysis team, in a refreshingly open comment remarked: *"For the Hume study, the simple approach (or perhaps the easy way out) was taken by considering only the upper bound."*

Concerning the second question, the analysis team had the following thoughts: *"At some sections, the highest representative probability was sometimes a couple of orders higher than the others. The answer to the question seemed to relate to the location of the high probability borehole. If it was under the downstream toe of the dam, it seemed quite plausible that localised liquefaction in that area could cause a small-scale slide, which might still endanger the dam. If the highest probability borehole was well upstream, toward the dam crest, it seemed less likely that a slide would result from local liquefaction in that area, although there obviously would be some impact on the post-liquefaction Factor of Safety, F. A search process was undertaken to see what situations gave the highest value for the product, probability of liquefaction times probability of a post-liquefaction slide times probability of dam failure, given the slide. In the case of Hume Dam, the result was that liquefaction over the whole area represented by the three boreholes was always the critical case."*

Moving on to the third principal question above, which arose from consideration of the previous two, it became clear that the boreholes represent only a small sample from very large areas that could be susceptible to liquefaction. For example, at Hume Bank No. 1, there was an area some 600m long by 120m wide where liquefaction is an issue. Sixteen boreholes had been sunk over the area in question. The analysis team reasoned that it seemed plausible that there would be areas with a higher probability of liquefaction than any of those examined. They also observed that strength may drop to a value below the static value but higher than residual undrained strength, either because drainage relieves pore pressure during shaking, or because too few cycles of shaking result in only a partial increase in pore pressure.

It was reported that the probability that the residual undrained strength would be reached, given liquefaction, was not an issue for Hume Dam, because the investigations revealed that all of the liquefiable zones were capped by finer, relatively impermeable sediments. The analysis team reasoned that there would be no opportunity for drainage to relieve excess pore pressures generated during, and immediately after, earthquake shaking. The analysts also reasoned that the conditional probability of reaching residual undrained strength, given liquefaction, was 1.0. This said, the analysts recognised that this will not always be the case. Making use of the work of Stark and Mesri as a basis for reasoning, they considered that the real issue that they were dealing with was the lowest strength reached, and the impact that that would have on the probability of sliding. It was considered that, where drainage would occur, the lowest strength may be a value somewhere between the static pre-earthquake strength and the residual undrained strength. It was noted that no probabilistic treatment of this issue could be found in the literature, but it was felt that it could be a real issue in many cases.

It was felt that there was more than one reason that the lowest strength reached during liquefaction could be intermediate between the static value and the residual undrained value. One was that there might only be a partial increase in pore pressure because of insufficient duration of shaking (the consideration of magnitude described in the Keenleyside Dam risk analysis is included to address this issue). The analysts also expressed the view that considering the post earthquake strength to be either the static strength or the undrained residual strength is simplistic and unrealistic. The analysts felt that these considerations point to the need for a comprehensive probabilistic treatment of strength reduction due to pore pressure increase during earthquake shaking.

Because of the dramatic reduction in Factor of Safety, F, that occurs it was felt reasonable to characterise the probability of failure in terms of a liquefaction induced slope failure. For the Hume study, the residual undrained strength was expressed as an equivalent friction angle. This value varied between 4 and 9 degrees typically, based on the strength versus N value relationship given by Stark and Mesri. The typical static F values of 1.5 to 1.7 dropped to post-liquefaction values of 0.8 to 1.0. Reliability analysis, with standard deviation in F estimated by FOSM, was used to produce similar system response curves to those shown in Fig. II-1. In this case, the liquefied horizontal foundation zones accounted for 84% of the variance in F. The conditional probabilities of a slide, given liquefaction, were typically high (0.02 to 0.9) because of the low post-liquefaction F values.

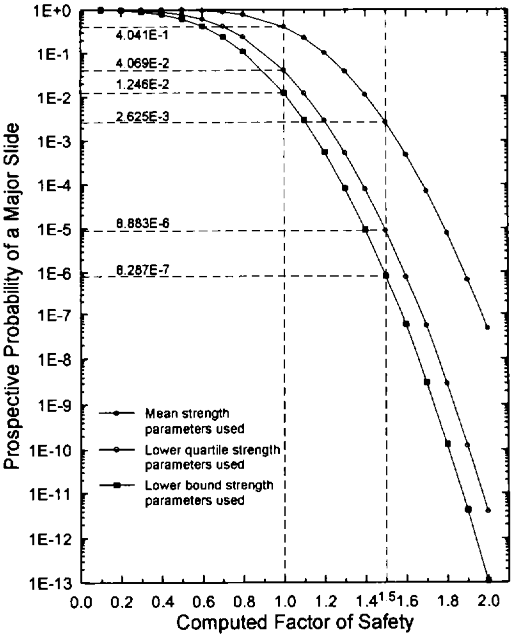


Fig. II-1. Prospective Probability of Sliding for Hume Dam Embankments

SEISMICALLY INDUCED SLIDING FAILURE OF EMBANKMENT DAMS (From Lin and Hung, 1999)

The following is a summary of a more detailed treatment provided by Dr. J-S Lin. The approach builds on Newmark's investigations (Newmark, 1965) which had shown that the factor of safety of slopes of embankment dams drops temporarily below one during earthquakes but, this does not necessarily represent 'failure'. As an earthquake shaking reverses its direction, a sliding instability may come to a stop. However, during a strong earthquake, a slope may undergo many slide-stop cycles and cumulates movements in a step-wise fashion. Newmark concluded that it is the total accumulation of movement that determines the stability of a slope, not the factor of safety per se.

The approach begins with the concept of a 'critical acceleration, where a slope sliding is initiated if the ground acceleration exceeds a critical acceleration, A_c. A_c is defined as the acceleration that reduces the slope factor of safety to one by introducing an adverse inertia force. A_c is obtained through static slope stability analysis.

$$A_c = \frac{FS - 1}{3.33} g$$

The mean and coefficient of variation were determined using conventional probabilistic techniques.

Other assumptions for the example were that:

- The most critical slope was one extending from crest to mid-height; and
- The mean, E[FS], and coefficient of variation, C.O.V.[FS], of the factor of safety FS, were 1.5 and 0.2 respectively.

The resulting mean, E[A_c] and coefficient of variation C.O.V.[A_c], of the critical acceleration, were 0.4 and 0.15g respectively. Using a lognormal distribution, and simplifying the distribution into four discrete points, the derived distribution of A_c was as shown in Table II-1.

A_c(g)	P(A_c)
0.075	0.195
0.125	0.381
0.175	0.250
0.250	0.174

Table II-1 Derived distribution of Critical Acceleration A_c

Failure Criteria

Analogous to the Keenleyside Dam Analysis, it was necessary for Lin and Hung to introduce a failure criterion, and a similar approach was adopted (based on suggestions by Legg et al (1982) for seismic slope stability evaluation). In this study, the risk associated with slope movement 'D' of $D \geq 20$ cm,

$D \geq 50$ cm, $D \geq 100$cm, $D \geq 150$cm, $D \geq 200$cm and $D \geq 300$ cm are to be obtained.

Procedure

The basic Newmark procedure of:

1. Identifying the sliding surface that has the smallest factor of safety through conventional slope stability analysis;
2. Conducting nonlinear dynamic analysis of the earth dams to obtain average response acceleration of the mass above the critical sliding surface;
3. Using the average absolute response acceleration and the critical acceleration, to calculate the slope movement, was employed.

Nonlinear dynamic analysis of earth dams was carried out using simple equivalent linear finite element programs, such as QUAD-4 developed by Idriss et al, 1973. For this particular application, simple shear wedge models were found to provide results compatible to those obtained from finite elements. The simple shear wedge model employed modal superposition in the dynamic analysis.

Considering a dam of 115 m high with an average shear wave velocity of 300 m/s, the average absolute response of the mass above a potential sliding surface extending from crest to mid-height of the dam is computed. A sample calculation showing the evolution of slope movement is depicted in Fig. II-2.

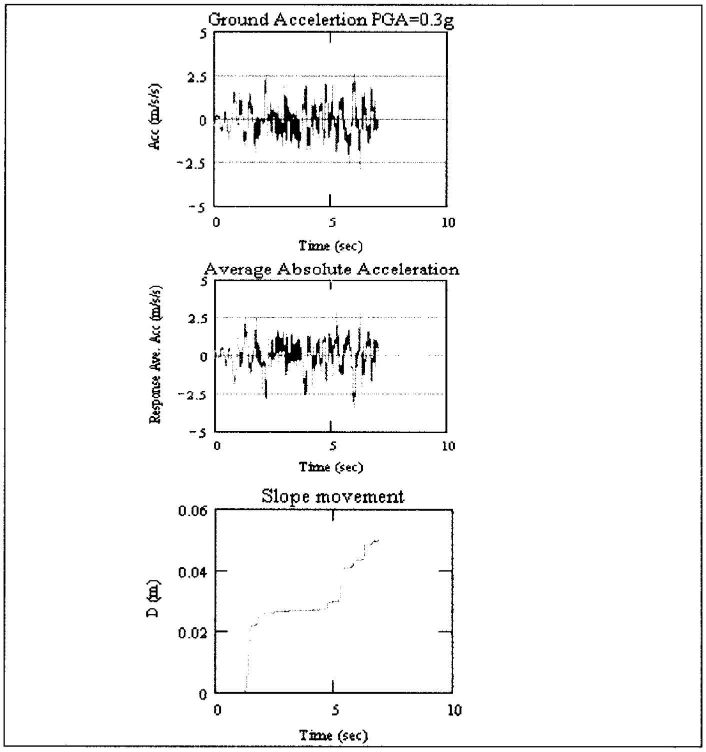


Fig. II-2 Evolution of slope movement under Earthquake excitation

Treatment of the uncertainty in the dynamic properties of the dam was not included in the study, but the authors' noted that, in practice, this component of uncertainty can be accounted for if adequate data were available.

To obtain the distribution of slope movement, P(D), Lin and Hung propose that first estimates of the conditional distribution $P(D|PGA, M, A_c)$ could be made by employing a probabilistic sliding block model as in Lin and Whitman (1984). This study also employed an ensemble of 30 rock site records from the 1971 San Fernando earthquake. This ensemble was considered a representative sampling of rock site motions. Its average response spectrum compares well with that derived by Seed et al. These records are further scaled to various magnitudes using the process proposed by Lin and Tyan (1986).

1. Under a set of A_c, PGA and M, conditional mean and variance of D were computed for 30 records.
2. Assuming the conditional distribution of D to be lognormal, $P(D>do|PGA,M,A_c,yr)$ for various do were computed.

3. $P(D>do|M, yr)$ was obtained by summing over the possible variation of A_c and PGA at a given earthquake magnitude, i.e.,

$$P(D>do|M,yr)=\sum\sum P(D>do|PGA,M,A_c,yr)P(PGA|M,yr)P(A_c)$$

4. The total risk ,$P(D>do|yr)$, was obtained by summing contributions from all magnitudes,

$$P(D > do \mid yr) = \sum P(D > do \mid M, yr)P(M)$$

In the probabilistic sliding block model, slope movement is expressed as a function of A_c, the duration of ground motion, S, together with some response statistics. Specifically, the statistics used are the root-mean-square, σ , a bandwidth measure, δ , and the central frequency, Ω, from the response spectral density function. The lognormal distribution was found to describe this conditional distribution well. The two parameters of the model, the conditional mean, $E[D \mid PGA, A_c, \sigma, \Omega, \delta)$ and the coefficient of variation, $COV[D \mid PGA, A_c, \sigma, \Omega, \delta)$, were also computed.

$$E[D \mid PGA, A_c, \sigma, \Omega, \delta) = \nu_r^+ S \frac{\sigma^2}{2A_c\Omega^2} g(r) f(\delta)$$

$$COV[D \mid PGA, A_c, \sigma, \Omega, \delta) = [0.38 + 0.62F(r)]\frac{\sqrt{2}}{\sqrt{\nu_r^+ S}}$$

where,

$$r = \frac{A_c}{\sigma}$$

$$\nu_r^+ = \frac{\Omega}{2\pi}\exp(-\frac{r^2}{2})$$

$$f(\delta) = 1 + 7.11(\delta - 0.2)^2 \qquad 0.2 \leq \delta \leq 0.8$$

$$g(r)=\begin{cases}25r & r<0.1\\ 2.5+0.723\ln(10r) & 0.1\le r\le 0.2\\ 3 & 0.2\le r<0.5\\ 1.74\ln(2.85r) & 0.5\le r<2.85\\ 0 & r\ge 2.85\end{cases}$$

$$F(r)=1-\exp(-\frac{r^2}{2})$$

To make use of Lin and Whitman's model, the dynamic analysis of the dam was carried out in frequency domain, and spectral density functions of the average response accelerations are computed. Following the procedure outlined above, the risk of slope movement exceeding various thresholds are computed.

The final result reflecting the risk of various levels of damages are as follows:

D> (cm)	Probability/year
20	4.16×10^{-3}
50	1.22×10^{-3}
100	3.69×10^{-4}
150	1.34×10^{-4}
200	7.62×10^{-5}
300	2.46×10^{-5}

Table II-2 Results of the analysis

This final result can now be incorporated into an overall dam risk assessment.

SIMPLIFIED APPROACHES

Simplified approaches to risk analysis of dams, such as the risk-based decision methodology described previously in Part I, model risk in a very coarse manner as illustrated in Fig. II-3.

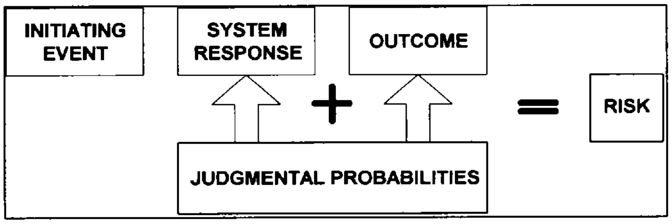


Fig. II-3. Simplified (coarse) 'judgmental' risk analysis model

This 'judgmental' approach, which is essentially that developed for the USBR's risk-based decision analysis methodology has value if the results are used in a relative sense to prioritise dam safety improvements and to plan investigations (SMEC, 1995, Watson et al., 1997).

Certainly, the simplified approach appears to have several attractive attributes if speed, cost and simplicity are the driving principles of the analysis. Unfortunately, these attributes have associated drawbacks as in the absence of a mathematical structure anyone can say anything. There is always the danger of the dubious notions that *a probability is what you believe it to be* and *everyone's probabilities are right even if they are different*, being invoked as the approach can be applied quickly, cheaply and easily by anyone. Of course, a defender of the method might argue that only those with special qualities and experience in risk assessment for dams can make these judgements.

Unfortunately, this 'simplified' and apparently 'practical approach' is not as straightforward or practical as it appears, if one abides by the rules of the exercise of judgement in engineering and the principles of estimating probabilities. One has to look no further than the Challenger Space Shuttle accident to question the validity of engineer's judgements of probability and see how tragic the consequences should the advice lead to a bad decision. *'Judgmental probabilities'* are more correctly termed *'subjective probabilities'*, where the theory of subjective probability forms an entire branch of the mathematics of probability.

It is erroneous to give any credence to the numbers or to assume that the rank order is in some way mathematically or scientifically valid. The vigorous debate concerning the validity of this approach and the meaning of the numbers generated, which originated when the notion of 'judgmental probabilities' first emerged in the early 1980's, has intensified in recent years. Recently, the debate has become more complex and divisive with analytical approaches to estimating risk being deemed by some to be *'not practical'* or *'too expensive'* for all but the wealthiest of owners. The idea of risk analysis being *'credible'*, *'defensible'* and *'transparent'* has been attacked by some practitioners, and the idea of risk analysis being carried out in terms of certain standards and norms denounced.

Objective (empirical frequency) probabilities and subjective probabilities, are not the same types of probability. The simplest way of obtaining objective probabilities is to perform repeated trials whereas the simplest method of obtaining a subjective probability is to simply ask the person what their 'degree of belief' is. After all *"a subjective probability is 'just someone's opinion"* (Cooke, 1991). However, Cooke pointed out while this might be the simplest way of obtaining a subjective probability, it is equally surely the worst. The challenge was, and still is, to ensure that the probabilistic statement of opinion is well founded. The apparently practical *'empirical/judgmental'* approach to probability estimation was clearly some kind of hybrid of two different concepts! Fundamentally, quantitative risk assessment of the form that was proposed requires an objective statement of the probability of failure of individual dams for comparison with 'objective' criteria. The empirical record, which characterises the properties of the population of dams can never be indicative of the probability of failure of individual dams (statistics don't apply to individuals). Also, *'judgmental probabilities'* are 'subjective'- they have no objective meaning and only exist in the mind of the person making the estimate. The hybrid as applied to individual dams cannot have an objective meaning as it is made up of two parts, neither of which exist in the real world.

For subjective probabilities to be well founded, it is important that those making the estimates have substantive (subject matter) expertise and normative expertise (be well calibrated) (Morgan and Henrion, 1990). They had to have basic training in probabilistic reasoning (a notoriously difficult discipline) and to be familiar with the mathematics of probability. They had to know how to transform evidence and experience into coherent statements of probability. Finally, because of the extent to which judgement pervades dam engineering, they also had to be people of judgement.

If anything, given the extensive role of judgement in engineering practice, the 'judgmental' quality should have been the most readily available. Di Biagio and Høeg (1989) provide a very eloquent account of where judgement comes from, and this advice, together with the experience in estimating subjective probabilities outlined above, provided an insight into the make-up of project teams assigning *'judgmental probabilities'* of dam responses. Ideally, the team should consist of:

- People of judgement;
  - People with theoretical knowledge, experimental evidence, empirical experience and the ability to integrate all elements of the exercise in a logical and transparent manner.
- Individuals with substantive expertise;
  - Subject matter experts in each of the physical processes involved in the failure mechanism.
- Who also have normative expertise; and
  - Are demonstrably well calibrated (have a good track record in 'guessing right'),
- All team members are trained in probabilistic reasoning; and
- Have detailed knowledge of the dam under investigation, its properties, its design and performance and its vulnerabilities.

Clearly, there is an enormous difference between asking someone to quantify their 'opinion' concerning the outcome of an event concerning a dam and asking properly qualified people of judgement (in the accepted engineering sense) to transparently transform their knowledge, experience and evidence into their 'subjective probability' of 'the event'. Obviously, this is not routine engineering and certainly not 'commodity' engineering.

The difficulties of making 'judgements' of probability (as opposed to asking someone's opinion) are manifestly obvious. Such judgements of probability are very uncertain because the data are scarce and difficult to relate to the case at hand (all dams are unique). Moreover, it is debatable whether it is really judgement that was being exercised, because those who were making these estimates lacked a rational mechanical model on which to base their beliefs. The dam safety analyst must "estimate," i.e. assign, probabilities subjectively in part, often describing them as "engineering judgements" of probabilities. Such guesses are used in lieu of probabilistic estimates of 'parameters' and 'states' made by means of observations and rational physical models. These guesses contaminate risk analyses, degrading quality. In the absence of realistic theories and mathematical structure, anyone could say anything, and in accordance with some interpretations of the theory of subjective probability, they would all be 'right'!

The practicality of making judgements of probability concerning the failure of dams clearly poses an enormous challenge. Setting aside any complexities associated with the mathematics, as they are numerous but essentially tractable if appropriate expertise is brought to bear on the problem, the most significant practical difficulties were found to be with the exercise of judgement concerning the behaviour of dams at or near failure.

The exercise of judgement in engineering practice requires an adequate theoretical basis, validated by experiments and observations. The role of theory in 'engineering practice' is well established, and its importance has long been recognised in dam engineering. Professor Terzaghi, a 'practical' engineer 'par excellence' was acutely aware of the need for adequate theories and their role in practice. The advice provided by Terzaghi concerning the role of theory in geotechnical engineering practice and the role of rigorous and simplified solutions is also applicable to the exercise of judgement in estimating failure probabilities of dams.

According to Terzaghi, *"the ability to obtain rigorous solutions is not a prerequisite for successful work in the field of soil mechanics. For both the research man and the practising engineer it is sufficient to know the general procedure by means of which the rigorous solutions are obtained. The rigorous solution of the problems should be left to professional mathematicians."* However, Terzaghi made it perfectly clear that practice is based on theory and that adequate theories are a necessary part of practical engineering and the exercise of judgement in engineering practice.

Immediate observations include:

- Estimating risks posed by dams requires adequate analytical theories to provide a basis for developing practical approaches to analysing risks,
- The empirical record of dam failures and incidents can not in itself provide an adequate basis for inferences concerning failure risks in individual cases.
- If *'judgmental probabilities'* were to be genuinely characterised as 'judgements', in the established engineering sense as opposed to quantified statements of opinion, they would be based on analytically derived predictions. In other words, the apparent differences between the *'analytical probability'* philosophy and the *'judgmental probability'* philosophy cease to exist if proponents of the *'judgmental probability'* philosophy adopt the established approach to exercising judgement in engineering practice.

In the absence of adequate theories of dam failure mechanisms on which to base judgements of probability, and given the philosophical problems associated with mixing objective and subjective probabilities, the *'empirical/judgmental'* approach to estimating probabilities of dam failure becomes an intellectual and philosophical failure. Thus, while it was clear that it might always be possible to make a subjective estimate of dam failure probability, this subjective estimate is no more a property of the dam than the betting odds on a horse are a property of the horse!

Owner's might find these 'simplified de-compositional degree-of-belief' of benefit in an overall decision-making process provided that they do not consider the risk numbers as having any objective meaning. Subjective estimates of dam failure probability cannot be compared with objective criteria.

SIMPLIFIED DE-COMPOSITIONAL APPROACHES

As described in Part I, BC Hydro embarked on an extensive investigation into the use of the 'de-compositional' event tree approach in the early 1990's in the interests of having sufficient experience in applying the method to a wide range of situations encountered in dam safety practice. In 1993, BC Hydro published its risk-based dam safety guidelines in interim form. Importantly, the procedures section was not developed but an illustrative example application of the simplified de-compositional process to BC Hydro's Alouette Dam was presented.

Initially, it appeared that the approach was feasible and the results of the studies were presented at various dam safety conferences to promote discussion. Oddly, apart from isolated situations, the expected barrage of objections did not materialise – *had we succeeded?* or, *were we being ignored?* Recognising well founded concerns from within BC Hydro and mindful that there were few opportunities for review and critique by knowledgeable peers, and in response to serious difficulties that were encountered during individual studies, BC Hydro embarked on its own critique of its work.

The most significant concerns from within the project team responsible for the developmental work were that the estimates of dam failure probability were artefacts of the event tree model and the subjective 'degree-of-belief' of the analysis team. It was all achieved in the absence of robust theories and analytical models, experimental evidence and empirical experience. In fact, the simplified de-compositional approach suffers from essentially the same drawbacks as the simplified 'judgmental' approach although it is less open to ridicule. The interpretation of the theory of subjective probability and the Kent Charts used to transform degrees of belief to numerical statements of probability do not overcome the difficulties in performing a de-compositional analysis. Anything short of total de-composition of the failure mechanism into its fundamental components means that the estimate of risk is an artefact of the event tree model and the mind of the analyst. By 1995, BC Hydro had abandoned the 'Kent Chart' approach to assigning 'degree-of-belief' probabilities.

This does not mean that these studies were of no value, as they have potential to assist in planning further investigations and in the prioritisation of dam safety improvements. The studies in question relate to the dams listed in Table II-4. However, they fell short of the objective of risk assessment; that is, determining *if the dam is safe enough.*

I have taken the step of presenting this list in this way to provide a clear warning against the application of the procedures outlined in these 'experiments' in dam safety practice. This said, these 'experiments' were immensely valuable in revealing the difficulties of performing quantitative risk analysis for different types of dams for a wide range of failure modes.

Dam Name/Type	Focus of Risk Analysis
Alouette/Earth	All failure modes
Coquitlam/Hydraulic fill	Hydraulic/Seismic
Coursier/Earth	Internal erosion
Duncan/Earth	All failure modes
Ladore/Concrete	Spillway reliability/Seismic
LaJoie/Rockfill	All failure modes
Ruskin/Concrete/Earth	All failure modes
Stave Falls/Concrete	All failure modes
Terzaghi/Earth	Seismic

Table II- 4. BC Hydro dams where the simplified de-compositional seismic risk analysis was not adequate for formal risk assessment

The outcome of this unprecedented investigation program was that, while certain, but by no means all, failure modes associated with extreme floods and earthquakes were amenable in principle to quantification, static failure modes, such as internal erosion, are not. This does not mean that it is not possible to make subjective estimates of probabilities of failure for all possible failure modes, , if only a quantified statement of opinion is adequate. However, such quantified statements of opinion are no more than a number that resides in the head of the estimator, which, if not generated through valid procedures, are nothing more than 'guesses'.

The failure of these 'experimental' studies to produce the desired result was actually a benefit in disguise as the experience gained led to the development of BC Hydro's risk-based dam safety prioritisation system (Hartford and Stewart, 1998) Further, and very importantly it led to a complete review of BC Hydro's dam safety management philosophy. The result was that BC Hydro has moved beyond the simple concept of estimating dam risks and comparing them with numerical criteria (expected value, f-N and F-N curves etc.) to determine *if a dam is safe enough.* We subsequently found that our re-aligned philosophy as entirely consistent with the position of the UK Health and Safety Executive, which is arguably one of the most experienced and advanced 'risk regulators' in the world.

THE ROLE OF SUBJECTIVE PROBABILITY

None of the above should be interpreted as implying that the theory of subjective probability does not have a place in risk analysis for dam safety; it does. In fact, the formal theory of subjective theory as applied through the careful use of Bayes' Theorem is central to the success of risk analysis in dam safety practice. However, in the vast majority of examples cited in the literature, Bayes' Theorem is remarkably absent. Application of Bayes' Theorem is essential for the subjective probability to be credible and defensible, as Bayes' Theorem provides the necessary mathematical structure to ensure robustness. However, one view in dam safety holds that *the formal application of Bayes' Theorem should not be confused with the "Bayesian" probability approach, as degree-of belief interpretations are sometimes called. This terminology results from the idea embodied in Bayes' Theorem that probability varies according to the information available, but does not necessarily imply formal application of the theorem itself* (Vick, 1999). The validity of this view has yet to be broadly accepted and appears to be contrary to the view expressed by experts in the field of Bayesian probability (Cooke, 1991., Morgan and Henrion, 1990., Paté-Cornell, 1996, Kaplan, 1997). Resolution of this issue rests with experts in probability and scientific inference, with appropriate involvement of knowledgeable engineers to ensure that the practical considerations are not lost in esoteric theory. However, until it is resolved, owners must recognise that it is an important issue that requires resolution and must take whatever steps are necessary to avoid any difficulties associated with it. Until the former view is 'validated' by the wider mathematical and scientific communities, and to proceed in a defensible manner, applications of 'subjective' probability should be carried out within the formal mathematical framework of Bayesian probability.

SCIENTIFIC VALIDITY AND TRANSPARENCY

There are increasing demands for risk assessment to be scientifically based. Miss J. Bacon, the Director General of the UK Health and Safety Executive gave what I believe to be sound advice, *the task of the risk regulator - and of the scientific and engineering communities - is to reassert the concepts of justified risk and of 'safe enough'; to demonstrate the effectiveness of good science and technology in providing robust systems of risk management and control; and to make transparent the process undertaken for arriving at scientific judgements and engineering decisions.*

In the same paper, Miss Bacon noted *"20 years ago an eminent engineer in the UK suggested that: Engineering is the art of moulding materials that we do not wholly understand into shapes we cannot precisely analyse, so as to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance."* This was accompanied by a clear warning by this risk regulator: *"I* [J. Bacon] *am afraid that 20 years on, such black box mysticism in dealing with sources of risk is no longer viable. The credibity of risk prevention and control is at stake."*

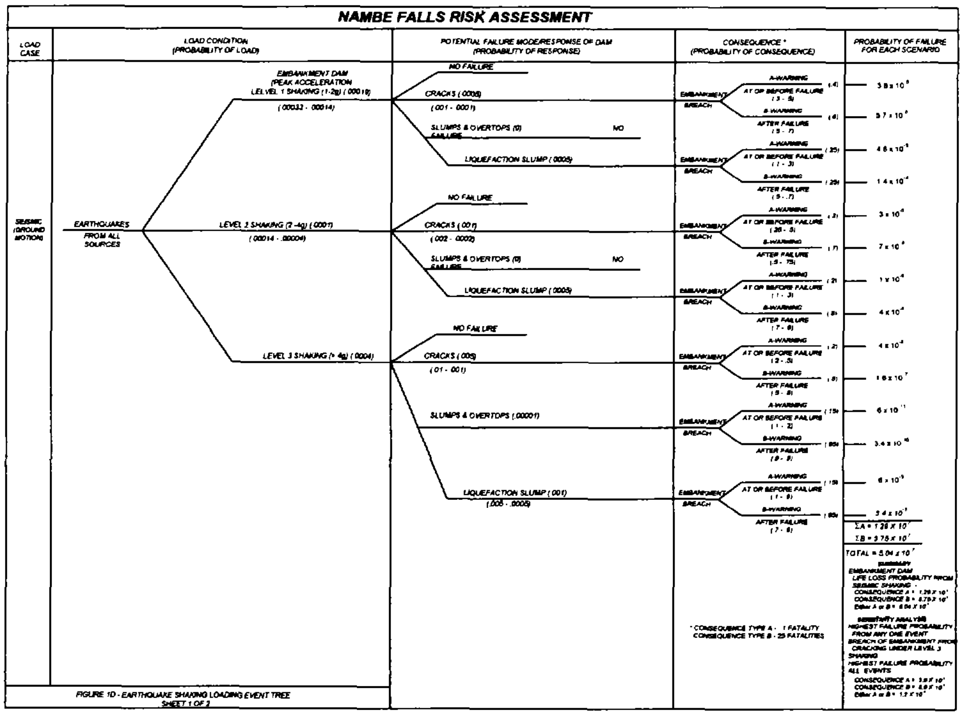


Fig. II-4 Event Tree Analysis using specialist opinion method of probability estimation

Here it is vitally important not to confuse 'scientific validity' (application of the scientific method) with 'scientific proof' as they are distinctly different concepts. Many real life decisions must be addressed before the scientific community can reach a consensus, and this applies to dam safety decisions which are fraught with uncertainty. What it does mean is that even under conditions of great uncertainty, the principles of scientific inference can be applied.

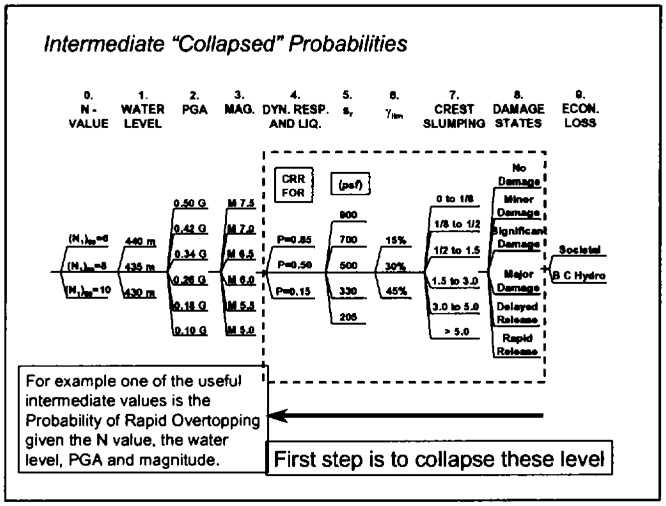
The following basic principles, which were formulated as part of a research project into models for expert opinion elicitation carried out under the auspices of the Dutch Government (Cooke, 1991.) are also of value in risk analysis for dam safety. These principles are:

Reproducibility: *It must be possible for scientific peers to review and if necessary reproduce all calculations. This entails that the calculation models must be fully specified and the ingredient data must be made available.*
Accountability: *The source of the expert subjective probabilities must be identified (this is particularly true for decision-making concerning the safety of the public).*
Empirical Control: *Expert probability estimates must in principle be susceptible to empirical control.*
Neutrality: *The method for combining expert opinion should encourage experts to state their true opinions.*
Fairness: *All experts are treated equally, prior to processing the results of observations.*

One challenge faced by proponents of risk assessment for dams is to demonstrate how these perfectly reasonable principles are applied in their practices. In my view, and from an analytical perspective, these principles are particularly important as they relate to the fundamental process of estimating probabilities and probable states. Scientific theories can never be conclusively verified, but, if a theory is in fact false, then in principle it should be possible to conduct a reproducible experiment to demonstrate that this is the case. This process is fundamental to empirical control - it is the safeguard against the argument that everybody's subjective probabilities are equally valid. The use of subjective probability does not permit the 'expert' to say whatever he/she wants, and adherence to these principles ensures that the analysis cannot be corrupted by institutional pressures and/or motivational biases.

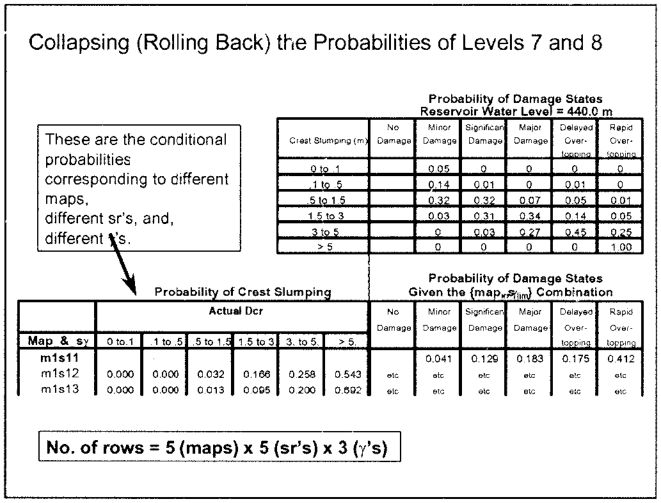
Consequently, there is a clear need for studies to demonstrate that there is detailed analysis behind the numbers in event trees. For example as in figure II-4 (Von Thun, 1996).

This does not mean that the numbers in this example are not based on detailed engineering analysis; rather there is a need to demonstrate that they are. 'Rolling back' a long complex event tree to illustrate results in a simple easily understandable form is a straightforward matter, as illustrated for Keenleyside Dam.


Intermediate "Collapsed" Probabilities

For example one of the useful intermediate values is the Probability of Rapid Overtopping given the N value, the water level, PGA and magnitude.

First step is to collapse these level


Collapsing (Rolling Back) the Probabilities of Levels 7 and 8

These are the conditional probabilities corresponding to different maps, different sr's, and, different γ's.

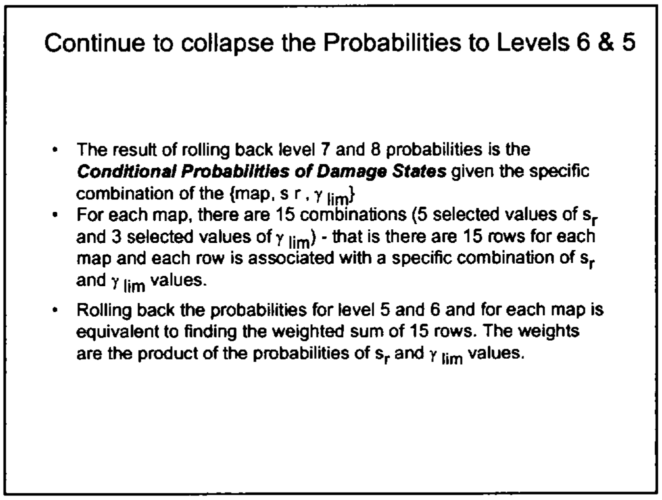
Probability of Damage States
Reservoir Water Level = 440.0 m

Crest Slumping (m)	No Damage	Minor Damage	Significan Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
0 to .1		0.05	0	0	0	0
.1 to .5		0.14	0.01	0	0.01	0
.5 to 1.5		0.32	0.32	0.07	0.05	0.01
1.5 to 3		0.03	0.31	0.34	0.14	0.05
3 to 5		0	0.03	0.27	0.45	0.25
> 5		0	0	0	0	1.00

Probability of Crest Slumping / **Probability of Damage States Given the {map, s_r, γ_{lim}} Combination**

	Actual Dcr											
Map & sy	0 to.1	.1 to .5	.5 to 1.5	1.5 to 3	3. to 5.	> 5.	No Damage	Minor Damage	Significan Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
m1s11								0.041	0.129	0.183	0.175	0.412
m1s12	0.000	0.000	0.032	0.166	0.258	0.543	etc	etc	etc	etc	etc	etc
m1s13	0.000	0.000	0.013	0.095	0.200	0.692	etc	etc	etc	etc	etc	etc

No. of rows = 5 (maps) x 5 (sr's) x 3 (γ's)


Continue to collapse the Probabilities to Levels 6 & 5

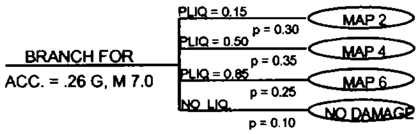
- The result of rolling back level 7 and 8 probabilities is the ***Conditional Probabilities of Damage States*** given the specific combination of the {map, s r, γ_{lim}}
- For each map, there are 15 combinations (5 selected values of s_r and 3 selected values of γ_{lim}) - that is there are 15 rows for each map and each row is associated with a specific combination of s_r and γ_{lim} values.
- Rolling back the probabilities for level 5 and 6 and for each map is equivalent to finding the weighted sum of 15 rows. The weights are the product of the probabilities of s_r and γ_{lim} values.

Probability of Damage States for a Given Liq. Map

Map No.	No Damage	Little Damage	Significant Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
1	0.00789	0.00383	0.02226	0.05480	0.06839	0.84282
2	0.00780	0.00381	0.02194	0.05406	0.06754	0.84485
3	0.01452	0.00871	0.03528	0.07013	0.08112	0.79025
4	0.24756	0.17313	0.23578	0.15561	0.10996	0.07796
5	0.88491	0.10404	0.00463	0.00000	0.00636	0.00006

Continue to Collapse the Probabilities to Level 4

- There are only 5 distinct maps with multiple damage states and probabilities. The damage state for map 6 is assigned 100 % 'no damage'. Each of these maps was assigned to the end-node of level 4 branches.
- Roll back to level 4 probabilities can be achieved, again, by finding the weighted sum of the probabilities of damage given the liquefaction map.

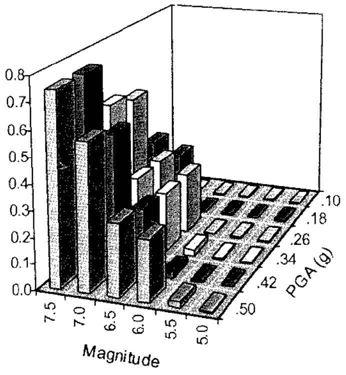


Probability of Damage States for a Given {Acc., Mag.} Combination

LEVEL 4

Probability (weight)	Map No.	No Damage	Little Damage	Significant Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
0.30	2	0.00780	0.00381	0.02194	0.05406	0.06754	0.84485
0.35	4	0.24756	0.17313	0.23578	0.15561	0.10996	0.07796
0.25	6	1	0	0	0	0	0
0.10	—	1	0	0	0	0	0
SUM		0.4390	0.0817	0.0891	0.0707	0.0587	0.2807

Collapsed Probabilities at Level 3 - 1 Damage State



Probability of Rapid Overtopping

given :

- $(N_1)_{60} = 10$
- Water Level = 440 m
- PGA, and,
- Magnitude

Continue to Collapse the Probabilities to Levels 2 & 1

Level 2 - Magnitude Contributions summed(weighted).

Acceleration		No Damage	Minor Damage	Significant Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
PGA (g)	Conditional Probability						
.50	8.696×10^{-6}	0.450	0.063	0.066	0.058	0.054	0.330
.42	5.216×10^{-6}	0.640	0.047	0.027	0.029	0.031	0.246
.34	7.824×10^{-6}	0.679	0.051	0.044	0.037	0.034	0.174
.26	1.841×10^{-5}	0.755	0.035	0.021	0.022	0.023	0.160
.18	$5.576 \times 10^{-}$	0.917	0.022	0.008	0.007	0.008	0.053
.10	6.690×10^{-4}	0.962	0.014	0.012	0.008	0.006	0.004

Level 1 - Summed (weighted) over acceleration intervals.

Middle Cross Section $(N_1)_{60} = 10$ Water Level = 440.0 m	No Damage	Minor Damage	Significant Damage	Major Damage	Delayed Over-topping	Rapid Over-topping
Weighted Sum	7.210 x10	1.233 x10	9.891 x10	6.891 x10	5.655 x10	1.403 x10

Therefore, the numbers in the simplified event tree in Fig. II-4 should be supported by analysis of the type illustrated for Keenleyside Dam, and the proposed procedure of Lin and Hung. This should not be misinterpreted as opposition to practical approaches, rather as reminding ourselves of the process which ultimately leads to practical engineering solutions to complex problems. The philosophy is quite simple and reflects the basic principles of engineering practice:

1. Develop a clear understanding of the problem, recognising that real world problems are generally too complex to be amenable to precise description or exact solution.
2. Radically idealise the problem to make it amenable to analysis by modelling the essential features and de-emphasising the less essential (this requires skill at modelling situations that are often beyond anyone's experience).
3. Develop a rigorous theoretical solution to the radically simplified model of reality.
4. Make further approximations to the model and the solution to create the 'practical solution', which can be applied in practice, recognising that the rigorous theoretical solution to the idealisation of the real problem

is necessary to 'calibrate' the approximate 'practical' solution

Unfortunately, for commercial and other reasons, including shifts in funding of learned endeavours, this established four-step process has, for the most part not been carried out in the evolution of risk analysis in dam safety practice. Rather, the 'empirical/judgmental' approach has been put forward as the 'practical' approach, even though they are generally devoid of the necessary theories and mathematical solutions. Regrettably, the 'empirical/judgmental' approach to risk estimation is now being staunchly defended, in the same way as clinical experience, which is also devoid of necessary theories and validated experimental results, is defended by clinicians.

Meeting requirements for scientific validity and transparency should not pose any difficulties in principle as the concept of dams being designed in terms of scientific principles was introduced over one hundred and thirty years ago. However, it might present enormous difficulties in practice at this time. Importantly, meeting requirements for scientific validity and transparency strengthens the role of judgement in risk-based dam safety decision making as it dispels any notions of 'black-box mysticism' or 'junk science'.

Most importantly, scientific validity and transparency provides owners, regulators and the public with a basis for having confidence in dam safety decisions based on the results of a risk analysis, something that does not exist at present. Here, I am putting forward the view that scientific validity and transparency of analytical procedures is essential for the acceptance of risk analysis as a legitimate means of informing the dam safety decision-making process.

CONCLUSIONS

That risk analysis in dam safety practice is controversial should not come as a surprise as it involves the mathematics of probability. Unfortunately, the modern literature on risk analysis for dams is decidedly unhelpful in dealing with this controversy as two opposite views, together with all possible views in between these two extremes, are frequently presented. At one extreme, there is the view that "methodologies for estimating the chance of dam failure are poorly developed and, at the present time, do not provide a defensible basis for the conclusive sign off on the safety status of a dam". At the other extreme, there is the view that "methods are available for estimating the probability of failure of dams for use in quantitative risk assessment for all failure modes". Such are the differences of opinion between proponents of risk assessment for dams in the same country! The controversy is not restricted to the probabilistic component of the analysis, as dam failure mechanisms are not well understood and generally difficult to model.

Regrettably, the modern literature on quantitative risk assessment for dams is increasingly suspect as there is clear evidence that it is being contaminated by re-cycled ideas, many which have been previously 'debunked' and others that can be classed as 'recycled and wrong'. This introduces a new problem which owners need to be aware of if they rely on the literature and/or those who write on the subject. There is a clear need to improve the quality of the literature and to raise the level of debate concerning risk analysis of dams and to continually improve professional practice to ensure that Professor De Mello's concern (De Mello, 2000) about *pseudo-professional analysing of risks* (Professor De Mello is not alone in holding this view) is consigned to the history books. If these vitally important issues are not addressed, scepticism and lack of confidence in risk analysis in dam safety practice will become even more entrenched.

Judgement has a vitally important role in the risk analysis process. However, greater openness and clarity about how judgements are exercised is increasingly being expected by those affected by decisions, in return for their trust and confidence. A great deal of work still needs to be done to explain how judgements in analysing risks posed by dams are exercised. It is no longer acceptable to present risk estimates and associated decisions as 'matters of judgement' without further explanation, still less to cloud them in the pretence of being matters of fact. Increasingly, there is a requirement to demonstrate that the exercise of judgement complies with defined procedures to ensure robustness and tractability. This will not be easy and will challenge jealously guarded professionalism. This challenge applies to proponents of deterministic approaches to dam safety as well as proponents of the risk analysis approach. Specifically, it applies to those who favour the empirical/judgmental and/or the 'degree-of-belief' approach to estimating probabilities of dam failures.

I hope that the reasons why I have concluded that judgement should be based on the knowledge that is revealed by an appropriate amount of analysis are understood because, unfortunately, they are often misinterpreted. I remain confident that provided we work in terms of accepted scientific principles, it will be possible to establish the scientific basis for risk assessment in dam safety. Of course this does not mean that we have to 'prove everything scientifically' along the way; real life decisions usually can't wait for the scientists to 'figure it all out' and come to a 'consensus'. Rather we must employ the established principles of the 'scientific method' and ensure that our 'estimation procedures' don't violate any of the laws of physics, or the principles of probability theory and scientific inference.

Failure to meet the expectations of scientific validity and transparency in an increasingly sophisticated society could well mean that we will not, i) overcome the growing mistrust by the public of advice given by scientists and risk calculators, and ii) earn the trust of the engineering and scientific communities, regulators and, most importantly, the public whose consent to own and operate dams is one of our most valuable assets.

Presently, from an owner's perspective, and in the light of my background research as summarised in this lecture, I have no option but to conclude that, for the most part, "methodologies for estimating the chance of dam failure are poorly developed and, at the present time, do not provide a defensible basis for the conclusive sign off on the safety status of a dam. In fact I go further and advise that at present, and for the purpose of legally defensible quantitative risk assessment, risks posed by dams can only be estimated in a scientifically valid way for a small number of failure modes, and only where the failure initiating event can be characterised probabilistically in a mathematically correct way.

This said, I have also concluded that the future for quantitative risk analysis and its use in dam risk management is decidedly bright, provided the appropriate resources are brought to bear on the problem of analysing dam risks. There are solid reasons to believe that risk analysis procedures for other modes of dam failure can be achieved if research and development efforts are carefully chosen, planned and implemented. It should not come as a surprise that a great deal of research and development into failure modes, mechanisms and their probabilistic description, is required. However, there is no option other than to address these challenges as uncertainty pervades all aspects of dam engineering. The Keenleyside Dam risk analysis is an example of what can be done and demonstrates at least in principle that scientifically valid and defensible risk analysis for dams can now be achieved under certain circumstances. Great strides have been made in the understanding of the fundamentals of risk analysis for dams during the past thirty- five years, and especially during the past three years. 1997 was a 'watershed' year in risk analysis in dam safety.

This State-of-the-Art and Practice lecture has provided me with the opportunity to set out a strategy for achieving scientifically valid, legally defensible estimates of risks posed by dams. I hope that the Canadian Electricity Association (CEA) Dam Safety Interest Group project *A Guide to Dam Risk Management* provides an organisational structure to achieve this end. I have concluded that, provided we move beyond the proposed practices of the 80's and 90's and embrace the ideas of scientifically-based risk analysis in dam safety, the future looks very bright indeed. I look forward to being joined by others committed to managing dam risks on the basis of scientifically valid and legally defensible risk analyses, and to working with them to achieve this objective.

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