15 Aug 2008, 9:15 am - 10:00 am

Risk Analysis in Geotechnical and Earthquake Engineering: State-Of-The-Art and Practice for Embankment Dams

D. N. D. Hartford
BC Hydro, Canada

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

SOAP 6

Dr. D. N. D. Hartford
Scientific Advisor: Safety and Risk Assessment
BC Hydro

ABSTRACT

The nature of risk analysis as applied to earthfill dams for the purpose of safety assessment is examined with particular reference to the matter of demonstrating the scientific validity of risk constructs used to inform important dam safety decisions. The qualities and attributes of what would be considered to be transparent, credible and defensible risk analyses for dam safety decision-making are outlined. A conceptual approach to addressing the problem of quantifying internal erosion risk that combines critical state soil mechanics theory and dynamic event tree analysis is proposed. Finally, an experiment aimed at assessing contemporary capability to detect the "changes of state" is described.

PREAMBLE

I am honoured to once again present my perspective on the State-of the Art and Practice of Risk Analysis for Embankment Dams. This lecture also provides me with an opportunity to reflect on developments in the domain over the past forty five years and over the past fifteen in particular. It is the last fifteen years that are of particular interest as risk analysis in dam safety assessment has gained greater acceptance, to the extent that dam safety programs are now seen as somewhat lacking if they don't have some element of risk-based thinking explicitly identified as part of the safety management process. Importantly, this lecture gives me the opportunity to explore where, in our enthusiasm to establish risk assessment in dam safety practice, we might not have got things quite right.

One area of particular concern is the respective roles of mathematics, scientific inference, and judgement, in the risk analysis process. I have used the term "judgement" as opposed to "engineering judgement", because probability resides in the domain of the philosophy of science and risk analysis of engineered systems (including dams) pertains to analysis of the mechanics of failure processes which pertain to physics and not to engineering design and construction where engineering judgement is essential. Mathematics which is central to good engineering is also central to risk analysis, although the types of mathematics may be different. Because of the complex probabilistic nature of the mathematics of risk analysis, one would expect that mathematics would be at the core of risk analysis practice. Yet for some reason the mathematics is often conspicuous in its absence, or reduced to a trivial form. Central to my lecture is how do we address the type of criticism of engineering judgments of probability levelled by the distinguished Nobel physics laureate, Prof. R. P. Feynman which went *"As Far as I can tell, 'engineering judgment' means that they are going to just make up the numbers!"* (Feynman, 1988).

BACKGROUND

Earth dams and other earthen water retaining structures have been essential elements of human development over the millennia. In many respects the discoveries of how to construct dams of different types in response to the social and political demands for the management of water resources in the public interest, have had some of the most profound impacts on human development. Very recently in the history of dams, soil mechanics has played a major role in the engineering design, construction and safety assessment of large dams. Sadly, dam failures can and do occur and it is an unfortunate fact that dam failures have resulted in more fatalities than the failure of any other peacetime industrial artefact. Thus understanding failure modes of dams is necessary to manage their safety.

Dam failure is terrifying; and the questions "is the dam safe?"; "what will happen if the dam fails?"; and, "are the consequences of dam failure manageable?" are central to the management of existing dams and water retaining structures in the modern context. However, despite the existence of earth dams and water retaining structures over the millennia, methods of answering these questions in transparent and scientifically-based ways have only begun to emerge over the past few years. How these questions are answered, and how robust and defensible the answers are, depends in many respects on whom you consult.

Decisions to build dams and the safety standards to which dams should perform are fundamentally matters of politics even though traditionally engineers have assumed a significant, even total responsibility for these matters. Whether or not this assumption of this responsibility – usually because the political process either expects it or because engineers have assumed this responsibility within a political vacuum – is not the subject of this paper, rather the paper explores some of the dimensions required for engineers to be properly equipped to enter into debate in the social-political arena that increasingly mistrusts "experts" and demands transparency and scientific validity.

Assessing the safety of a dam requires that the engineer make inferences from incomplete and uncertain data. To do this the engineer necessarily must hypothesise, and then draw conclusions recognising that a hypothesis is *a basis for reasoning without any presumption of its truth.* In many instances, dam safety engineers are not dealing solely with facts – the entire safety assessment process is inferential and utilises inductive logic. Inductive logic pertains to arguments that are not certain, and inductive logic analyses inductive arguments (hypotheses) using probability.

This State-of-the Art and Practice lecture attempts to focus on unravelling the problem of how and how well these issues can be answered. As such, and unlike my previous State-of-the-Art and Practice lecture in 2001 (Hartford, 2001), I will not deal with the specifics of how to apply State-of-the-Art or State-of-the-Practice (if there is a difference) methods of risk analysis to individual dams.

I do not propose to discuss the "State-of-the-Art and Practice" in the analysis of the behaviour of earth dams under dynamic and static loading conditions as others have already provided comprehensive treatments of the "state-of-the-practice" in the two domains of interest, seismic analysis of embankment dams and internal erosion of dams under static loading conditions. Dr. W. F. Marcuson III and his colleagues (Marcuson et. al, 2007) provided an exemplary account of the state-of-the-practice in embankment dam analysis for seismic conditions; and Professors Robin Fell (Fell et al., 2005) and his colleagues have provided a comprehensive account of the Geotechnical Engineering of Dams. Professors Fell and Fry (Fell and Fry, 2007) have described what might be considered to the State-of-the-Art of analysis of the propensity for internal erosion, although, in terms of the above definitions this would be state-of-the-practice.

Comparison of the state-of-the-practice in embankment dam analysis for seismic conditions with the invited workshop consensus view of the state-of-the-art of internal erosion analysis as presented by Fell and Fry reveals a stark difference between the "states" of the practice for the two failure modes. The state of the art for the internal erosion failure mode is extremely weak in comparison with that of the seismic failure mode (which itself is hardly sophisticated). In fact, the state-of- the-art of internal erosion analysis appears lacking of any soil mechanics equations! That there is such an imbalance between the analytical capabilities for these two failure modes should be of great concern particularly since internal erosion has been the cause of approximately 48% of historic embankment dam failures. Overtopping failures have been the cause of approximately 48% of failures with all other failure modes including seismic contributing just 4% of the total (the figure for "other" goes up to 17% if tailings dams are included (USSD, 1994)).

Concerning risk analysis as applied to dams, ICOLD Bulleting 130 (ICOLD, 2005) contains a reconnaissance of risk analysis practices around the world. Further, I gave as complete an account of risk analysis of dams under dynamic conditions as I could in my State-of-the-Art and Practice lecture in 2001 (Hartford ibid); and there have not been any significant fundamental discoveries in the soil mechanics of embankment dams since then.

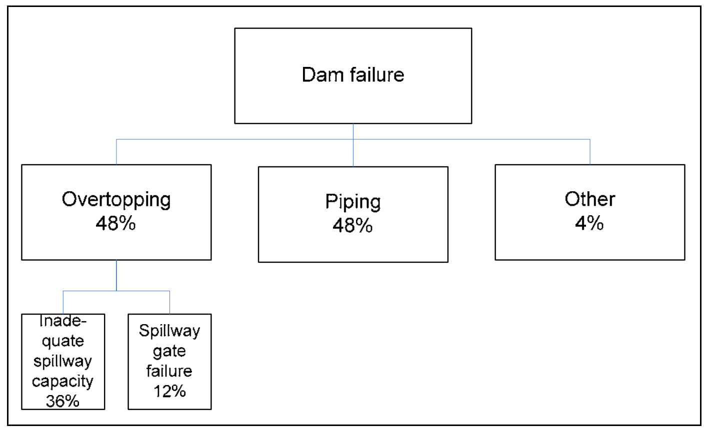


Figure 1. Embankment dam failure statistics (approximate) (Foster et al, 1998)

Obviously, this last point is debatable as no doubt there are researchers working at a fundamental level in the science of soil mechanics who would claim otherwise, and I don't want to discount their work in any way. Notwithstanding all of this, in practice the soil mechanics that underpins the analysis of the performance of dams has not changed in any significant way over the past 20 or more years. The lack of any soil mechanics models and equations in the *"State of the art of assessing the likelihood of internal erosion of embankment dams, water retaining structures and their foundations"* (Fell and Fry, ibid.) means that it is not possible to deal with the problem of internal erosion risk analysis in a scientifically meaningful way. There is other work in this domain e.g. Sellmeijer and Koenders which provides a mathematical model for piping under a dam (Koenders and Sellmeijer, 1992, Sellmeijer and Koenders, 1991) and the work of Ojha et al. (2001).

Against this background, my focus is on risk analysis techniques as they apply in dam safety assessment and some of the challenges that have yet to be overcome. This is followed by an outline of a conceptual approach to addressing the problem of quantifying internal erosion risk that combines critical state soil mechanics theory and dynamic event tree analysis. Finally, an experiment aimed at assessing contemporary capability to detect the "changes of state" is described.

PART I
RISK ANALYSIS

THE NATURE OF RISK ANALYSIS

Risk analysis is one of two classic decision support models that can be used to help structure and inform complex choices under uncertainty, the second being *"decision analysis"*. Risk analysis is the process of characterising the risk associated with the system of interest and in some cases it can be extended to include the identification and benefit assessment of some risk management options. It is based on systems analysis and probability, and it excludes the actual decision phase, which requires risk evaluation and risk assessment (Hartford and Baecher, 2004). While the text *Risk and Uncertainty in Dam Safety* refers specifically to dams in the title, many of the concepts, theoretical considerations and methods apply across the domain of the built environment, and beyond to engineered systems in general.

As explained in *Risk and Uncertainty in Dam Safety*, risk analysis and decision analysis have some similarities and are often complementary. Both risk analysis and decision analysis rely on probability theory to model uncertainties, usually the subjective or Bayesian degree of belief interpretation of probability. In risk management, risk analysis and decision analysis are often inter-related because a decision analysis may include a risk analysis as one of its constituent parts, and the design of a risk management plan may require decision analysis support. The challenge for risk analysts is to characterize potential failure problems before decision options have been identified, and when there is no single decision maker, or group of decision makers, who can provide preference functions and degrees of belief. Yet, a correct and complete model of uncertainties in the probabilistic risk analysis phase is important if the results are to be used later for decision support, especially when the number of systems involved and the duration of their operations is unknown (Paté-Cornell and Dillon, 2006). These considerations are pertinent to dams and geotechnical structures in general, especially when the consequences of a bad decision are potentially catastrophic or where the effects of a decision have lasting impact on the performance of the system.

These distinctions and interrelationships between risk analysis and decision analysis; between decision support and risk management; and particularly the risk characterisation function of risk analysis are important because they are often mixed in common usage. The words of risk analysis have presented opportunities for confusion for many years (Kaplan, 1997) as they are used differently in different professions and domains. In some cases, the term risk analysis is employed in a way such that it includes risk assessment, risk management and risk communication (e.g. OGTR, 2005). The diversity of use of the term "risk" ranges from "risk = probability" in the healthcare industry to "risk = consequence" in the insurance industry. In engineering, risk is taken as:

Risk = Probability x Consequence

The potential for misinterpretation and misunderstanding goes far beyond the definition of the risk as the term probability, which is fundamental to risk analysis means different things to different people and it is very difficult to obtain precise information as to what people mean when they use the term probability. In the domain of geotechnical and earthquake engineering, even the terms Bayesian probability, subjective probability and degree of belief probability present problems. For some, the term Bayesian does require the formal application of Bayes Theorem, whereas others refer to a Bayesian probability approach that does not require the actual application of Bayes theorem (a dubious position, see Hacking 2001).

SCIENTIFIC VALIDITY

The matter of the scientific validity of the results of risk analyses of dams has always been a contentious issue. The suggestion that risk analyses of dams should be credible and defensible (Hartford and Salmon, 1997), were met with scepticism and even outright resistance. However, I was simply drawing attention to the fact that there are increasing demands for all types of risk assessment to be scientifically based. Miss J. Bacon, the former Director general of the UK Health and Safety Executive expressed the view that, *"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"* (Bacon, 1999).

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 credibility of risk prevention and control is at stake."*

This emphasis on scientific validity is not peculiar to the UK Health and Safety Executive, as the scientific validity of risk analyses in Europe is essentially taken as given. Recently, in the United States, the Office of Management and Budget introduced new guidelines for Federal Agencies performing risk assessments (OMB, 2007).

(Note, the Office of Management and Budget use the term Risk Analysis to include Risk Assessment, Risk Management and Risk Communication.)

The memorandum which specifically states that the term scientific applies to engineering (footnote 17) sets out a number of "Principles for Risk Assessment". The first of these principles states: "Agencies should employ the best reasonably obtainable scientific information to assess risks to health, safety, and the environment." There is a clearly stated expectation that risk analyses should be based upon the best available scientific methodologies, information, data, and weight of the available scientific evidence. Principle 3 states: "Judgments used in developing a risk assessment, such as assumptions, defaults, and uncertainties, should be stated explicitly. The rationale for these judgments and their influence on the risk assessment should be articulated."

Regardless of the differences in risk analysis terminology, such demands for scientific validity of risk analyses are real and justified and should not come as a surprise. Those involved in risk analysis of dams will need to demonstrate the scientific validity of their practices to pass regulatory and public scrutiny. How dam owners and their engineers respond to this challenge could well be problematic for some, particularly those who resisted and even continue to resist the notions of transparency and scientific validity.

Precisely why requirements for demonstrating the scientific validity of risk constructs in risk analyses for dams are variously overlooked or discounted is not at all clear. The Bayesian view of probability is central to risk analysis for dam safety and an increasing number of philosophers and scientists accept the Bayesian view that *"scientific reasoning is essentially reasoning in accordance with the formal principles of probability"* (Howson and Urbach, 1991). I have argued in favour of *credible and defensible* probability assignment for over 10 years, and this can be achieved by adhering to the Bayesian approach.

PHILOSOPHICAL PRELIMINARIES

Although the concepts of probability and risk have been known since the 14th century, they have not found widespread use in geotechnical engineering practice until recently, and then only to a limited extent. This might appear to be rather strange given that uncertainty is such a dominant factor in geotechnical engineering, but the practice has been to adopt conservative designs to cater for all of the uncertainties. However, it is a simple fact that the extent to which a "conservative" solution actually covers all uncertainties and eventualities remains unknown.

Uncertainty and randomness

It is necessary to make a clear distinction between randomness and uncertainty.

Randomness concerns natural processes that are inherently unpredictable. To describe something as *random* is to presume that its occurrence can be described only probabilistically.

Random (adjective). Date: 1565. 1. a: lacking a definite plan, purpose, or pattern b: made, done, or chosen at random; 2. a: relating to, having, or being elements or events with definite probability of occurrence. b: being or relating to a set or to an element of a set each of whose elements has equal probability of occurrence (Merriam-Webster, 2000).

The role of dice, patterns of the weather, occurrence of an earthquake, and other such unpredictable occurrences have been called *aleatory* by Hacking (1975) and others after the Latin *aleator*, meaning "gambler" or "die caster." This term is now widely used in risk analysis, especially in applications dealing with seismic hazard, nuclear safety, and severe storms. The term *probability*, when applied to such random events, is taken to mean the frequency of occurrence in a long or infinite series of similar trials. This frequency is a property of nature, independent of anyone's knowledge of it. It is innate, and has a "true" value. Two observers, given the same evidence, and enough of it, should eventually converge to the same numerical value for this frequency.

The term uncertainty means different things to different people and it is difficult to find an unambiguous definition of the term. At least since the 18th century and arguably much earlier, the notion of *uncertainty* has concerned what we know.

Uncertain (adjective). Date: 14th century. 1: Indefinite, indeterminate 2: not certain to occur: Problematical 3: not reliable: Untrustworthy 4 a: not known beyond doubt: Dubious b: not having certain knowledge: Doubtful c: not clearly identified or defined 5: not constant: Variable, Fitful (Merriam-Webster, 2000).

Such unknown things have been called *epistemic*, after the Greek, επιστημη, meaning "knowledge." This term is now widely used in risk analysis, to distinguish imperfect knowledge from randomness

The notion of uncertainty is disconcerting to engineers and to those they serve. To engineers, especially those grounded in the philosophy of determinism, it perhaps implies a degree of ignorance, something that is apparently unacceptable even if it is true. It is disconcerting to those who accept engineering services because they have become conditioned to expect that the engineers they retain know what they are doing with their money.

From its dictionary definition, *uncertainty* means a lack of sureness or a lack of confidence about someone or something, ranging from falling just short of complete sureness or confidence, to an almost complete lack of conviction about an outcome or result.

There appears to be three facets to uncertainty: *Uncertainty* with respect to the world means that an outcome or result is unknown or not established and therefore in question. *Uncertainty* with respect to a belief means that a conclusion is not proven or is supported by questionable information. *Uncertainty* with respect to a course of action means that a plan is not determined or is undecided. The term uncertainty has a variety of shades. Each of these express an aspect of uncertainty that comes to play somewhere in risk analyses.

In modern practice, risk analysis usually incorporates uncertainties of both the aleatory and epistemic types. That is, the term *uncertainty* is used as an over-arching term that includes randomness. The National Research Council (1996) describes different types of uncertainty, using the following terminology:

Aleatory uncertainty is attributed to inherent randomness, natural variation, or chance outcomes in the physical world; in principle, this uncertainty is irreducible. These uncertainties may include things such as stream flows, assumed to be random processes in time, and geotechnical properties of levees, assumed to be random processes in space. Aleatory uncertainty is sometimes called, random variability, stochastic variability, objective uncertainty, or external uncertainty or natural variability (NRC 2000).

Natural variability associated with the "inherent" randomness of natural processes, manifesting as variability over time for phenomena that take place at a single location (temporal variability), or as variability over space for phenomena that take place at different locations but at a single time (spatial variability), or as variability over both time and space. Such natural variability is approximated using mathematical simplifications, or models. These models may or may not provide a good fit to natural phenomena. In the best of cases, they are close but only approximate fits.

Epistemic uncertainty is attributed to lack of data, lack of knowledge about events and processes that limits our ability to model the real world. Epistemic uncertainty is sometimes called, subjective or internal uncertainty. Epistemic uncertainties divide into two major sub-categories: model uncertainty and parameter uncertainty. Model uncertainty has to do with the degree to which a chosen mathematical model accurately mimics reality; parameter uncertainty has to do with the precision with which model parameters can be estimated. The NRC panel called this, *knowledge uncertainty*.

Knowledge uncertainty is most commonly associated with *model* and *parameter uncertainty*. Model uncertainty reflects the inability of a model to precisely represent a system's true behaviour, or our inability to identify the best model, or a model that may be changing in time in poorly known ways (e.g., flood-frequency curve changing because of changing watershed). Parameter uncertainties result from an inability to accurately assess parameter values from test or calibration data, from limited numbers of observations, and from the statistical imprecision attendant thereto. Parameter uncertainties may also arise from data uncertainties, including measurement errors, inconsistency of data, transcription errors, and inadequate representativeness

Probability

The term *probability*, when applied to imperfect knowledge, is usually taken to mean the degree of belief in the occurrence of an event or the truth of a proposition. In this sense, probability is a property of the individual. We may or may not know what the value of the probability is, but the probability in question can be learned by self-interrogation. There is, by definition, no "true" value of this probability. Probability is a mental state, and therefore unique to the individual. Two observers, given the same evidence, may arrive at different probabilities, and neither be wrong. This is one of the dilemmas of probability; one never knows the true answer. One expert might assign a probability of 0.1 to the occurrence of an event and another might assign a probability of 0.01 to the same event. The occurrence or non-occurrence of the event does not negate either of these expert's probabilities.

While the term "degree of belief" is not without its own difficulties, and perhaps the term "degree of confidence" might be more useful, it is clear that in terms if the "belief" interpretation of probability it is not quite right to refer to the Probability of Failure of Dam X as something like:

$$p_f = Ax10^{-b} / yr$$

Rather, it would be correct to claim that "the degree of confidence" in the ability of a dam to survive various conditions is:

$$C = (1 - p_f)$$
$$\therefore C = (1 - Ax10^{-b}) / yr$$

In short, a dam, or any other structure for that matter does not have a "probability of failure" as an intrinsic property.

I would suggest that much of the debate, and on some occasions heated arguments, about the role of probability and risk in engineering and in the safety assessment of dams in particular could have been avoided by this simple. It is not as though it wasn't known in the mathematical and scientific community that *"probability doesn't exist in the real world"*, it was; but it was not and still isn't universally accepted. This was particularly true when Casagrande first proposed the concept of calculated risk in geotechnical engineering because there were several great philosophers such as Sir Karl Popper who held that probability should be objective.

Probability assignment

In general, probabilities are assigned to distinctly different variables in the risk analysis, (1) chance event variables associated with natural variability (also termed aleatory uncertainties), and (2) state or condition variables associated with knowledge uncertainties (also termed epistemic uncertainties). Whether variables are chance variables or state variables is an artefact of the model within which the probabilities are assigned. Thus the assignment of probabilities is inextricably linked to the model being used to characterize the performance of the dam, its loading conditions, and the consequences that follow dam failure.

The frequency interpretation of probability is well established in engineering practice and the belief interpretation, which one suspects has been used implicitly and often unsuspectingly in engineering practice, is increasingly being used intentionally in engineering. Recent demands for explanation and transparency in dealing with uncertainty through risk analysis, means that increasingly the belief interpretation is being used explicitly.

In parallel to these alternative meanings for the concept of *probability* are alternative approaches to the way inferences are drawn from evidence, that is, from statistical data. Frequentist statistical inference is a widely applied body of doctrine comprising, among other things, estimator theory and the theory of significance tests.

Classical frequentist inference evolved in an effort to create an 'objective' appraisal of scientific theories, and treats probability as frequencies of random variations in the physical world, for example, as the naturally occurring variations among experimental results. Howson and Urbach (1991), point out that the frequentist theory of estimation, "(…) has two branches, known as point estimation and interval estimation. Point estimation aims to select a specific number as the so-called best estimate of a parameter; it is contrasted in the literature with interval estimation, a method of locating the parameter within a region and associating a certain degree of 'confidence' with the conclusion that is drawn".

Inferences about degrees-of-belief, in contrast to frequentist inference, are built upon Bayes' Theorem. Bayes' Theorem describes the degree to which observed evidence should logically change a degree of belief (*i.e.,* a probability) held before the evidence was observed, to a logically following degree of belief after.

Degree-of-belief inference has sometimes been called, "subjective probability," but Kaplan and Garrick (1981) put forward the view that the term is misleading, and that it has caused confusion and controversy. They put forward the view that the battle between the "frequentist school of thought" and the "Bayesian school of thought", has been due to a misunderstanding. The root cause being the desire for objective science on the part of the 'frequentist school of thought', a view shared by scientists in general.

Kaplan's views are not unique, similar arguments concerning the objective nature of the Bayesian approach have been put forward by other experts in probability and risk, the works of Howson and Urbach (ibid.) and Morgan and Henrion (1990) being just two examples.

Recently, Hacking (2001) presented the view that there are two types of belief probability, the interpersonal/evidential type, and the personal type. This distinction permits the analyst to reveal the fundamental nature of each probability construct, the extent to which probability constructs are founded in data and the extent to which a probability has been constructed in terms of established logical and mathematical principles.

However, the belief interpretation of probability does not simply imply that, "a probability is what one believes it to be". As Orkin (2000) points out, "without essential mathematical form, anyone can say anything". Thus, while a loose interpretation might be attractive from the perspective of facilitating the easy generation of numbers, it has limitations and inconsistencies if the belief is not correctly constructed. The problems associated with such a limiting interpretation can be overcome by adding additional constraints that strengthen the interpretation of probability. The result of adding such constraints is an interpretation of the form "a probability is what the evidence, as correctly assembled in terms of the necessary mathematical and scientific principles, permits one to believe it to be as a basis for action". It is this combination of all of the information (ranging from objective data through rational judgment to entirely subjective senses) in a logically consistent way through mathematical procedures that provides a probability construct with its essential mathematical form.

Against this background, the interpretations of probability as belief and probability as frequency are considered to be complimentary with both interpretations being necessary elements of probability theory as it applies to dam safety risk analysis. The interpretations are complimentary and scientifically valid when properly applied, and should be applied to the appropriate extent. There is no question of the two interpretations being mutually exclusive, or one being superior in its totality to the other, because the two approaches are complimentary, and depending on the situation, the use of one interpretation may be more appropriate than the use of the other. In this regard, the two interpretations are not necessarily alternatives.

EXPERTS, OPINION, JUDGEMENT AND SCIENTIFIC VALIDITY

"Engineering judgment" is held at an elevated level of respect amongst geotechnical engineers, and while engineers are generally held in high esteem by the public, the same public increasingly questions whether engineering judgment can be relied on to answer questions of public safety. The geotechnical engineering community can no longer rely on the paternalistic sentiment embedded in the notion of engineering judgment - that professionals know best - because it is out of fashion and unjustifiable in the modern context. In recent years, US federal government agencies such as the Nuclear Regulatory Commission have even discouraged the use of the term engineering judgment in their deliberations.

Thus while engineering judgment is raised to transcendent heights within the geotechnical community, it is often questioned by policy makers and the public. Despite the benefits provided to society by modern constructed facilities, adverse environmental consequences and other unfavourable impacts of those same facilities seem to be more on people's minds.

Within the dam safety community (although not original to it) there are at least two schools of thought on what constitutes judgment. (1) One holds that judgment reflects a base of knowledge held by a person or persons, and manifests in quantitative estimates of probabilities or other parameters as a *reflection of intuition*. (2) The other holds that judgment reflects an analytical process of reasoning, and manifests in quantitative estimates as a *reflection of logic*. These contrasting views of judgment reflect an age-old rivalry between the mathematical and the intuitive mind (Berlin and Hardy 1980; Berlin et al. 1979); Pascal (1966) even thought the two ways of thinking to be incompatible within the same person. Nonetheless, each approach is supportable and internally consistent, and each relates to the other, but they differ in their practical implications.

Within the school of thought that holds judgment to reflect an intuitive process, judgment is seen as based on the recognition of patterns in the world from which correlates can be identified. This is sometimes referred to as the "lens theory" and is attributed to Brunswik's (1952) research on perception and cognition (Hammond 1996). Brunswik theorized that people do not directly perceive the essence of an object or a situation, but rather perceive a set of implicit cues about it which may be ill defined. Such cues are statistically related in a person's mind, whether consciously or not, with the essential aspects one is attempting to draw a judgment about, and these statistical relationships are learned from experience.

Within the school of thought that holds judgment to reflect an analytical process, judgment is seen as based on *reasoning* from observations, known facts, and physical principles; wherein, *reasoning* means to determine or conclude something by logical thinking. Reasoning is similar to mathematical argumentation, but with verbal statements and relationships rather than symbolic ones. An important quality of the reasoning approach to judgment, in the eyes of its proponents, is the paper trail of evidence it leaves to justify conclusions that are reached.

Within the normal enterprise of risk analysis, an *opinion*, in contrast to a *judgment*, is a belief held with confidence but not substantiated by positive knowledge, proof, or explicit reasoning. This contrasts, and should not be confused with the meaning of the term in the legal arena, where an *opinion* is a formal statement by an adjudicative body of the legal reasons and principles for a set of conclusions.

Coherence and correspondence

The philosophical world distinguishes between two types of truth or judgments: coherence and correspondence (Hammond 1996). The *coherence* theory of judgment focuses on whether an individual's judgmental process is internally consistent. The *correspondence* theory focuses on whether an individual's judgments have empirical accuracy.

The cognitive basis of intuitive judgment is poorly understood. Brunswik's model, which has been the basis of later work by Hammond (1996), and others–and which has been cited by Parkin (2000), Vick (2002), and others, is based on perception, specifically the perception of attributes which Brunswick callecd, *cues*. Such cues are statistically related to objects and situations based on experience. When faced with a new object or situation, the individual perceives a relatively limited number of cues (Brunswik speculates that the number seldom exceeds seven) from among the almost limitless possibilities, and from these draws conclusions. The cues tend to be complex, thus they many not be interpreted in the same way each time they are perceived, or they may be perceived differently each time. Different people, presumably, perceive and interpret cues in different ways, presumably place different weights on them, and presumably combine cues in different ways, and thus may come to different conclusions about the same object or situation.

Hammond combined Brunswik's model of cues and intuitive judgment with reasoning and calculation to form cognitive continuum theory. Cognitive continuum theory holds that intuitive judgments should be evaluated by the *correspondence* between the weighted average of the cues perceived about an object or situation, on the one hand, and the critical attributes of the real object or situation they reflect, on the other. If these two correspond, then the judgment is said to be valid. In contrast, reasoning or calculation should be evaluated by the *coherence* of the model produced. If the parts of the model form an internally consistent totality, then the reasoning or calculation is said to be valid. The correspondence of this logically sound model to physical reality is of secondary importance.

Cognitive continuum theory further holds that people do not - or cannot - simultaneously think in both correspondence mode (intuitive judgment) and coherence mode (reasoning and calculation), but rather flip back and forth between these two cognitive processes. People form intuitive judgments, then subject those judgments to reasoning and calculation, and then take the results back into an intuitive correspondence mode, and so on, and so on. Hammond calls this, "quasi-rational cognition." In solving a difficult problem, one might first look to hunches, intuitive guesses, or premonitions, and then subject whatever arises to analytical thought. When the analysis becomes bogged down, one might go the other way and seek hunches about the analysis. This is something akin to Sir Karl Popper's (1968) hypo-deductive view of the scientific method, in which an hypothesis is developed intuitively, but then tested deductively.

In practical applications, analytical cognition is both more highly accurate on average than is intuitive judgment, yet sometimes can be wildly inaccurate. This is unsurprising. When underlying assumptions are more or less correct, analytical cognition can be both accurate and precise; but when those same assumptions are incorrect, the conclusions based on analysis can be widely off. Large errors were sometimes made in the analytical mode, but research suggests that they are less frequent than in the intuitive mode (Hammond 1996).

The confidence that people, both professionals and the public, place in a prediction appears to be related to the degree of internal consistency that manifests in the arguments or model underlying the prediction.

Parameter estimation

The whole area of obtaining quantitative estimates of parameters which cannot readily be quantified through direct measurement or other sampling techniques, has changed dramatically since Casagrande's time and even since Whitman resurrected Casagrande's concept (Whitman, 1984) or others began to apply the concept in practice in the late 1980's and 1990's.

The introduction of probabilistic concepts for treating uncertainty requires an engineer to exercise a form of judgment which differs from the conventional professional judgment that he (or she) may have developed during his or her career through training and practical experience (Brown and Aspinall, 2004). This alternative form of judgment, which arises in all attempts at estimating probabilities, regardless of the domain, is generically termed 'expert judgment', and involves enumerating subjective probabilities that reflect an expert's degrees of belief. Typically in the practice of risk analysis for dam safety (Nielsen et al., 1994, USBR, 1999, Vick, 2002, Brown and Godson, 2004, URS, 2007) this subjective element in assigning probabilities has often been treated, in terms of a limited personal interpretation of subjective probability, treated informally (that is without formal consideration of coherence and correspondence, or ignored altogether. However, requirements for scientific validity and methodological advances such as those described in *Risk and Uncertainty in Dam Safety* are bringing a more rigorous form of eliciting judgment increasingly to the forefront of risk analysis practices.

The first question that arises in expert judgement elicitation is "How does one define an 'expert'?"

Experts

Typically, experts have undergone rigorous intellectual training. Experts can be distinguished from non experts by two characteristics; specifically their *substantive expertise*, and their *normative expertise* (Morgan and Henrion, ibid.):

- "*Substantive* expertise can be measured by how well a set of assessments predicts the actual outcomes; a substantive expert should on the average assign high probabilities to those events that turn out to occur, and low ones to those that do not.
- *Normative expertise* is measured through the process of calibration. It is also known as reliability. An assessor is said to be well calibrated if the assessed probability of events corresponds with their empirical frequency of occurrence. For example, for a large set of events to each of which the assessor assigns a probability of 0.8, about 80% should actually occur if the assessor is well calibrated.

Scientific validity of expert judgements

Expert judgements in risk analyses can be demonstrated as conforming to accepted scientific norms through the use of elicitation schemes such as that developed by Professor R. Cooke (Cooke, 1991), which is one of the most widely used processes. Use of the level 3 and level 4 methodologies developed by the Senior Seismic Hazard Analysis Committee in the United States (Budnitz et al., 1998) which is analogous to Cooke's method is an alternative. Cooke's method is particularly attractive as its basis replicates the formal scientific method. One of its most valuable attributes is the scope it provides for quantifying realistically the spread of scientific or engineering uncertainty in relation to any parameter of interest.

Cooke's procedure is usually framed to elicit suitable lower and upper percentile confidence estimates from the experts, as well as a central or 'best' estimate value (which can be the mode, mean or median, depending on the distributional properties being sought). This aspect of the structured elicitation procedure is especially important for those variables for which adequate data do not exist for conventional statistical analysis. This is where the need for precise differentiation between engineering judgment and expert judgment matters.

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. However, 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 of particular value in risk analysis of dams. 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 task for proponents of risk analysis for dams is to demonstrate how these perfectly reasonable principles are applied in their practices. From an analytical perspective, conformance to these principles is 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. Thus, the application of Cooke's or an equivalent method that replicates the formal scientific method in eliciting subjective probabilities from suitably qualified experts will meet the requirements for scientific validity.

TECHNIQUES OF RISK ANALYSIS

Event tree analysis

The event tree is a graphical construct that shows the logical sequence of the occurrence of events in or states of a system. Event trees offer the analyst the capability to construct a logic model of a system that is visual and therefore is easy to view and read, and that provides a qualitative and quantitative insight to the system's operations and reliability.

An event tree can be thought of as a fragility curve representation of the system's response to the loading. The fragility curve is treated as primarily reflecting limited knowledge of system behaviour, modelled as epistemic uncertainty. Initiating events are brought into the start of the event tree to cause the system to respond. Typically in event tree analysis, initiating events are treated as naturally varying phenomenon occurring randomly in time. Even though the uncertainties associated with external initiating events may be attributable to limited knowledge, in practice they are normally modelled as due to natural or random variability (*i.e.*, as aleatory uncertainty). This implies annual probabilities of events of given size occurring or being exceeded, as for example, in flood frequency relations or earthquake recurrence functions.

It is important to define what the event tree is intended to represent as this determines the nature of the variables represented in the tree. The meaning of the term "event" should be clearly defined and understood as should the description of system states. It will often be necessary to make a clear distinction between the state of the system and the state of the operating environment of the system as there are often important interactions between the two which can be come "mixed" in the event tree if sufficient care is not taken.

Originally, event trees were used to represent binary changes of state of systems as illustrated in Figure 2.

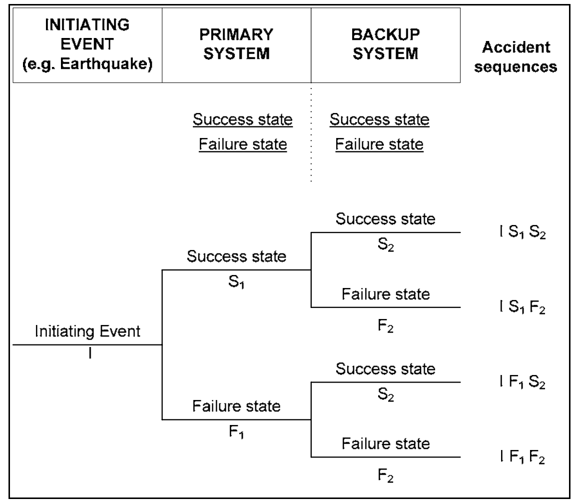


Figure 2. System states modelled in an event tree

This straightforward notion of binary change of state must be modified for application to dams as the states will not always be binary. With respect of event trees representing changes of state, the general concepts are illustrated in Figure 3. Importantly perhaps, the change of state concept provides us with a clue as to how internal erosion risk might be quantified in event tree analysis.

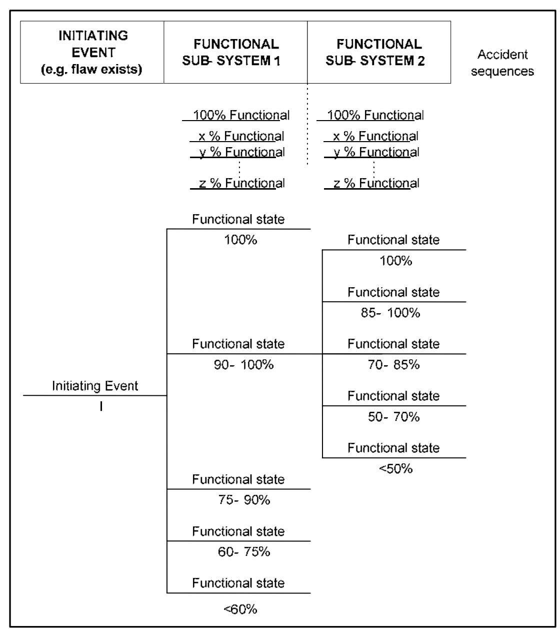


Figure 3. Generalised event tree representation of "change of functional state"

Event Tree Analysis (ETA) is an apparently straightforward endeavour that finds widespread application in many industries and businesses. It is an inductive type of analysis that, unlike fault tree analysis, is not supported by an extensive theoretical basis. ETA is the most widely used form of analysis in risk analysis for dam safety, although the lack of theoretical basis means that the correctness of these constructs is difficult if not impossible to determine at this time.

Fundamentally, creating an event tree model of a dam is a knowledge-based endeavour. Different analysts will have different ways of defining events, different ways of linking events together, and different ways of estimating parameters and assigning probabilities to events. All these things, combined with inadequate data and poorly understood models, mean that event trees and their numerical results are never unique. An event tree reflects a belief structure about a dam, about the natural environment within which the dam resides, and about the natural and human processes that affect dam performance.

The uncertainties that enter an event tree analysis–both in the way events are structured in the tree and in the way numerical values of probability are assigned to branches have mostly to do with limitations in knowledge, not with random processes, although for modelling convenience they may be represented either or both as natural variations (*aleatory* uncertainties) and knowledge uncertainties (*epistemic* uncertainties). This is true about the external environmental forces acting on a dam, about internal response of the dam to those forces, and about the estimation of properties and parameter values that enter the calculations.

While this does not imply that ETA is not useful in safety assessment of dams, it does limit the extent to which it can be relied on in an absolute sense in decision-making.

FAULT TREE ANALYSIS

Fault tree analysis (FTA) is one of the techniques available to the engineer conducting a reliability or safety analysis for a dam. It is a technique whose theoretical foundation is well-developed and that has been applied extensively in reliability and safety assessments for a wide range of engineered systems such as missile launch systems, chemical process facilities, nuclear power plants, dams, control systems and computers. In addition, the software and the databases available for conducting a FTA are sophisticated and add significantly to the efficiency of performing a risk analysis.

The fault tree is a graphical construct that shows the logical interaction among the elements of a system whose failure individually or in combination could contribute to the occurrence of a defined undesired event such as a system failure. Fault trees offer the analyst the capability to construct a logic model of a system that is visual and therefore is easy to view and read, and that provides a qualitative and quantitative insight to the system's operations and reliability. FTA is a deductive analysis, in which the analyst reasons what can lead to the occurrence of a specified undesired event. In a top-down manner, a FTA works from the general to the specific. One of the early steps in a FTA is to specify a particular but general undesired event, such as failure of a system. The analysis then proceeds to determine what the specific causes or modes of system failure are.

FTA can play a particularly valuable role in forensic analysis of failures of systems, including dam failures. It can also be extremely valuable in mining case histories of failures, be it of dams or other engineered systems. In particular, FTA provides a means of demonstrating the validity of "explanations" for dam failures. The extensive theoretical basis that exists for fault tree analysis, together with the fact that FTA does not suffer from the inability to demonstrate the correctness of tree structure (as is the case with event trees), renders FTA a vastly superior means of explaining failures. Any difficulties that arise in explaining case histories will be immediately revealed by the logical rules of fault tree construction. The fundamental elements of Fault Tree construction are illustrated in Figure 4.

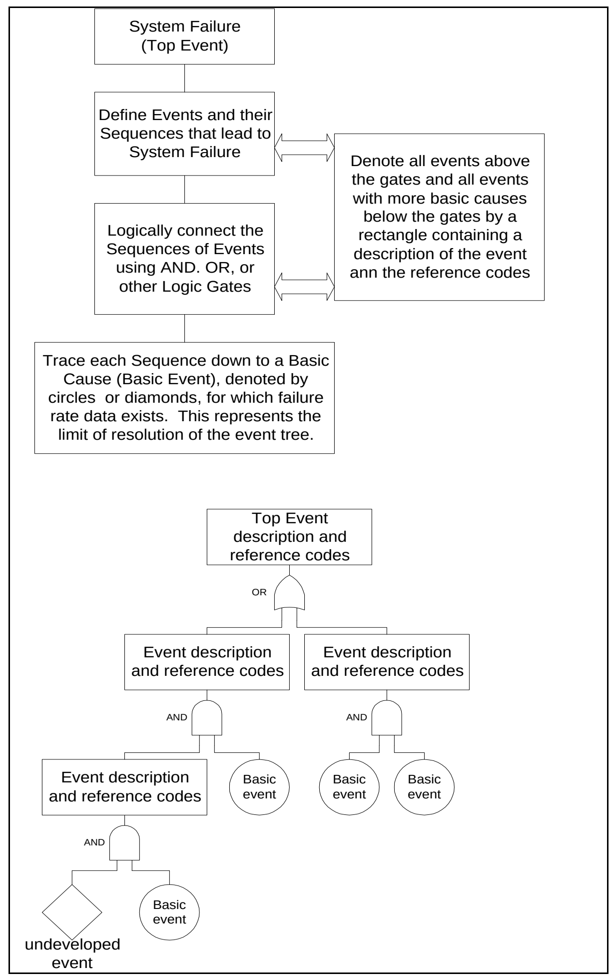


Figure 4. Essential elements of Fault Tree Construction

This does not look overly difficult, so why is it that FTA is not the analytical method of choice in the forensic analysis of failures of geotechnical structures? I would suggest that the problem is not with the method of fault tree analysis per se, rather its demands for both data and logical reasoning between claim and evidence appear to be at odds with the traditions of engineering judgement in geotechnical engineering practice.

One of the most significant problems that arises in constructing fault trees of dam failures is the lack of information about the failure because the evidence is literally swept away by the dam breach flood. Unfortunately, any inability to construct a fault tree of a dam failure means that any account of the failure will be incomplete and therefore not necessarily reliable. However, the inability to construct a complete fault tree is no reason not to attempt to do the best that one can because it is the only way to determine the extent to which any account of the failure can be relied on in informing analyses, judgements and decisions.

PART II
INTERNAL EROSION RISK ANALYSIS

INTRODUCTION

The ability to mechanically model failure mechanisms for dams in general remains very weak, and is unlikely to improve in the foreseeable future as research into the physics of failure mechanisms is extremely limited. From Figure 1, it is clear that internal erosion is worth of significant attention, and while it has received some attention, spearheaded in recent years by Professor Robin Fell at the University of New South Wales, much work remains to be done to develop appropriate mechanical models of the internal erosion process that can be cast in mathematical form.

Most approaches to assessing the propensity for earth dams to fail by internal erosion are now based on two design criteria; specifically filter criteria and criteria for internal stability of the core material. However, it is not at all clear that failure to meet certain filter and internal stability criteria means that the dam in question has a propensity to fail as a result of internal erosion.

This is a manifestation of a more general problem in dam safety as many dams do not meet modern safety criteria yet they appear to perform quite satisfactorily. On the other hand, conformance to these filter and stability criteria in design and material selection does not guarantee that the propensity for failure by internal erosion is eliminated because there is presently no way of knowing that the as-constructed dam actually strictly conforms to the design criteria. Segregation during handling and placement are natural phenomena that must be considered in any safety assessment of a dam. Dam owners and their engineers face complex questions, the solutions to which are not found in design rules, when trying to determine the propensity of earth dams to fail by internal erosion.

Semi-empiricism dominates the various approaches to analysing the propensity of dams to undergo internal erosion. I say semi-empiricism because in most cases, it is not possible to demonstrate that the methods used conform to the "principle of empiricism".

"Probability of failure by internal erosion"

The notion of expressing an annual probability of failure of earth dams as a result of the internal erosion failure mode has been discussed for over 20 years. The quantification of internal erosion risks based on annualised probabilities presents particular problems because it is not clear what it means to express the probability of failure as an annualized rate. The problem arises because the driving force for internal erosion is reservoir level, without which there would be no water pressure against the upstream face of a dam, no internal pore pressure gradients, no seepage, and consequently no internal erosion. However, it is not the fluctuation of reservoir level through time that causes internal erosion; a constant high reservoir would just as likely, or even more likely, lead to internal erosion.

The uncertainties inherent to the analysis of internal erosion in a fill dam have somewhat to do with frequencies, and somewhat to do with knowledge uncertainties. On the first count, many models of piping start with the random presence of a "flaw." This flaw can be one of design or one of construction. It is often taken to occur randomly in space within the dam. Thus, the flaw is partly an epistemic uncertainty (does a flaw exist?), and partly an aleatory uncertainty (if so, where?). On the second count, the process of internal erosion, even given a flaw, is poorly understood. There are significant limitations to the understanding of the physics of internal erosion, and thus to the models and material properties that apply. These have little to do with randomness and almost nothing to do with frequencies in time.

From a risk point of view, two things are uncertain: first, will a particular dam under particular load conditions fail by internal erosion if left forever to do so, and second, if the answer to the first question is, yes, then over what time period does this failure unfold? The probability that the dam will fail by piping in a given year, t_0, is the product of an absolute probability, the probability that it can fail by piping at all, and of a time-dependent probability of how long the process will take (Figure 5).

All these uncertainties may be epistemic, and yet they may lead to "annualized" probabilities having to do with uncertainties over how long the process takes to complete. These annualized probabilities (i.e., the derivatives of the cumulative curve) change with time, rising slowly from zero, cresting at the most likely time to failure (presuming a failure occurs at all), then falling off again. The asymptote of the cumulative probability is the absolute probability that piping failure occurs at all, which may be less than 1.0.

The extent to which uncertainty dominates many dam safety decisions is often used as a reason for not pursuing risk analysis of dams. This is unfortunate and grossly erroneous as the same theoretical and scientific principles apply regardless of how great the uncertainty. A decision problem with a little uncertainty must be dealt with in the same fundamental way as one with a great deal of uncertainty. The only difference will be the extent to which the results will be uncertain. The above text demonstrates that we understand the issues and how they should be considered in analysis, but not much more and Figure 5 illustrates the form of the analytical result.

The ability to characterize internal erosion risks will not improve until an understanding of the physics of internal erosion improves. This is not a risk analysis issue, it is a mechanics issue. In the mean time, the best that can be done is to try to understand the nature of time-dependency in describing the internal erosion risk (and risks similar to it, in this sense).

The loads driving a potential internal erosion failure (i.e., reservoir levels) may or may not have a frequency aspect to them, but if they do, it can be ignored. The process of internal erosion depends on physics and material values about which there is limited knowledge and thus considerable uncertainty, but internal erosion failure does not occur instantaneously. It is a time-dependent physical process.

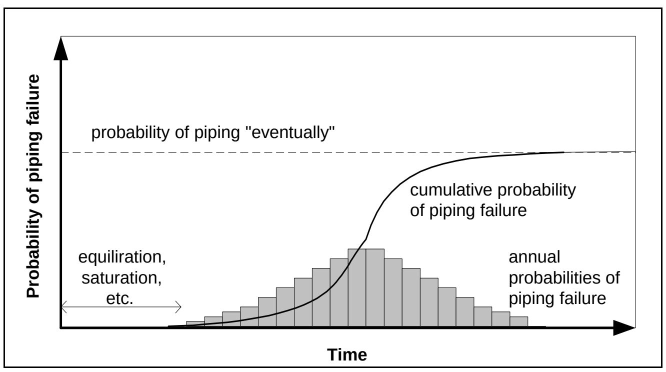


Figure 5: Probability of failure by internal erosion (Hartford and Baecher, 2004)

Against this background, it is clear that the notion of the annualized probability of failure by internal erosion is problematic. This means that establishing numerical criteria for internal erosion risk assessment is not the straightforward matter that the contemporary literature might suggest.

The internal erosion failure mode is just one of a general set of problems faced by dam owners that arises from the general uncertainties in the design, construction and performance of dams. It is a complex area where dam owners necessarily should hold somewhat different degrees of confidence in the functional performance of the dam than the designers and constructors of the dam. This is because the designers working in their individual engineering disciplines should be confident with their designs and, with proper quality control are entitled to assume that their colleagues have “got their parts right”, and that the constructor “has got everything right”, whereas the dam owner cannot assume perfection. Rather, it is the extent to which the design and construction are not quite perfect with respect to the design assumptions and their validity that should be of concern to dam owners.

The increasing use of probabilistic risk analysis in dam engineering has led to a realization that many of the approaches for modelling and analyzing failure processes for dams are inadequate. The event tree is one modelling technique that has been used in attempts to model dam failure processes. That is, there are event trees of the type wherein the “events” may be described, but the probabilities associated with those events are not readily estimated from existing understanding of the physics of the processes and the knowledge of the dam. As a result, estimates of probability of internal erosion are highly subjective (that is of the mind) even though the process of internal erosion is entirely physical and in principle measurable. This has led to the observation that the profession needs to develop models that are more helpful in analyzing actual mechanisms of failure rather than focusing on comparison to design standards. Internal erosion is one of the mechanisms of failure is one such failure mode where significant improvements in scientific knowledge are required. Failures due to internal erosion are not easily modelled, and even if they can be modelled approximately, the estimation of risk presents at least a significant a challenge. Different workers in the field of internal erosion risk analysis have developed event tree structures that are slightly different variations of the same construct. However, developing well-structured event trees to model internal erosion is difficult, in part because the mechanics of the process is poorly understood and therefore difficult to represent, and in part because the nodes of an event tree represent transitions from one system state to one or more new states. Typically, for event tree models of functional states, outcomes of precursor events are binary, Functional or Not Functional (Success/Failure, Yes/No). Correctly accounting for the timing of the events is a significant issue in event tree analysis, which is more amenable to representation of instantaneous state transitions rather than time dependent changes in functional state. The failure logic sequence might actually change depending on the rate at which interdependent “changes in states” in the systems and its sub-systems take place.

In the case of internal erosion, the “system state” changes from “fully functional” to “completely failed” in a gradual or even sporadic way. Precisely what “the system” is, needs to be carefully defined before change in system state can be defined, and this is not an easy task. For example, the system to be modelled in the event tree could just be the filter, or just the core, or the core and filter as interdependent sub-systems, or the core, filter and drains as interdependent sub-systems. Then the definition of what the physical “change of state” of “the system” is and the time at which the “change of state” occurs are particularly important if internal erosion is to be modelled using event tree techniques.

Not withstanding the facts that failures due to internal erosion are not easily modelled, and that developing well-structured event trees is difficult, all safety assessments of earth and rock fill dams need to address internal erosion. Risk analysis provides the only available means of expressing what is known and what is uncertain in a rational way. That an internal erosion risk analysis might be dominated by knowledge uncertainties is simply a fact that must be dealt with. However, the preponderance of uncertainty is not a reason for not attempting a coherent, well-structured risk analysis.

Recent work has determined that the notion of utilising the historic frequency of dam failures that are due to internal erosion, while intuitive and clearly applicable to populations of dams, is problematic with respect to individual dams. This is not the only method of estimating the probability of failure by internal erosion that appears to have fallen from favour. The methods for quantifying internal erosion risk using what might be loosely termed as subjective Bayesian prior probabilities and Kent Charts that emerged in the 1980's and 1990's appear to be diminishing in the literature and are not mentioned anywhere in *Internal Erosion of Dams and their Foundations* (Fell and Fry, ibid.).

These observations suggest that despite valiant efforts and significant investment, the apparently straightforward method of quantifying the probability of failure by internal erosion using event tree analysis and the subjective probability interpretation as encoded in Kent Charts. A radically different, soil mechanics-based approach appears to be the next frontier in dealing with this difficult, and thus far irresolvable, problem.

EVENT TREE MODELLING OF INTERNAL EROSION RISKS

Event tree modelling of internal erosion risks (e.g. Whitman, 1984) began to emerge in practice in the early to mid 1990's. However, the engineering and scientific communities have not been able to accept these methods as being appropriate and valid risk analysis constructs. This lack of general acceptance is an important factor to be taken into consideration by dam owners dealing with internal erosion.

Typically, the event tree models of internal erosion that have emerged over the past fifteen years are of the form illustrated in Figure 6, which is subtly different from the "functional state" concepts of Figure 2. Refer to Hartford and Baecher (2004), pages 208 – 213, for an account of the early evolution of event tree analysis of internal erosion.

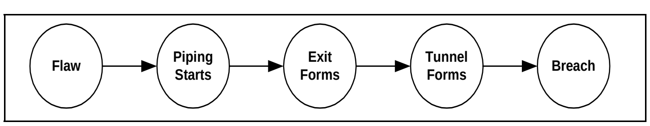


Figure 6. Published internal erosion risk analysis models (Hartford and Baecher, 2004.)

The process illustrated in the influence diagram in Figure 6 is a more specific version of the more generic deterioration process form proposed by the researchers at the University of New South Wales (UNSW) (Fell et al., ibid) (Figure 7). The UNSW 4-step generic process is based on the generic deterioration process that applies generally to engineered and natural systems, and is not specific to internal erosion. The published models referenced by Hartford and Baecher is readily represented in the UNSW model (Figure 8).

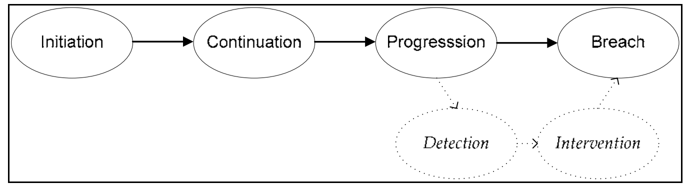


Figure 7. UNSW model of internal erosion (Fell et al., ibid)

The "detection" and "intervention" steps, which are sometimes included in contemporary risk analysis practices are not internal states of the "dam/reservoir" system and should normally be exclude from the risk analysis process. Rather, these interventions are external to the dam and are more correctly associated with risk management measures.

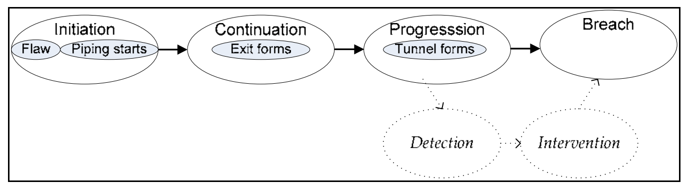


Figure 8. Contemporary internal erosion model

Any intervention must necessarily result in an "imposed change in the system" that is not in any way related to the process of internal erosion. From a risk management perspective, it is better to construct the "base-case" event tree without consideration of detection and intervention as it is not possible to determine the probabilities of success if one does not know the seriousness of the problem at the time of detection or the effectiveness of any subsequent intervention. There are also good reasons to suspect that the inclusion of detection and intervention nodes in an event tree will result in an overly optimistic view of the level of risk.

In terms if the "State-of-the-Art" of ETA, the state of the system should be fully defined by a logic tree prior to the initiation of the failure mode in order to ensure that the event tree is restricted to being a representation of the system response. This approach is distinctly different to the event tree analysis practices for dams that emerged in the 1990's where pre-existing system states were often represented at nodes within the event tree.

At the outset, the state of the system prior to the occurrence of the initiating event must be defined. This means that the complete set of states that the system normally operates in, for example reservoir elevation, operating temperature, etc. are defined prior to constructing the event tree. It is also important that the knowledge (epistemic) uncertainties concerning the pre-existing state be represented if they influence the analysis of the system response. Logic trees provide a useful way of representing system states where each end branch of the logic tree describes a pre-existing system state.

When it is necessary to consider more than one precursor system state and/or uncertainty in the precursor state, it is necessary to use several event trees and to condition each event tree for each failure mode by all possible system states. Correctly accounting for the timing of the events is a significant issue in event tree analysis, which is more amenable to representation of instantaneous state transitions rather than time dependent changes in functional state. The analyst should be aware that, as is the case in some nuclear power applications, the failure logic sequence might change depending on the rate at which interdependent changes in states take place.

The use of event trees in modelling internal erosion failures, presents a number of difficult questions, including the absence of scientifically verified models of the start and continuation of internal erosion. It also suffers a lack of good information about the as-constructed internal condition of most dams. The failure of a dam by internal erosion during first filling, illustrates another aspect of the problem of characterising internal erosion risks as in most cases (some flood control dams being an exception) first filling of a dam is not necessarily a random event, and thus is not necessarily modelled as an annualized, random (aleatory) variable. Thus, the initiating event for internal erosion is usually associated with flaws or deterioration. While event tree analysis is especially well suited to representing the potential consequences of natural hazards; it is less well suited for dealing with internal initiating events with time-dependent failure mechanisms.

Against this background, and with reference to Figure 2 and 3, I would like to propose a generalised "change of state" approach to event tree construction for internal erosion, where the time dependent functional state of the "core-filter-drain" sub-system that controls internal erosion can be represented (Figure 9).

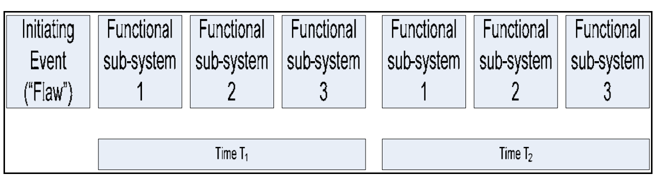


Figure 9. Time-dependent functional state framework for internal erosion event trees

The "change of state' concept is distinctly different from the contemporary models illustrated in Figure 6 through 8 and as described in *Internal Erosion of Dams and their Foundations* (Fell and Fry, ibid.).

This "change of functional state" approach is a generalisation of the "functional process" model that provides a means of decomposing the functional state into time based steps. It is aimed at overcoming the limitations of the conventional approach to event tree analysis of this important failure mechanism.

The functional elements of the dam that are critical to the analysis of the probability of failure by internal erosion are; Core; Filter; and Drain (Figure 10).

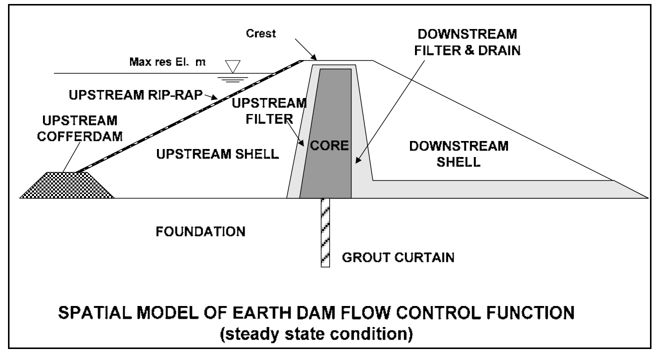


Figure 10. Spatial model of earth fill dam

The spatial model can be transformed to a functional model as illustrated in Figure 11. The core-filter-drain subsystem is represented generically in the event tree shown in Figure 9 as sub-systems 1, 2 and 3. Thus, if one can determine the functional states of the core, the filter and the drain, in Figure 11 then they can be represented directly in event tree form.

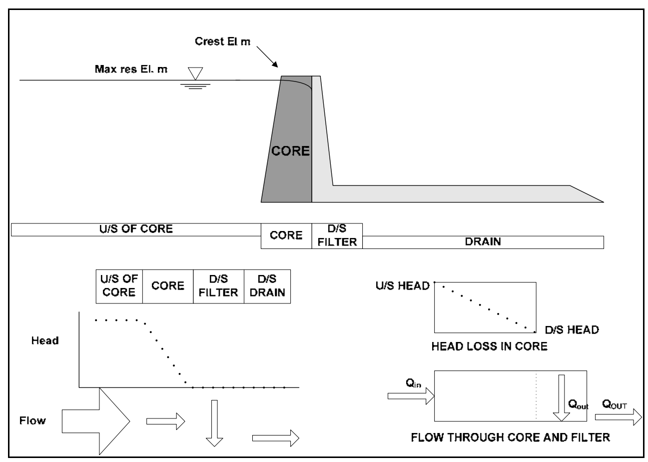


Figure 11. Functional model of internal flow control

While the sub-systems in the event tree have been arranged in terms of their relative spatial positions, the states of each sub-system are matters of knowledge and therefore the uncertainties and associated probabilities are epistemic in nature. Here I propose that the sub-tree for the three element (core- filter-drain) sub-system can be considered as a graphical representation of statements about the joint probabilities of variables that can be modelled as random at time "t_i" , then, from the total probability theorem, the order of the events is not a consideration. Thus the spatial arrangement of the event tree nodes for time "t_i" does not imply that the changes of state of the core-filter-drain occur sequentially.

By focusing event trees for internal erosion on the time-dependent functional state of the critical defensive components of the dam, I suggest that it may be possible to transfer these heuristics and biases from event tree construction to the mechanics of internal erosion (Figure 12).

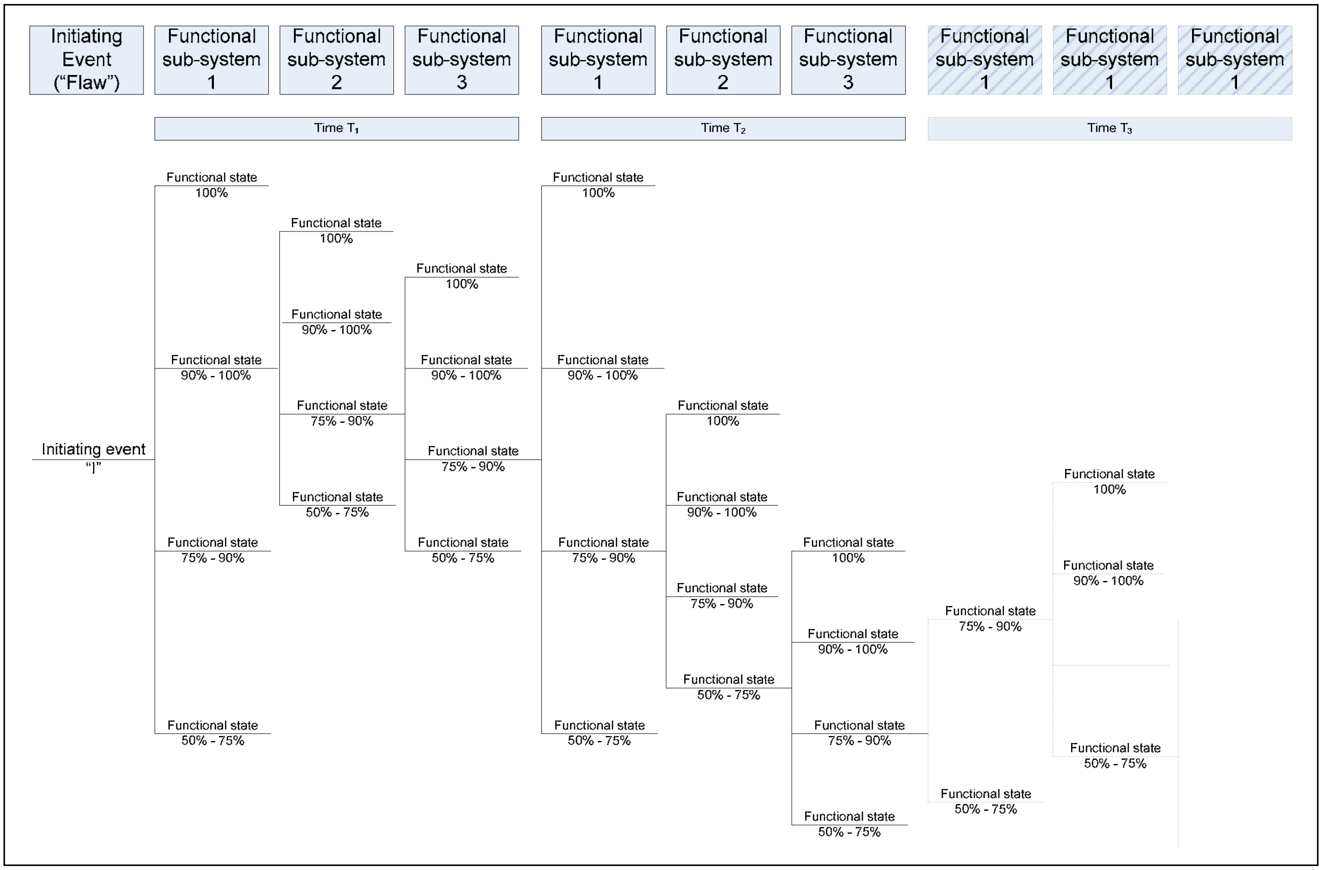


Figure 12. “Functional state” approach to event tree construction for internal erosion

Ideally, to characterise the functional state one must have details of the fundamental properties of the dam and the physical manner in which internal flow of seepage water is controlled over time. To characterise the functional state, one would conceivably determine fundamental soil properties of the core, filter and drain such as density, void ratio/specific volume, permeability, friction angle etc.

If these properties are known, then it would appear reasonable to apply the theory of critical state soil mechanics as a means of characterising the “physical state” of the key elements of the dam. Once the physical state is characterised, its time dependent functional state could be expected to follow directly from consideration of the relationship between flow control capacity and the specific volume and permeability of the soil.

While I do not consider that determination of the physical state of the interior of the core, filter and drain of a dam will be straightforward, I do consider that research efforts in this direction, such as cross-hole seismic tomography, and other methods of physical state determination such as temperature and resistivity methods is worthwhile.

The soil mechanics of the internal erosion problem

By reasoning from first principles, the problem of internal erosion is an effective stress problem because particle transportation (internal erosion) occurs when the tractive forces of the seepage water on the soil particles overcomes the frictional resistance that holds individual particles in the soil matrix. Also by reasoning from first principles, the movement of particles of a unit volume of soil results in a change in the void ratio (and therefore specific volume). This change in specific volume is a “change in state” making the Critical State Soil Mechanics (CSSM) family of models a suitable choice for analysis of the problem.

Given that internal erosion is an effective stress problem where the important parameters pertain to the state of stress as determined by (p', q, u) and the tractive forces that the flowing water applies to the soil particles, it seems that the relationship between the state of stress and the pore pressure would be an important factor in dealing with the problem of internal erosion risk analysis. The theory of Critical State Soil Mechanics (CSSM) (Schofield and Worth, 1968) can be used to calculate pore pressures in laboratory tests and in the field. Since internal erosion involves a change in dry density as fines are lost, that can be represented in terms of a “change in state”, and because this change in state can be related to specific volume v, a fundamental soil property, it appears that it would be worth exploring if critical state soil mechanics theory, coupled with a dynamic change in state event tree analysis might provide a rational means of dealing with the problem of internal erosion risk analysis for dams.

The only obvious problem at the outset of this exploration is that the type of many soil types that dams are constructed from do not conform to the stress-strain and deformation predictions of theoretical models such as the Cam-clay model. Such a problem would typically be a “show-stopper” in a practical sense and practicing engineers have long been able to reject these theoretical models as too idealised to be of practical value. I took a different view because there is nothing fundamentally wrong with the CSSM concept or its theoretical foundations, and it has been applied to certain soils encountered in engineering practice.

The tri-axial test is a good place to start to explore the relationship between *(p′, q, u)*. It also gives an opportunity to explore the differences between the behaviour of real soils in the tri-axial test and the CSSM Cam-clay and modified-Cam clay theoretical model predictions.

Although the conditions under which internal erosion of dams occurs is overall a “drained” condition, un-drained tri-axial tests on soils used in the cores of dams provide a useful starting point for a theoretical investigation. Whether or not the process of internal erosion at its early stages involves transitions from un-drained conditions to drained conditions back to un-drained conditions will not be discussed here, rather it will suffice to note that the understanding of the behaviour of soils used in dam construction under un-drained conditions is a necessary element of a comprehensive understanding of how soils behave in engineered structures such as dams.

In un-drained tri-axial tests on saturated soil specimens, the excess pore pressure generated is made up of two components: one component due to the response of the soil to the shearing process represented by Δq, the change in shear stress; the second component due to the change in mean total stress Δp applied to the specimen (Figure 13):

$$\Delta u = \alpha \Delta q + \Delta p \quad \text{...(Eq.1)}$$

As mentioned previously, many soils used in engineering practice do not exhibit the behaviour of theoretical CSSM models, with many soils showing both a compressive behaviour at very small strains and a dilative behaviour at larger strains during the test.

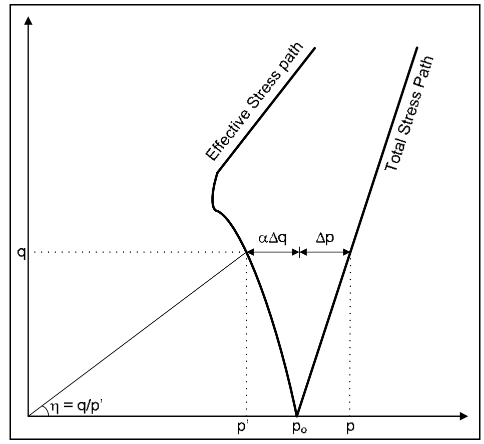


Figure 13. Relationship between *(p′,q,u)* for well-graded soils in the tri-axial test

While this might challenge some of the tenets of the CSSM family of models and other models, it will suffice to note that the soil remains in compression until it approaches and then sharply transitions to a more or less constant *(p,′-q)* relationship (approaching the critical state).

From the experimental observations of the pore pressure response of tri-axial tests on two quite different engineering soils with similar well-graded particle size distributions (Figure 14), I observed a linear relationship between generated pore pressure and mobilised friction over the portion of the effective stress path where p′ is decreasing that is of the form:

$$\frac{u}{p_o'} = K\frac{q}{p'} \quad \text{...(Eq. 2)}$$

where *K* is a constant for a particular soil (and can be derived from the tri-axial test data). To ensure that this observation was not simply an artefact of my testing procedure and the soils involved, I examined the results of similar tests carried out by others ranging from clay to sand (Figure 15).

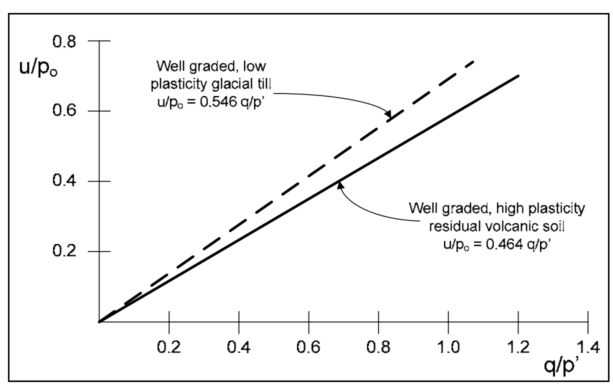


Figure 14. Relationship between generated pore pressure and mobilised friction from un-drained tri-axial tests on two well graded soils with different origins and other properties

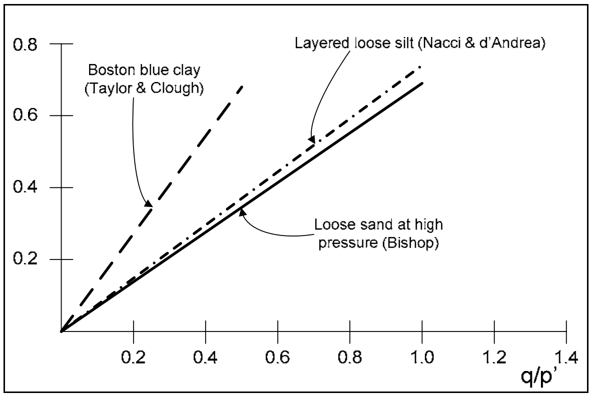


Figure 15. Relationship between generated pore pressure and mobilised friction from un-drained tri-axial tests on clay, sand and silt with different origins and other properties

These results indicate that the linear relationship between mobilised friction and pore water pressure under un-drained conditions was not simply an artefact of the soils that I was testing or the way that they were being tested and suggested that a more detailed theoretical treatment would be worthwhile. Since the clay soil shown in Figure 15 can be successfully modelled in the CSSM framework, it seemed that perhaps this observation might open up the opportunity to explore one of the missing links between theoretical soils and the behaviour of soils used in dam engineering practice.

In any un-drained tri-axial test starting at an isotropic pressure $(p=p'=p_o')$, the following relationship holds:

$$u = p_o' + \frac{q}{3} - p'$$

This equation can be combined with (Eq. 2) giving the equation of the un-drained effective stress path.

$$\frac{q}{3}p' - p'^2 - Kqp_o' + p_o'p' = 0 \quad \text{…(Eq. 3)}$$

Equation (3) can be factorised as follows:

$$\frac{q}{3} - p' - p_o'(3K-1))(p' - 3Kp_o') = p_o'^2\, 3k(3K-1)$$

…(Eq. 4)

Equation 4 is now in the standard from for the equation of a hyperbola with asymptotes:

$$\frac{q}{3} = p' + p_o'(3K-1)$$

and

$$p' = 3Kp_o'$$

Thus, the un-drained effective stress path is part of a hyperbola passing through the points $(p_o',0)$, and by inspection (0,0). It should be noted that p_o' has the role of "normalising", the effective stress path in the sense that the basic geometric shape of the curve is the same for different values of p_o'. Thus far, there has been no reliance on CSSM. Rather, on the basis of experimental observations and reasoning mathematically from first principles, it has been possible to determine the shape of the un-drained effective stress path of saturated engineering soils under conditions of compression in the tri-axial test. The conditions of the test are such that a soil mass transitions from stable state to an unstable state in (p', q) space. In general, and in terms of CSSM theory, the state of the soil mass is represented in (p', q, v) space (as noted above, v is the specific volume).

The above equations can now be introduced into the CSSM framework. The equation of the stable state boundary surface (SSBS) can now be obtained by associating the intersection of the hyperbola with the p' axis (i.e. the point p_o', 0) with the corresponding point on the isotropic normal consolidation line (NCL).

$$v_o = N - \lambda p_o' \quad \text{…(Eq. 5)}$$

where λ is the slope of the isotropic NCL in a $(v, \ln p')$ plot and N is the value of v when $p_o' = 1\ kPa$. Equation (5) can now be used to eliminate p_o', from (4), setting q/p′ = η after a little manipulation we obtain:

$$v_o = N - \lambda \ln(1 - K\eta) - \lambda \ln(p' - \frac{q}{3})$$

Since v_o can take on any value, we can drop the subscript to obtain the SSBS equation for the hyperbolic Cam clay model:

$$v = N - \lambda \ln(1 - K\eta) - \lambda \ln(p' - \frac{q}{3}) \quad \text{…(Eq. 6)}$$

This SSBS equation can be compared with the corresponding Cam clay and modified Cam clay SSBS equations (Britto and Gunn, 1987).

Cam Clay SSBS.

$$v_\lambda = \Gamma + (\lambda - \kappa)(1 - \frac{\eta}{M})$$

Modified Cam Clay SSBS.

$$v_\lambda = \Gamma + (\lambda - \kappa)\{\ln(2) - \ln(1 + (\frac{\eta}{M})^2)\}$$

The relevant CSSM soil constants are:
Γ:- specific volume of soil at the Critical State for p' = 1.0 kPa
λ, and κ:- are the slopes of the compression and swelling lines in isotropic consolidation tests
M:- the Critical State friction constant

The equation of the yield locus for hyperbolic Cam-clay can be obtained by taking the intersection of the elastic κ-line equation with the SSBS. If p_c' is the pre-consolidation pressure which specified the size of the yield locus, then the value of v corresponding to this pre-consolidation pressure on the isotropic NCL is given by:

$$v_c = N - \lambda p_c'$$

In addition the standard relations for the κ-line are

$$v_\kappa = v_c + \kappa \ln p_c' \text{ and,}$$

$$v_\kappa = v + \kappa \ln p' \text{ (see Figure. 16)}$$

Manipulating these last three equations to eliminate v_κ and v_c:

$$v = N - \lambda \ln p_c' + \kappa \ln\left(\frac{p_c'}{p'}\right) \quad \text{…(Eq. 7)}$$

v is now eliminated from (6) and (7) and after some manipulation the equation of the yield locus for hyperbolic Cam-clay is obtained.

$$q = \frac{p_c'\left[1-\left(\frac{p'}{p_c'}\right)^{1-\frac{\kappa}{\lambda}}\right]}{\left[K\left(\frac{p_c'}{p'}\right)-\frac{1}{3}\left(\frac{p_c'}{p'}\right)^{\frac{\kappa}{\lambda}}\right]} \quad \text{…(Eq. 8)}$$

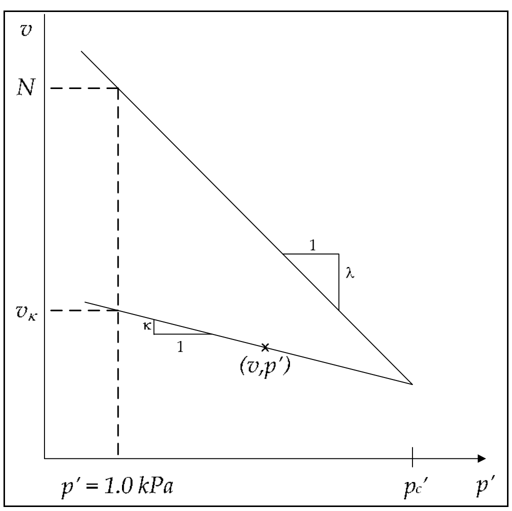


Figure 16. Generalised consolidation characteristics of soils

The form of the yield locus is given in Figure 17. Importantly, throughout this derivation of the yield locus it has not been necessary to assume or know the value of the critical state friction parameter M. However, M can be calculated from the soil parameters already calculated because to ensure the zero dilatancy condition the critical state line must intersect the yield locus where the tangent is horizontal. This is achieved by differentiating Eq. 8 and setting the resulting expression for dq/dp' to zero. This leads to a quadratic equation in $(p_{cs}'/p_c')^\Lambda$ where:

$$\Lambda = 1 - \frac{\kappa}{\lambda}$$

The solution of this quadratic equation yields:

$$\left(\frac{p_{cs}}{p_c}\right)^{\Lambda} = \frac{3K(1+\Lambda)+(1-\Lambda)\pm\sqrt{9K^2(1+\Lambda)^2+(1-\Lambda)^2-6K(1+\Lambda^2)}}{2} \quad \text{…(Eq. 9)}$$

From which the ratio (p_{cs}'/p_c') (see Figure 17) can be obtained. Substituting back into Eq. 8, the value of q at the critical state is obtained and hence $M = q/p'$.

At this point, a complete specification of the response of this model material to any implied loading in the tri-axial test as all of the basic equations of the hyperbolic Cam-clay model have been provided. There is no reason that this basic model cannot be extended to cover all conditions to which Cam clay and modified-Cam clay have been applied. Since, the hyperbolic Cam clay model provides a good fit to the pore pressure response in the tri-axial test for diverse natural soil types, some of which are used in the construction of dams, hyperbolic Cam-clay provides a potential model for predicting soil behaviour where the change of state is "change in v" and where the total stress state is constant.

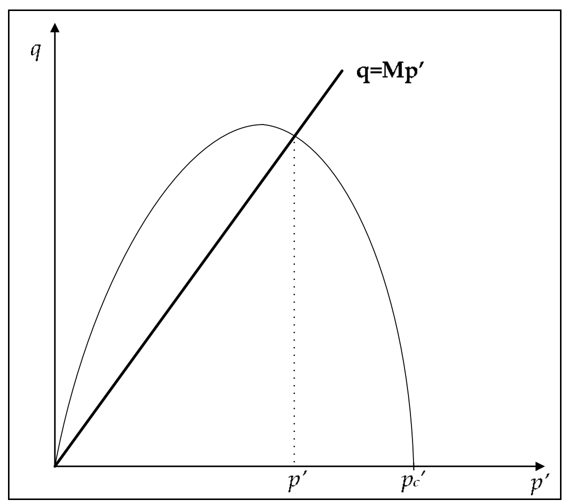


Figure 17. Yield locus for hyperbolic Cam clay

Thus, it is possible that hyperbolic Cam-clay might provide a theoretical soil mechanics framework to examine the problem of "change in state" associated with internal erosion of dams. If it were possible to determine v at various locations within the core of a dam, then by re-arranging the above equations, perhaps it might be possible to determine the proximity of unit elements of core soil within a dam relative to the core's Stable State Boundary Surface. If this were possible, and if it were possible to measure in some way "change in specific volume" with time, then the idea of risk analysis of the internal erosion failure mode might become a reality. Interestingly, Popielski et al. (2002) have proposed that the Modified Cam Clay Model provides an analytical framework for the problem and have performed finite element modelling of the problem within the CSSM theoretical framework.

PART III
DETECTION OF CHANGES IN STATE

The final part of my paper outlines a field experiment aimed at determining contemporary capability to monitor the seepage through the core of a dam from the surface and to indirectly detect these "changes in 'specific volume' state". Other methods of testing such as cross-hole seismic tomography can also be used to detect changes in density through changes in cross-hole velocities.

At the outset, I referred to the inferential nature of dam safety assessment where the engineer is required to take incomplete and uncertain data and draw conclusions as to the performance of the dam up to that point in time. The engineer is also expected to forecast the performance of the dam for the foreseeable future. As mentioned at the outset, all of this involves hypothesising and, in the case of dams, often little in the way of hypothesis testing as it is often at a minimum unwise to embark on tests that cannot be terminated without doing any harm. Hypothesising from direct evidence is difficulty enough, doing so from indirect evidence is even more difficult and the complexities should not be under-estimated. This experiment is at the extreme of indirect hypothesising in dam performance analysis.

Typically, measurements of earth dam performance are done very indirectly. For example, the functional effectiveness of the seepage control functionality of the core might be measure at the downstream end of the drain (several hundred metres from the core), or even more indirectly through the response of piezometers in the downstream shell and or drain. Surface measurements of "properties at depth" such as Ground Penetrating Radar (GPR), Resistivity, and Self Potential (SP) are amongst the most indirect monitoring methods available. The questions that arise are, "what are the signals from these monitoring instruments telling us?" and "what are they not telling us?" about the "changes in state" of the dam.

These are not usual problems in science, as the statements of "what the signals are/are not telling us" are in the form of hypotheses, and are dealt with in terms of hypothesis testing. The idea of conducting "blind tests" and "double blind tests" to test hypotheses is common in the scientific method, with the view to determining of the hypothesis can be falsified. These tests are essentially mandatory and taken for granted in the sciences. However, such tests are rarely conducted in civil engineering outside the laboratory and it is extremely difficult, even impossible to carry out on full scale structures such as dams.

BLIND TEST OF SEEPAGE MONITORING CAPABILITY

If one accepts the hypothesis that under conditions of constant hydraulic head, changes in seepage volume are indicative of a "change in state" within the dam, then monitoring of seepage within the body of the dam should be of considerable value. The only reliable way to determine the meaning of the signals from these monitoring methods is to test the method in a controlled way under the full spectrum of conditions where the method might be used. The following describes just one such test with the view to illustrating what must be done to gain confidence in inferences from dam monitoring instruments.

Geo-electrical and temperature profiling methods of seepage detection in earth dams emerged as potentially promising non-invasive methods of monitoring leakage in through cores in earth dams in the 1990's. During the late 1990's and early 2000's, significant research work on application of these methods to earth dams was carried out in Canada, Sweden and the United States. While not directly related to detection of the "change in specific volume state" that is of specific interest, an increase in seepage volume is indirectly indicative of "change in state" and internal erosion.

The test dam

EBL Kompetanse (EBL), the Norwegian Electricity Industry Association conducted a major research investigation into the stability and breaching of rockfill dams in 2002 - 2005. This involved constructing and testing to failure a number of 5m - 6m high, 40m long zoned rockfill dams. This was a very ambitious project that led to very valuable and significant improvements in the scientific knowledge of rockfill dam stability, including overtopping erosion failure mechanisms and the internal erosion mechanism. This important EBL initiative was also incorporated in the European Union's IMPACT project that was investigating Extreme Flood Processes and Uncertainty.

Exploratory discussions concerning the possibility of adding a "blind test" of emergent Resistivity, SP and Temperature monitoring methods to the existing testing programme were held with EBL's representatives. These discussions were sufficiently fruitful to permit BC Hydro, ELFORSK, the research branch of the Swedish Electricity Industry and EBL Kompetanse, as represented by Statkraft Grøner (now Sweco Grøner) and advised by Professor Kaare Høeg, to agree to proceed with a "blind test" of these emerging seepage monitoring methods for earth dams.

The "blind test" concept

The objective of the "blind test project" was to simulate the outward manifestations of internal erosion by building "one or more zones of relatively high leakage" into the core of a zoned earth/rockfill dam, and ask a specialist in these emerging detection technologies to find it (or them)! Put simply, we were challenging the technology and its proponents to demonstrate its scientific credentials and to demonstrate that it is not simply “high tech water-divining”! Of course, one has to also account for the complications of nature which make it impossible to build a dam precisely in accordance with the design!

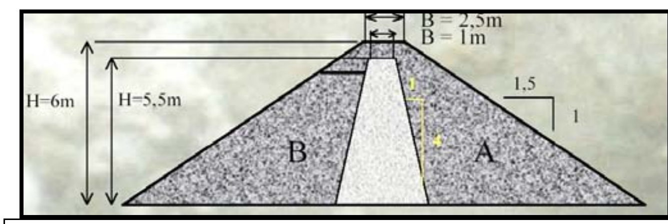
While the proposed project was solely motivated by scientific inquiry, it became clear that pursuit of such inquiry involved serious consideration of many aspects of dam ownership and operation including; complex ownership arrangements; financial and environmental risk management and risk transfer arrangements; design and construction challenges. Some went far beyond “good practice” considerations with questions like “you want me to design what!?”, and reactions like “you have to be crazy to try and build a “defective dam!”; on top of all of the usual complexities and challenges of dam ownership and operation.

For the blind test to succeed, and over and above all of the considerations involved in dam design and construction, we needed;

- A dam designed and built such that it would leak, as if undergoing internal erosion, in realistic and measurable way without failing;
- Have zones of seepage that would provide a fair but strong challenge to the technology;
- To ensure that the locations of the defects remained unknown to everyone except those involved in the design and construction of the dam.

The test dam

The basic design of the dam was:



Central moraine core (fines > 25%; dmax<60mm) constructed in layers with a 4 ton vibratory roller.
A: Downstream rock fill support (0-500mm, d10>10mm)
B: Upstream rock fill support (300-400mm)

Figure 18. Cross section of original test dam

The basic design was modified to incorporate zones of high seepage through the core. A total of three zones with high seepage characteristics were hidden in the dam. As is clear from the measured seepage in the seepage measuring weir, the seepage flows closely follow the reservoir elevation. Needless to say, the weather was not fully co-operative and it was necessary to account for the effects of the periods of rain.

Overall, we succeeded in realistically simulating many of the conditions that we are normally faced with in dam surveillance including; the age-old problem that those interpreting the monitoring data normally lacking much of the information that they would like to have about the design and construction of existing dams; the influence of weather effects; construction anomalies; short periods to take measurements; and, interpretation difficulties due to uncertainty and necessarily incomplete data sets. From the perspective of the “blind test”, the dam leaked perfectly (Figure 19). Full details of the blind test are provided in the ELFORSK report DAMMSÄKERHET, Internal Erosion Detection at the Røsvatn Test Site. (Johansson et al., 2005).

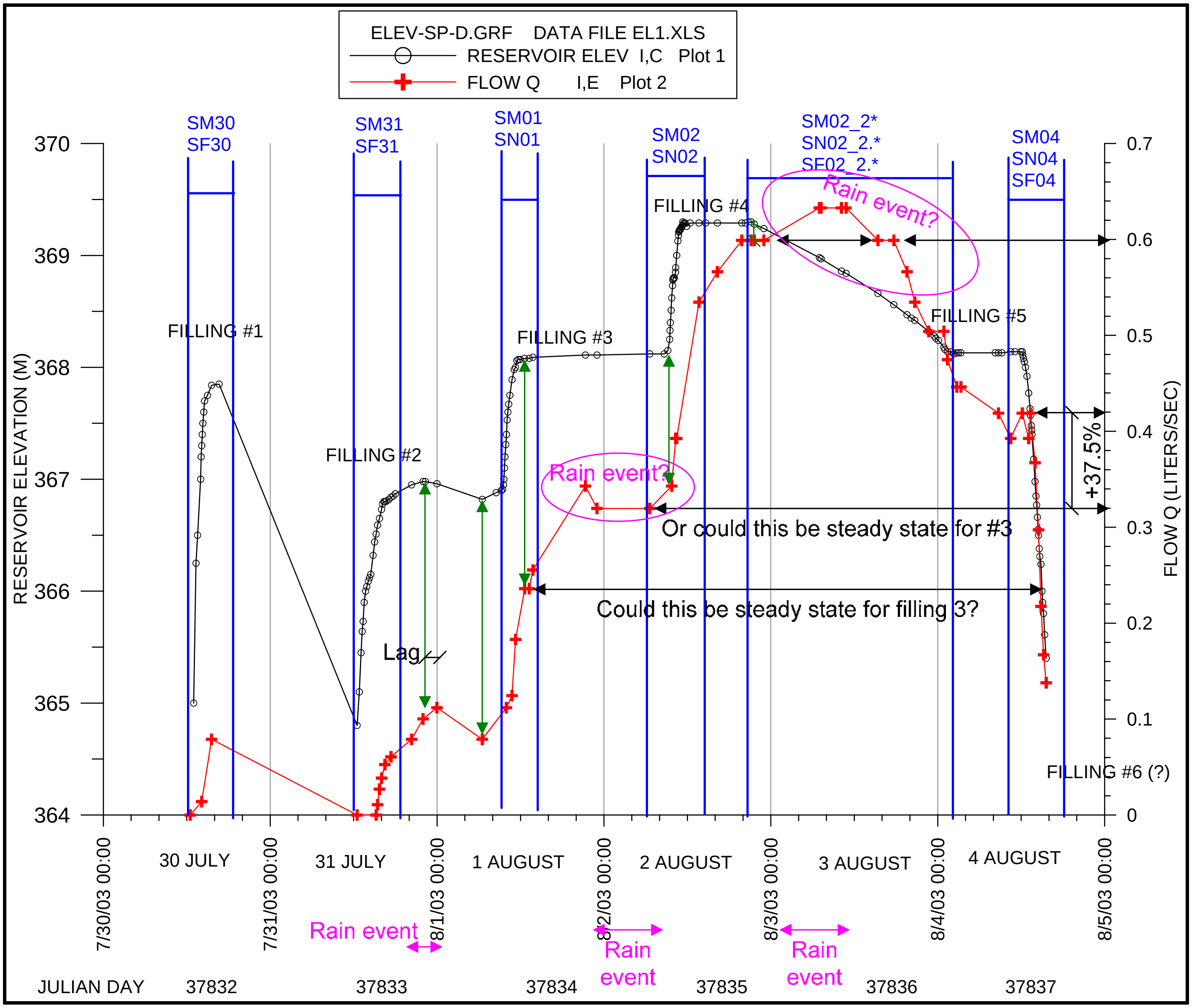


Figure 19. Seepage through the test dam

Photo 1. Construction of "hidden defects"

Outcome

The test provided important corroboration of the value of temperature measurement methods in seepage monitoring detection. It provided encouraging results concerning the value of resistivity methods, especially during initial saturation of the core of the dam. While the results for self-potential were less encouraging, they were not negative suggesting that further research might be beneficial in assisting arriving at a conclusion as to the role of the self-potential method in seepage monitoring of dams.

From the perspective of a dam owner, the results indicate that increased reliance on temperature measurement methods in practice appear warranted. The prospects of the use of resistivity methods for long term monitoring remain promising, although more work on calibration is warranted.

The weight of evidence to support heavy reliance on self-potential methods remains low.

The importance of constructing realistic dams to calibrate "change in state" monitoring capability is now recognised and is achievable. Full scale calibration tests can obviously be supported by complementary small scale laboratory studies.

CONCLUSIONS

The safety assessment of dams involves the engineer taking incomplete and uncertain data and drawing conclusions as to the performance of the dam up to that point in time and for the foreseeable future. The entire process is inferential requiring the use of inductive logic. Inductive logic pertains to arguments that are not certain, and inductive logic analyses inductive arguments (hypotheses) using probability. It is simply impossible to be certain that a dam is "safe" in an absolute sense.

The scientific understanding of the inductive process as is required for dam safety assessment has changed dramatically since Casagrande first introduced the notion or calculated risk in geotechnical engineering and since it emerged in the practices. We now know that risk analysis for dams involves a combination of philosophy of science (reasoning under uncertainty), probabilistic mathematics, natural hazard analysis, soil mechanics, and, dam performance data collection, interpretation and analysis. We also know that the type of expert judgement utilised in risk analysis for dams is distinctly different to the "engineering judgement" used commonly in geotechnical engineering.

Together the recent exposition of the philosophical and scientific nature of probability and risk as they apply in dam safety assessment together with the explicit demands for scientific validity has exposed some significant gaps between the contemporary capability to characterise the risk associated with earth dams, and the regulatory, public and legal expectations. The public, political and regulatory expectations concerning the logic and scientific validity of safety claims and the transparency of the process of arriving at these claims is a matter that dam owner, their engineers, dam safety regulators and the profession must address. To do so will require involvement of experts from different domains outside geotechnical engineering, and engineering in general.

The matter of scientific validity of risk analyses in the safety assessment of dams is not a matter of argument about "subjective" and "objective" per se when it comes to "belief-type probability" as such arguments are little more than mud-slinging. Rather, and while "belief-type" probability is central to the safety assessment process, there are many variations belief-type or "Bayesian" probability between two extremes; the "personal type" and "logical type"; and since in theory apparently, there are 46,656 ways to be a Bayesian (Hacking, 2001). Therefore it is necessary for the analyst to be explicit where in this spectrum a specific statement of belief probability lies. Any policy-maker, regulator of member of the public is obviously entitled to know where in this spectrum any probability that they are presented with lies! However, Bayes' Theorem is the unifying construct across all belief-type probability and it is central to applications of personal probability as it provides the logical basis for individuals to update their personal beliefs as new information becomes available. Importantly, Bayes rule doesn't help "Bayesians" to come to an initial position about their "belief probabilities", it just enables them to change their minds in a logical way as new information becomes available.

Despite strenuous efforts, the use of semi-empirical design rules in the analysis of risks associated with dams remains unsatisfactory and there is no reason to expect that it these design rules will ever provide a satisfactory means of analysing internal erosion or other failure modes, as they are aimed at conservatively avoiding failure states. The only thing that compliance with design rules can provide us with is some degree of comfort that the dam should perform satisfactorily, and conversely, failure to comply with design rules should create a corresponding degree of discomfort. The best that can be done using these semi-empirical rules in risk analysis for dam safety at present is a verbal statement of perceived relative likelihood - qualitative "degrees of belief" - whatever that means. Suggestions that these senses can be transformed into quantitative probabilities by means of Kent Charts that are meaningful and with attendant indicia of reliability are misplaced and obsolete.

I have proposed that the Critical State Soil Mechanics framework that utilises a hyperbolic Stable State Boundary Surface may provide a suitable approach to developing a soil mechanics solution to the problem of internal erosion. I have also indicated the nature of the field testing required to validate inferences from dam performance monitoring data.

Finally, I do not see this new position as being at odds with what Casagrande proposed for risk analysis for dams. After all, it was Casagrande who discovered the concept of "shearing at constant volume" as subsequently formalised in the Critical State family of models, and it was also Casagrande who proposed that calculated risk had an important role to play in geotechnical practice.

ACKNOWLEDGEMENTS

This wide-ranging paper was only made possible by the support of BC Hydro and in particular Ray Stewart, the Chief Safety, Health and Environment Officer and Director of Dam Safety. Much of the theoretical and philosophical treatment of inference, probability and risk has depended on close co-operation with Dr. G. B. Baecher, Dr. P.A. Zielinski and Mr. K. Dise during and subsequent to the preparation and publication of *Risk and Uncertainty in Dam Safety*.

Concerning the material on Critical State Soil Mechanics, I relied on my early work in this field when I was heavily reliant on the late Mr. V.W. Graham and on Mr. M.J. Gunn, formerly of the University of Surrey and now Professor of

Geotechnical Engineering, South Bank University, London. The practical value of this work is now re-emerging in the domain of internal erosion of dams involving Dr. D. Muir Wood of Bristol University, Mr. M. Jefferies of Golder Associates and Mr. S. Garner (BC Hydro).

The "blind test project was only possibly because of the commitments to research of the sponsors BC Hydro (R. Stewart and J. Gurney), Vattenfall Vattenkraft (U. Norstedt and S. Berntsson), Vattenfall Power Consultants (formerly SwedPower), ELFORSK and EBL Kompetanse who provided the funding and in-kind support and the project participants; Prof. K. Høeg, A. Lövoll, E. Ødemark, S. Garner, Å. Nilsson, S. Johansson, J. Friborg, T. Dahlin, P. Sjödahl, L. Hammar, T. Fridolf, and M. Cederström.

REFERENCES

Bacon, J. H., (1999). *Categories and Structures of Man-made Risks and related Basic Problems - A risk-regulator's perspective.* Forum Engelberg - Risks and Safety. 23/24 March.

Berlin, I., and Hardy, H. (1980). *Against the current: essays in the history of ideas*, Viking Press.

Berlin, I., Hardy, H., and Kelly, A. (1979). *Russian thinkers*, Penguin Books, New York.

Brown, A.J., and Aspinall, W., (2004). Use of expert opinion elicitation to quantify the internal erosion process in dams. *Long-term benefits and performance of dams*. Thomas Telford, London.

Brown, A.J. and Godson, J. (2004). Interim Guide to Quantitative Risk Assessment for UK Reservoirs. Thomas Telford.

Brunswik, E. (1952). *The conceptual framework of psychology*, University of Chicago Press, Chicago.

Budnitz, R. H., Apostolakis, G., Boore, D. M., Cluff, L. S., Coppersmith, K. J., Cornell, C. A., and Morris, P. A. (1998). "Use of technical expert panels: Applications to probabilistic seismic hazard analysis," *Risk Analysis*, 18(4), 463-469.

Cooke, R. (1991). Experts in Uncertainty: Opinion and subjective probability in science. Oxford University Press.

Eie, T. (2007). E-mail advertisement - @Risk training in Any Industry. Palisade Corporation.

Fell, R., MacGregor, P., Stapledon, D., Bell, G. Geotechnical Engineering of Dams. Taylor and Francis

Fell, R. and Fry J-J. (Eds.) (2007). In Internal erosion of dams and their foundations. Balkema.

Feynman, R.P., (1988). "What do You Care What Other People Think?" W.W. Norton and Company.

Foster, M., Fell, R., and Spannagle, M. (1998). Analysis of Embankment Dam Incidents. UNICIV Report R-374, University of New South Wales.

Hacking, I. (1975). The Emergence of Probability, Cambridge University Press, Cambridge.

Hacking, I. (2001). An Introduction to Probability and Inductive Logic. Cambridge

Hammond, K. R. (1996). Human judgment and social policy: irreducible uncertainty, inevitable error, unavoidable injustice, Oxford University Press, New York.

Hartford, D.N.D., and Gunn, M.J. (1987). "Pore Water Pressure Generation and Related Effects in the Tri-axial Test". Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp 59 - 62, Dublin, 1987.

Hartford, D.N.D. and Salmon, G.M. (1997). Credibility and Defensibility of Dam Safety Risk Analysis. Proceedings of the Hydropower '97 Conference, pp. 387 - 394, Balkema.

Hartford, D.N.D., (2001). Risk analysis in geotechnical and earthquake engineering: Proc. 4th Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering. University Missouri-Rolla.

Hartford, D.N.D. and Baecher G.B., (2004). Risk and Uncertainty in Dam Safety. Thomas Telford.

Howson, P and Urbach, P. (1991) *Scientific Reasoning - the Bayesian Approach,* Open Court Publishers, La Salle, Illinois.

International Commission on Large Dams (ICOLD) (2005). Bulletin 130, Risk Assessment in Dam Safety Management

Johannson, S, and Nilsson A. (2005) DAMMSÄKERHET, Internal Erosion Detection at the Røsvatn Test Site. ELFORSK Report 05:42.

Kaplan, S., and Garrick, B. J. (1981). "On the quantitative definition of risk." *Risk Analysis*, 1(1), 11-27.

Kaplan, S. (1997). The Words of Risk Analysis. Risk Analysis Vol. 17, No. 4.

Koenders, M., and Sellmeijer, J.B. (1992). A mathematical model for piping. Journal of Geotechnical Engineering. ASCE. 118, 943-946.

Morgan, M. G. and Henrion, M. (1990). Uncertainty: A Guide to Dealing with Risk and Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press.

Marcuson, W.F. III, Hynes, M-E and Franklin, A.G., (2007). Seismic Design and Analysis of Embankment Dams: The State of Practice"

Merriam-Webster, 2000. Webster Dictionary, Merriam-Webster, Incorporated, New York, http://www.m-w.com/.

National Research Council. (1996). Understanding risk: Informing decision in a democratic society, National Academies Press, Washington, DC.

National Research Council (2000). Risk Analysis and Uncertainty in Flood Damage Reduction Studies, National Academy Press, Washington, DC.

Nielsen, N.M., Vick S.G. and Hartford, D.N.D. (1994) "Risk Analysis in British Columbia" by International Water Power and Dam Construction, March.

Orkin, M., (2000). What are the odds? Chance in everyday life. W.H. Freeman

Office of the Gene Technology Regulator (OGTR), Australia, (2005). Risk Analysis Framework http://www.ogtr.gov.au/pdf/public/raffinal2.2.pdf.

Parkin, J. (2000). *Engineering judgement and risk*, Thomas Telford, London.

Pascal, B. (1966). *Pensâees*, Penguin Books, Harmondsworth.

Pate-Cornell, M.E, and Dillon, R.L. (2006). The Respective Roles of Risk and Decision Analyses in Decision Support. Decision Analysis Vol.3, No. 4.

Popielski, P., Dłużewski, J.M., and Stasierski, J., (2002). Numerical model of suffusion in terms of finite element method. Proceedings of the 5th International Conference on Hydro-science and Engineering, Warsaw.

Office of Management and Budget (OMB), (2007). Updated Principles for Risk Analysis. Executive Office of the President, Office of Management and Budget, and Office of Science and Technology Policy

Ojha, C. S. P., Singh, V. P., and Adrian, D. D., (2001). Influence of porosity on piping models of levee failure. Journal of Geotechnical and Geoenvironmental Engineering, December.

Schofield, A.N., and Wroth, C.P., (1968). Critical State Soil Mechanics. McGraw Hill.

Sellmeijer, J. B. and Koenders, M. (1991). A mathematical model for erosion under a dam. Applied Mathematical Modelling 15, 646-651.

Sherard, J.L. (1979). Sinkholes in dams of coarse, broadly graded soils. *13th Int. Congress on Large Dams, New Delhi.* Q47, R2, 325-334. International Commission on Large Dams, Paris.

Stratton, J.H. [1966]. Discussion on *Role of the "Calculated Risk" in Earthwork and Foundation Engineering*. ASCE J. Soil Mechanics and Foundation Engineering Division. SM1. January

United States Society on Dams (USSD), Committee on Tailings Dams (1994). Report on Tailings dams incidents.

URS (2007). Prioritization of dams through risk categorization: User Manual. Pre-release version. FEMA.

US Bureau of Reclamation (USBR) (1999). Risk Methodology: Appendix A, Considerations for Estimating Structural Response Probabilities in Dam Safety Risk Analysis.

Vick, S.G. (2002). Degrees of Belief: Subjective Probability and Engineering Judgment. ASCE.

Whitman, R.V. [1984]. Evaluating Calculated Risk In Geotechnical Engineering. *ASCE Journal of Geotechnical Engineering. Vol. 110, No. 2, pp. 145 –188.*