

The use of the “Unified Method of Risk Analysis” on a United Utilities Pennine type dam.

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SYNOPSIS. United Utilities has been using Portfolio Risk Assessment (PRA) since 2002 to evaluate the vulnerability of their dams to piping and internal erosion. Remedial works have been proposed on a number of dams but the degree of risk reduction likely to be achieved by these works cannot be ascertained at Portfolio level. It was recognized that a method was needed to estimate dam performance before and after remedial works to justify the expenditure. Therefore UU engaged their engineering service provider, MWH, to research and develop a methodology based on event tree methods. Research by MWH in the UK and America indicated that the recently developed “Unified Method of Risk Analysis for Dam Safety” (referred to as a Toolbox) would provide the required methodology.

The paper outlines UU’s approach to risk assessment, summarises the history and the principles behind the Toolbox, and describes the experience of UU/MWH in using it on a trial dam.

INTRODUCTION

United Utilities (UU) have been working with Professor David Bowles and Professor Loren Anderson of RAC Engineers and Economists (Utah State University), assisted by Dr Andrew Hughes of Atkins, on the risk assessment of their reservoir portfolio since 2002. The output of these assessments is in the form of a Portfolio Risk Assessment (Hughes and Gardiner, 2004) which forms the basis for the prioritization of UU’s capital expenditure on reservoir remedial works and to justify their submission to the UK government for funding. The Portfolio Risk Assessment uses the University of New South Wales (UNSW) method (Foster, Fell and Spannagle, 1998) to estimate the probability of failure due to seepage and piping. The PRA indicated that seepage and piping is in many cases the most likely cause of dam failure. UU needed a method to evaluate the reduction to the probability of failure after remedial works have been carried

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out to address the internal erosion threat, since this cannot be determined by the basic UNSW method. In addition it was also recognized that the PRA was a screening level assessment and that a more rigorous method was required to ensure that all failure modes were considered

To this end UU commissioned MWH, to undertake a study into the use of event tree methods and how they might be applied. MWH brought to UU's attention the series of papers presented at 28th United States Society on Dams Annual Meeting and Conference, April/May, 2008, by Cyganiewicz, Foster, Fell et al, describing the "Seepage and Piping Toolbox". Indications were that the "Toolbox" could be applied to UU dams.

Subsequently a meeting was held in Chicago, in September, 2008 between personnel from UU, MWH Warrington, MWH Chicago, David Bowles, Loren Anderson and John Cyganiewicz retired from the US Bureau of Reclamation (Reclamation). John gave a demonstration of the "Toolbox" and UU obtained a copy (August 2008) from Reclamation to trial on a UU Pennine type dam.

DEVELOPMENT OF THE "TOOLBOX"

Reclamation has been performing risk analysis on its inventory of dams since about 1998 (Cyganiewicz and Smart 2000). Development of the methodology for determining the probability of failure by internal erosion and piping failure modes (a.k.a. the "Toolbox¹") has been progressing since that time, much in collaboration with Emeritus Professor Robin Fell of the University of New South Wales and his colleagues. Since 2005, the US Army Corporation of Engineers (USACE) had also been developing risk assessment methodologies (Schaaf and Schaefer 2006). Since early 2005, personnel from Reclamation and the USACE have been working jointly on a state-of-the-art revision to the Seepage and Piping Toolbox.

To incorporate the best expertise in this field, the USACE and Reclamation contracted with the URS Corporation to review and provide comments on an early draft. Based on the results of this review, it was agreed that both agencies would financially sponsor and actively participate in the development of the new version of the piping toolbox, to be performed under contract with URS. The goal was to provide a single procedure that both agencies would use. Professor Fell also indicated the desire to make the eventual procedure available to the Australian Dam Safety Community, thus making it a truly unified procedure.

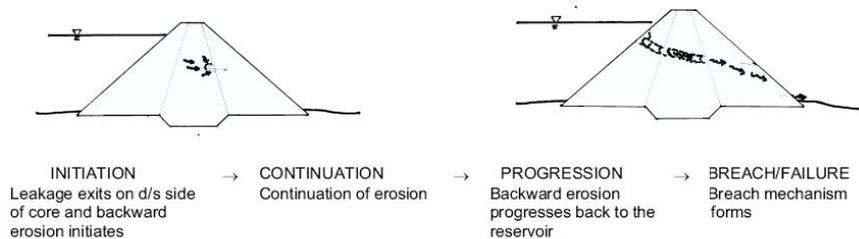
¹ Note that there are other 'toolboxes' under development to provide methodology in other aspects of risk analysis. For example, seismic and hydrologic failure modes are some of the other failure modes.

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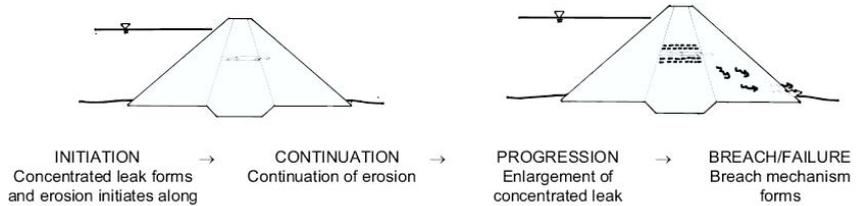
The final product has been titled “A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping”. The term Unified was specifically chosen to indicate the commitment to a single procedure that would be used seamlessly between the US agencies.

TOOLBOX METHODOLOGY

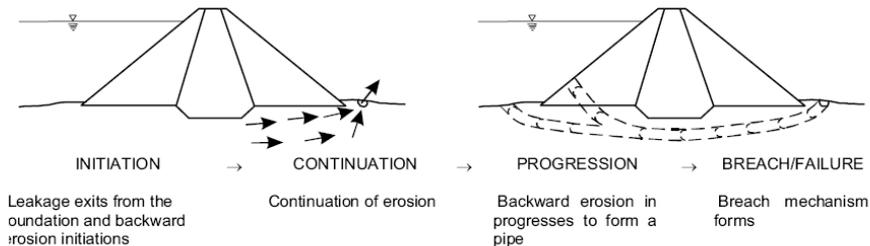
The developers of the Toolbox found it is useful to divide the process of internal erosion and piping into four phases: initiation of erosion, continuation of erosion, progression to form a pipe, and formation of a breach.



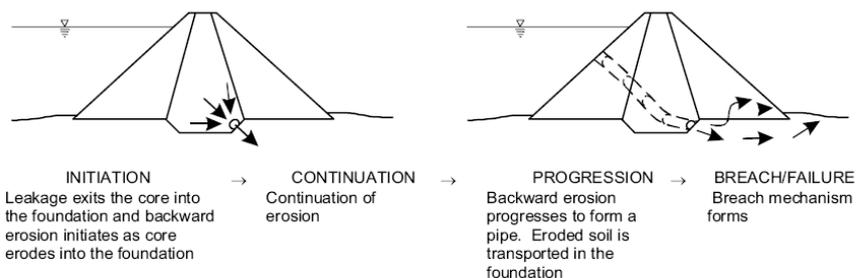
(A) PIPING IN THE EMBANKMENT INITIATED BY BACKWARD EROSION



(B) PIPING IN THE EMBANKMENT INITIATED BY EROSION IN A CONCENTRATED LEAK



(C) PIPING IN THE FOUNDATION INITIATED BY BACKWARD EROSION



(D) PIPING FROM THE EMBANKMENT TO FOUNDATION INITIATED BY BACKWARD EROSION

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This is shown in Figure (A) for piping through the embankment initiated by backward erosion. Similar processes apply for piping initiated by a concentrated leak (Figure B); piping through the foundation (Figure C); and from the embankment to the foundation (Figure D). Further details are given in Fell et al (2007) and Fell and Fry (2007).

The principal technique in the quantification of failure by piping is the use of event trees. An event tree is a sequence of logical events (nodes) that describe the failure process. An event tree is essential to the quantification of the risk of failure as it organizes information and allows technical discussions to be considered in a consistent fashion. This necessitated that the event tree become somewhat standard so that various risk analysts could reasonably speak the same language. Early versions of event trees were developed by Foster and Fell (2000). Reclamation and the USACE then developed their own because practice with the event tree showed that some modifications would further help in understanding the various factors. Once the alliance between the USACE and Reclamation occurred and close work with Professor Fell and Dr. Foster (both with URS) began, the three organizations met to discuss their differences in the event tree methodology eventually resulting in a unified approach to their application.

The following generic sequence of events has been developed for internal erosion failure modes;

↳ Reservoir Rises

↳ Initiation – Flaw exists ^{(1) (2)}

↳ Initiation – Erosion starts

↳ Continuation – Unfiltered or inadequately filtered exit exists
(consider: no erosion/some erosion/excessive erosion/continuing erosion)

↳ Progression – Roof forms to support a pipe

↳ Progression – Upstream zone fails to fill crack

↳ Progression – Upstream zone fails to limit flows

↳ Intervention fails

↳ Dam breaches (consider all likely
breach mechanisms)

↳ Consequences occur

- (1) A ‘flaw’ is a continuous crack, high permeability or poorly compacted zone in which a concentrated leak may form.
- (2) For Backward Erosion Piping (BEP) no flaw is required but a continuous zone of cohesionless soil in the embankment or foundation is required.

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The methodology contained in the Toolbox follows this event tree explicitly and estimates the probability of each of the nodes. Estimating the consequences of failure is shown on the event tree for completeness but is not part of the Toolbox as other methodologies are used for this. Up until the beginning of the development of the unified methodology, each organization would estimate the probability of each node of the event tree using expert elicitation and the descriptors shown in Table 1.

Table 1. Probability Descriptors (Bureau of Reclamation, 2003)

Verbal Descriptors	Descriptor Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

With the USACE just beginning to develop risk estimates for all of its dams, it was realised that they would require estimating by a large number of experienced geotechnical and dam engineers. The three organizations formulated a more scripted approach in which probability estimates would be developed within the Toolbox relying less on expert elicitation than in the past. This would not only help bring consistency to the process, but would also utilize most of the available science regarding the subject of internal erosion and piping.

Expert elicitation was used extensively during the development of the current unified approach and a series of workshops were conducted with experts from each agency participating. After much discussion and consensus building during these workshops, the factors considered important for each node of the event tree was determined and the probability scale set based on the factors. Examples of some of the factors and probability assignments for the event tree nodes are discussed by Fell et al (2008) and Foster et al (2008).

To improve the procedure, the methodology was trialled twice during development. During the first set of trials, termed Alpha, dam practitioners from each of the three organizations applied the procedure on Reclamation

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and a USACE dam. Following changes that resulted from the Alpha trial, a second set of trials, termed Beta, was performed. During this trial, personnel from each organization practiced the methodology on a dam. Comments were collected and changes were made during another workshop and the final Beta Draft version (August 2008) has been provided to UU. The process for estimating the annual probability of failure by piping and internal erosion includes the following general steps:

- Step 1: Review all information pertinent to piping and internal erosion
- Step 2: Identify all potential failure modes and paths associated with internal erosion and piping, considering each of the failure locations;
- Internal erosion through the embankment;
 - Internal erosion through the foundation; and
 - Internal erosion of the embankment into or at the foundation.
- Screen those failure paths that are assessed to have negligible contribution to the annual probability of failure and document the reasons for their exclusion. Develop detailed descriptions and sketches of all realistic failure paths.
- Step 3: Decompose each of the potential failure paths into event trees. Generic event trees have been developed for each general failure mode using navigation tables provided in the Toolbox Appendices. If the failure path cannot be matched with one of the generic event trees, then develop a different event tree using the guidance provided.
- Step 4: Select the loading partitions and estimate loading probabilities for each of the load conditions (static, seismic and hydrological).
- Step 5: Estimate the conditional probabilities for each node on the event tree, fully documenting the rationale. Specific guidance is given for estimating the conditional probabilities for various initiating mechanisms and failure locations in the Toolbox.
- Step 6: Calculate the probability of failure by internal erosion and piping for each failure path and review for consistency between failure paths.
- Step 7: Use the annual probability of failure estimates in follow-on risk analysis and assessment.

Currently, both the USACE and Reclamation continue to evaluate and improve on the Toolbox. Given the complexity of the topic, this is to be expected. The extent to which the toolbox is used in conducting the risk analysis is dependent on the agencies preferences.

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Following years of work on risk analysis, two other issues have proven to be the key to the success of a risk analysis. The first is the importance of the documentation. Providing the rationale and assessments used in the analysis in a written document where all discussions of the probability evaluation team, known as the Risk Estimating Team (RET), are captured gives a level of transparency to the process that reviewers and decision makers can rely on.

The responsibility of the RET is to develop failure modes, analyse the failure modes by the event trees and estimate the probabilities for each event node following discussion, consideration and challenging of the evidence and conclusions drawn to date. The RET should:

- Be small enough so as to be conducive to detailed and comprehensive discussions
- Have sufficient knowledge and experience to be able to elicit independent views
- As far as is reasonably practical, derive correct conclusions from the evidence presented
- Contain sufficient engineering expertise to be able to consider all parts of the dam being assessed, e.g. Dams, Geotechnical, Risk Analysis etc

Full documentation of workshop outputs is of such vital importance that a designated 'report writer' is assigned to the team during the analysis whose sole job is to keep notes and produce the final report. Team members review the notes in real time during the analysis to assure that all thoughts and information are accurately captured. All of these notes go into the final document.

The final step in the risk analysis is to 'make the case'. This term refers to the final summary of the findings of the RET. The RET prepares a summary statement that describes the key assessments that went into their judgments regarding the individual failure modes by strictly using engineering terms. Probabilistic terminology and probability estimates are avoided to the extent practical. In this way, the RET supplies reviewers and decision makers with defensible information that explain their judgments.

WORKSHOP TRIAL ON A UNITED UTILITIES DAM

A UU Pennine type dam with a well documented history that had previously identified issues relating to piping and seepage was chosen to trial the Toolbox. The trial was facilitated at two Workshops in autumn 2008 and spring 2009 as detailed below.

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Risk Estimating Team

As detailed above an important part of the Toolbox application on the dam projects is the use of a facilitated Risk Estimating Team (RET) formed from a consistent group of suitably qualified and experienced dam and geotechnical specialists. The full team for the UU trial consisted of the following:

Risk Estimating Team (RET) comprising: Geotechnical/Dam Lead Engineer; Senior Geotechnical Engineer; Reservoir Safety Manager; All Reservoir Panel Engineer; Risk Analysis Expert.

Other contributors included a Facilitator; Report Writer (with geotechnical/dam engineering experience); relevant support staff (part-time) e.g. Flood Hydrologist and Dam/PRA/QRA Expert and Observers (part-time): decision makers e.g. Project Sponsors, Supervising Engineer, Remedial Works Project Manager and Designers.

Failure Mode Identification

A potential failure mode is an existing inadequacy or defect originating in the natural foundation condition, the dam or appurtenant structures. At the Workshop the RET and other participants 'brainstorm' any and all information that is pertinent to identify all potential failure modes, develop a thorough understanding of any failure mode, and screen out failure modes that are judged to be inappropriate or unrealistic.

The Workshop identified seventeen failure modes for the embankment dam being trialled including transverse cracking due to differential settlement and settlement above a bench in rock foundation, concentrated seepage due to flaws associated with: poorly compacted or highly permeable zones; hydraulic fracture; erosion around and into the outlet culvert through embankment through existing cracks; erosion through and beneath cut off trench; around the existing grout curtain; cracking adjacent to spillway walls and erosion through jointed rock.

Probability Scoring

Each failure path identified was assessed against the Navigation Tables given in the appendix to the Toolbox. These defined the event tree structure and allowed condition probabilities to be defined at each event tree node. Probability is defined in the Toolbox method as a measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the occurrence of the uncertain future event. During the workshop two methods were used to assess the condition probabilities at each event tree node.

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1. Toolbox probabilities - The methods in the Toolbox provide “Toolbox Estimates” of the conditional probabilities of failure. The estimates are determined by expert judgment based on research, analyses and laboratory tests modelling the physical processes. They are designed to avoid systematic bias towards conservative or non-conservative probabilities. Probabilities for some of the most important initiating modes within the embankment are calibrated in the Toolbox against the historic performance of dams from a large database of around 10,000 dams in the ICOLD (1995) survey of failures and accidents.
2. Subjective probability (degree of belief) - Quantified measure of belief, judgment, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly and with a minimum of bias using the descriptors in Table 1. This was the process used in risk assessments in the US Bureau of Reclamation prior to the introduction of the toolbox. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

During the assessment of the UU Dam, the toolbox was supplemented by an expert elicitation process where each node of the event tree was first evaluated by listing the factors making the node more likely and less likely followed by elicitation of the node’s probability using the descriptors given shown in Table 1. All the information pertinent to the failure mode was written on a flip chart and recorded for information in the workshop notes. Following this the Toolbox’s estimate of the nodal probability was determined. Given this knowledge of both estimates, the RET decided on the consensus best estimate. In some cases, the elicitation estimate was used, and in others the toolbox estimate was chosen.

The total probability of a particular event occurring is simply the product of the scores allocated to each node of its event tree.

To prevent abortive effort in the consideration of virtually impossible events the RET decided to truncate the consideration of an event tree as soon as a ‘virtually impossible’ score of 0.001 is allocated to an event tree node by the RET. This is then indicated by the term ‘de-minimis’ in the Workshop records. Prior to assigning a probability score to a particular event node the RET were all given the opportunity to comprehend, challenge and discuss the same evidence.

During the workshop full event trees and probability assessments were undertaken on five of the main failure modes listed above and a number of

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variations within the main failure paths identified. An important outcome of the workshop was the identification of a potential failure path by erosion through the jointed rock foundation. This would not have been mitigated by the preliminary remedial works designs being considered prior to the workshop.

Evaluating Risk Reduction Alternatives

The workshop participants recognised that the information developed in the course of preparing the Toolbox event trees could be used as an aid in formulating alternatives which effectively mitigate the risks identified. By understanding the nature of the risks involved and the operational needs of the dam, a group of alternatives (including operational and remedial works) could be identified to evaluate the effectiveness of potential risk reduction measures. In the case of the UU dam, a baseline estimate of the probability of failure for all of the key failure modes was first established for the existing conditions using the above event tree procedure. Once this was determined, the reduction in the failure probability afforded by the proposed modifications was examined. This was accomplished by reviewing which nodes on the event tree were affected by the modification along with an estimate of the reduction in the nodal probability. Comparing the two shows the level of risk reduction that the modification will accomplish. At the workshop the effectiveness of slurry trench walls, grouting and the use of weighted filters were evaluated using the same event trees developed for the various failure paths identified by the Risk Estimating Team.

The RET noted that when risk reduction becomes an evaluation criterion along with cost optimization and any other appropriate objectives, the resulting evaluation criteria provide an effective framework for choosing alternatives. Estimates of the cost of a number of potential remedial options were available and developed as part of the workshop. By applying risk reduction criteria to, and brainstorming a variety of possible remedial options, alternative remedial measures were identified for further consideration later by the remedial works project team at an early stage. An identified alternative with higher costs and lower risk reduction are inferior to an alternative with lower cost and greater risk reduction when there are no other criteria to be evaluated. Those alternatives which have no reasonable chance of being selected as the alternative to be implemented can be eliminated and preferred options evaluate in more detail as part of the option evaluation process.

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LESSONS LEARNED FROM THE PILOT WORKSHOPS

1. Choose appropriate mix of experience and expertise to form the RET.
2. It is important to have defined objectives at the start of the Workshop identifying what scenarios are to be assessed e.g. just existing or improvement options as well.
3. A robust procedure needs to be in place for identifying appropriate/relevant initiating mechanisms (the starting point for all toolbox assessments).
4. A good description of each failure path must be documented prior to beginning the toolbox assessment, covering all elements from initiation through to dam breach.
5. It is useful to identify which are the most likely failure paths and potential “de minimis” paths.
6. Toolbox Initiating Mode references from the Navigation Tables need to be assigned to the failure paths based upon their ranking.
7. The RET should resist short cutting by referring to previous failure modes.
8. The Reporter must record and check everything for easy reference when reporting later.
9. Template spreadsheets should be available for doing the calculations associated with probability determinations.
10. A session should be set aside at the end of each day to go over what has been done and make sure everything is in order.

LESSONS LEARNT FROM APPLYING THE TOOLBOX

Following the initial trial, the toolbox has been used on other UU dams.

1. As well as justifying a remedial measure, it has been found in some cases that the measure that was recommended at portfolio level may in fact not be required at all after the event tree analysis. For example on certain Pennine type dams examined using the toolbox, the material downstream of the clay has been found to be self-filtering and/or the upstream shoulder material/core has been proved to be self-healing obviating the need for the proposed weighted filter
2. A re-evaluation of the probability of failure may lead to re-prioritization of that particular measure and the promotion of a different measure at another dam in its stead thus enhancing risk reduction.
3. The toolbox may identify failure modes that were not considered at the screening level of the Portfolio Risk Assessment.

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FURTHER DEVELOPMENT AND CONCLUSIONS

The full toolbox process is long and time consuming often taking many days. However if the method can be refined for application to the Pennine type dams, common in the UK, many of the failure modes may be justifiably excluded. Also as practitioners become more experienced in the use of the methodology and reference can be made to earlier analysis on similar dams the process may be streamlined.

The “Unified Method of Risk Analysis” can be used effectively to justify expenditure on the remedial measures recommended at the PRA level, has been shown to identify additional failure modes and has also justified not proceeding with proposed works.

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