Foreword

These proceedings document the single-day Risk Assessment Short Course, delivered as part of ICOLD's 91st Annual Meeting at Gothenburg, Sweden on 11 June 2023. These proceedings are meant to serve as a lasting compendium of the short course for the attendees and as a testimony of the contemporary state of risk assessment and its challenges for those who, though absent from the event, maintain a vested interest in this topic.

Many owners, consultants, and researchers have struggled with the enigmatic domain of tailings dams risk assessment for an extended period, and this struggle only intensified after the importance of risk assessment was pointed out and the acronym "ALARP" was included in the Global Industry Standard on Tailings Management (GISTM), released in 2020. ICOLD Bulletin 194, released as a preprint in 2022, partially addressed this issue by offering an overview of a typical risk assessment process, while making reference to other ICOLD and national committee guidelines, which were primarily designed for water storage dams. The members of the ICOLD Committee on Tailings Dams and Waste Lagoons have committed to a series of initiatives aimed at assisting professionals involved in tailings dams to develop appropriate approaches to risk. This short course was part of that broader initiative.

The common framework of risk, as a measure of probabilities and consequences, finds its origins in the games of chance, wherein both the likelihoods and consequences of repetitive events unveil themselves predictably. However, tailings dams failures are one-off events, and the a priori likelihoods and consequences of such events are estimated by tailings practitioners and subject matter experts. These estimates, by their very nature, are subjective to the perspectives of those who proffer them based on limited inputs and imperfect techniques used in absence of phenomenological models of dam failures. Consequently, the level or magnitude of risk of a tailings dam failure is not an objective attribute intrinsic to the dam itself but rather a measure of belief in the proposition of the dam failure and the potential consequences. This concept of risk holds, irrespective of the type of tailings dam risk assessment, and the tools and level of sophistication adopted, and is consistent with the definition of risk provided in ICOLD Bulletin 130. Unfortunately, comprehending the essence and the magnitude of risk of a tailings dam failure does not inherently elucidate whether the risk is being maintained as low as reasonably practicable (ALARP) or necessitate further risk reduction actions.

I accepted the convenor's role with the mission to convey the key messages from David Bowles, Desmond Hartford and Malcolm Barker who, amongst others, introduced the concept of risk assessment to the dams' profession in the 1990's and have been dedicated to this discipline for decades. Their collective knowledge holds paramount significance for the tailings profession for three principal reasons. Firstly, the tailings industry can learn invaluable lessons from the successes and pitfalls encountered in the application of risk assessment primarily for water dams, thereby accelerating the progress in the realm of tailings dams. Secondly, the speakers were involved in developing leading industry guidance, including the ICOLD Bulletins 130 and 154 and ANCOLD Guidelines on Risk Assessment, which tailings practitioners rely upon and interpret. Finally, their independence from mining organisations liberates them from corporate or industry mandates, rendering them more amenable to candid discussions.

As most tailings dam owners have only recently embarked on the course of risk-informed dam safety management, they may find it useful to learn the perspective of an organisation that has been on this journey for a much longer time. Dom Galic from the US Department of Interior Bureau of

Reclamation (Reclamation) kindly accepted the challenge and presented the Reclamation's risk assessment and dam safety management practices, which now spans over three decades.

Finally, recognising that the legal considerations for tailings dams and risk assessment are often underappreciated and misunderstood, I invited Joel Mårtensson to present the legal considerations for tailings dams and risk assessment within the host country, Sweden.

Notwithstanding the very different backgrounds and area of practices, it was intriguing to observe that the presenters converged on the following pivotal facets of risk assessment:

- What is reasonably practicable refers to risk control actions not the risk magnitude or risk level, and ALARP ought to be understood as a process whereby all reasonably practicable risk controls are in place. A good practice is to identify all practicable risk controls and if not all of them are implemented, justify the reasons for not implementing them.
- Discerning reasonably practicable risk controls goes beyond cost-benefit analyses and is intertwined with current industry practice and standard of care.
- Risk tolerability frameworks were constructed for specific contexts and objectives. Hence, their application should remain circumscribed to their intended purview. Adopting risk tolerability criteria as the sole basis for decision making may not be legally and morally defensible after a failure occurred and lives were lost.
- Risk assessment is meant to provide inputs into a wider decision-making process, which factors in the nuances of ethics, perception, legal and regulatory imperatives, politics, culture and other intangible aspects of making a decision affecting the lives of others.

As part of the short course, the attendees identified and analysed a potential failure mode (PFM) based on the information provided from a real tailings dam and experienced the difficulties of estimating the probability of the dam failure by this PFM. The activities, undertaken in small groups, were intended to provide participants an insight into the process, the role of personal judgement and the difficulties of having incomplete data, which is common for tailings dams.

The short course concluded with two panel discussions adeptly moderated by Paul Ridlen, wherein the discourse revolved around compliance with GISTM requirements, difficulties in assessing risks of static liquefaction and the meaning of ALARP in different jurisdictions. The benefits of having presenters with no direct affiliation to mining entities were fully manifested in the high-quality discussions, which did not avoid deliberations upon attainability of the GISTM requirements and the ultimate goal of zero-harm.

I extend my gratitude to all presenters, moderators and all attendees of the short course for their generous contribution, unwavering support and active engagement.

Jiri Herza, Short Course Convenor

Table of Contents

1 Motivation

The members of the ICOLD Committee L – Tailings Dams and Waste Lagoons recognised that there was no specific guideline available for risk assessment for tailings dams, although risk assessment was made mandatory in many jurisdictions and the Global Industry Standard on Tailings Management (GISTM) required risks presented by tailings facilities to be reduced to as low as reasonably practicable.

ICOLD Bulletin 194 (2022) partly addressed the issue by providing an overview of the typical risk assessment process. However, for further details the reader was referred to applicable ICOLD and national guidelines, which were primarily developed for water storage dams. Therefore, the members of Committee L explored how ICOLD could assist tailings practitioners in developing risk assessments of tailings dams and this short course formed part of that process.

2 Background

This short course was built upon a risk assessment short course held as part of the Tailings and Mine Waste (TMW) Conference in November 2022.

The main objective of the TMW short course was to provide an overview of risk assessment for tailings storage facilities that included lessons learned from water dam risk assessment, legal perspectives, approaches by different mining companies, quantitative risk assessment, and the ALARP concept.

The TMW short course was attended by over 100 practitioners from the mining industry.

3 Course objectives and scope

The ICOLD short course objective was to present the current state of practice of risk assessment for tailings dams, building upon the principles outlined in Bulletin 194, with the view to improve the safety of tailings operations across the world.

The course covered the following aspects of risk assessment:

- Importance of understanding risk assessment objectives
- Key steps in the risk assessment process
- Clarification of risk tolerability concepts
- Identification of risk control measures and their verification
- Evaluation of what is reasonably practicable
- Integration of risk assessment into tailings management systems

Group activities provided an opportunity for the attendees to engage in the key risk assessment activities including hazard and failure mode identification, risk analysis, probability calculations, evaluation of the risk magnitude and consideration of reasonably practicable measures to address risks.

The short course was intended for dam owners, regulators, authorities, designers and consultants, contractors and NGOs.

4 Presenters

David S. Bowles
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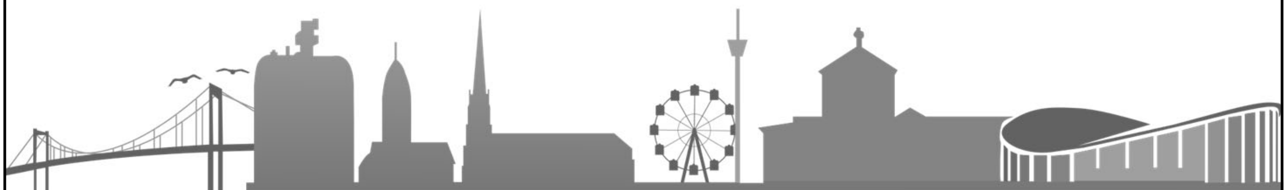
5 Content and Program

No.	Item	Start	Duration (min)
	Introduction	08:00	
	Workshop opening, Wider program of risk-related ICOLD activities, purpose of workshop, agenda review	08:10	10
Part 1	**Risk Assessment Overview**	08:10	
1.1	Why we conduct RA, objectives and methods	08:10	15
1.2	What is Risk - a measure of uncertainty, measure of consequence and probability	08:25	15
1.3	Question of Probability - Classical, Relative frequency, Bayesian theorem	08:40	15
1.4	Triplets of scenario, probability, consequences, representative failure scenarios	08:55	15
1.5	Risk tolerability questions - is a line on F-N plot defendable and does it meet the equity criteria?	09:10	25
1.6	Steps in risk assessment and what is and is not covered in B130, B194 and ANCOLD 2022	09:35	15
	Morning Tea	09:50	20
Part 2	**Prepared example - Risk Identification**	10:10	
2.1	Dam description and definition of problem - potential piping through the dam body	10:10	15
2.2	Piping assessment - owner's practice	10:25	45
2.3	Group activity 1 - Development of piping failure mode - event tree, fault tree, bowtie	11:10	45
2.4	Identification of risk controls	11:55	20
	Lunch	*12:15*	*40*
Part 3	**Prepared example - Risk analysis**	12:55	
3.1	Estimation of system responses	12:55	25
3.2	Estimation of probability of occurrence	13:20	25
3.3	Group activity 2 - Estimate of failure probability of embankment piping	13:45	45
	Afternoon Tea	14:30	20
Part 4	**Prepared example - Risk Evaluation**	14:50	
4.1	Defensible decision making - basic requirements	14:50	20
4.2	Assessment of risk controls to assist in decision making (what is ALARP)	15:10	30
4.3	Group activity 3 - selection of control measures to be implemented to mitigate the risk of piping	15:40	20
4.4	Societal confidence in dam risk assessments	16:00	20
4.5	Architecture of Dam Safety Management Systems	16:20	10
	Panel discussion	16:30	30

Appendix A. Short Course Presentations

Short Course 3

Risk assessment – Current state of practice for tailing dams



1

Introduction

- Evacuation – through main lobby
- Coffee break – Area H
- Lunch and afternoon tee – Area E

- **Objectives** : present and discuss the current state of practice of Risk Assessment for tailings dams
- **Short course context** : builds upon a SC at T&MW 2022

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

2

Short Course Program

	Item	Start	Duration
	Introduction	08:00	00:10
Part 1	**Risk Assessment Overview**	**08:10**	**01:40**
	Morning Tea	09:50	0:20
Part 2	**Risk Identification**	**10:10**	**02:05**
	Lunch	12:15	00:40
Part 3	**Risk analysis**	**12:55**	**01:35**
	Afternoon Tea	14:30	00:20
Part 4	**Risk Evaluation**	**14:50**	**01:40**
	Panel discussion	16:30	00:30

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Part 1 Risk Assessment overview

Part 1	Risk Assessment Overview	Presenter
1.1	Why we conduct Risk Assessment, objectives and methods	David
1.2	What is Risk - measure of consequence and probability, measure of uncertainty,	David
1.3	Question of Probability - Classical, Relative frequency, Bayesian theorem	David
1.4	Triplets of scenario, probability, consequences, representative failure scenarios	David
1.5	Risk tolerability questions - is a line on F-N plot defendable and does it meet the equity criteria?	Des
1.6	Steps in risk assessment and what is and is not covered in B130, B194 and ANCOLD 2022.	Jiri

5

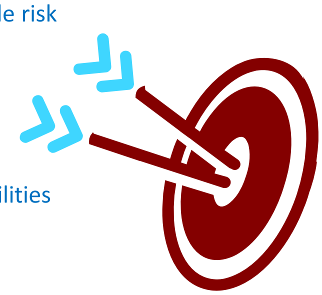
1.1 Why do we conduct Risk Assessments?

Improving Dam Safety

- Identifying and understanding failure modes
- Identifying knowledge gaps – need for investigations/priority-urgency
- Identifying reasonably practicable risk control options/justifications/priority-urgency
  - Improving monitoring and surveillance program
- Demonstrating that risk is reduced ALARP (GISTM), which includes tolerable risk

Informing Business/Stakeholders

- ICMM members and other owners committed to compliance with GISTM
- Comply with legislative and regulatory requirements in some jurisdictions
  - Demonstrating duty of care is met
- Enterprise risk management - Identifying and understanding potential liabilities
  - Identifying insurance/loss financing implications
- Maintaining license to operate/safety case
  - Justifying utility rate case
- Justifying capital budget/financing



6

1.1 GISTM: As Low As Reasonably Practicable (ALARP)

- ALARP originates with **Edwards v. The National Coal Board (1949 1 All ER 743)**:
  - What risk controls are reasonably practicable?

  *"**Reasonably practicable**" is a narrower term than "**physically possible**" and seems to me to imply that **a computation must be made** by the owner in which the **quantum of risk** is placed on one scale and the **sacrifice involved in the measures necessary for averting the risk** is placed on the other and that if it be shown that there is a **gross disproportion between them** the defendants discharge the onus on them.*

- This formed a precedence for numerous court rulings and Work, Health and Safety (WHS) acts in Commonwealth countries.
- Risk assessment is explicitly required to demonstrate safety of dams or storage of hazardous materials (including tailings) in some countries:
  - Including Czech Republic and France
  - 2022 ANM Resolution No. 95 (Brazil)
  - Some Australian states
  - Hydropower dams regulated by FERC in USA
- Legal and regulatory frameworks differ by country/state.
  - Practitioners must be aware of specific legal and regulatory requirement for risk assessment and risk controls.

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

7

1.1 As Low As Reasonably Practicable (ALARP)

Gross Disproportion – Protecting Lives: Cost >> Benefit

Benefit = Cost

An Investment: Benefit > Cost

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8

1.1 "Tolerable" and "Acceptable" are not the same

- **Tolerate***:*
  - *2b: to put up with <learn to tolerate one another>*
- **Accept**:
  - 1 a: to receive willingly <accept a gift>
  - 3 a: to endure without protest or reaction <accept poor living conditions>
  - b: to regard as proper, normal, or inevitable <the idea is widely accepted>

Merriam-Webster Dictionary

Tolerability of Risk Framework for Dams

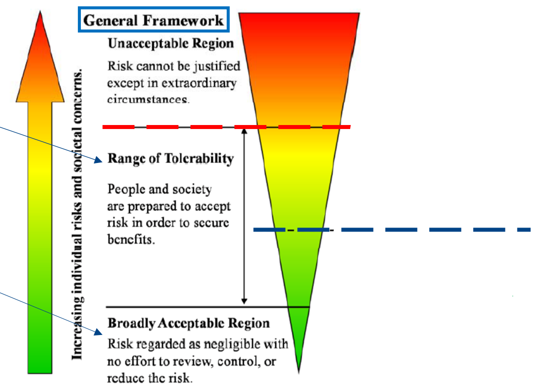
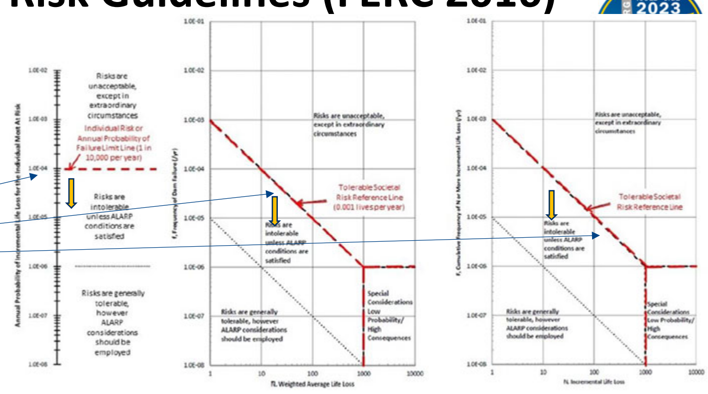


Figure 3-1. Generalized and Project Specific Tolerability of Risk Framework (Adapted and Modified from HSE, 2001 and USACE, 2014)

9

1.1 Example of Tolerable Risk Guidelines (FERC 2016)

1. **A definition of tolerable risk**, which includes the dam owner's responsibility to:
   a. keep dam safety risks under review and reduce them further if and as practicable; and
   b. ensure that society is confident that dam safety risks are being properly managed.
2. **Total risk limits** that should not be exceeded with adequate confidence:
   a. Individual Risk – person most at risk
   b. Societal Risk – multiple fatalities
3. **An as-low-as-reasonably practicable (ALARP) evaluation** to justify how far below the tolerable risk limits to reduce the risk:
   a. the disproportionality of the investment in risk reduction measures to the benefits including prevented fatalities
   b. good practice; and
   c. societal concerns as revealed by consultation with the community and other stakeholders



a. Individual Life-Safety Incremental Risk (Adapted from Figure 3-2 in FERC 2016).

b. Societal Life-Safety Incremental Risk on f-N̄ Chart (Adapted from Figure 2E-2 in FERC 2016).

c. Societal Life-Safety Incremental Risk Chart (Adapted from Figure 2E-1 in FEF

Reasonably practicable. Definition adapted from Department of Mines, Industry Regulation and Safety (2022), Government of Western Australia - our context is dam safety branch rather than industry/mine health and safety:
… a registered manager or other statutory ***appointed person*** *(Accountable Executive/Board) must meet the standard of behaviour expected of a reasonable person in that position. There are* ***two elements to 'what is reasonably practicable'****.*
The appointed person needs to first consider what can be done – that is, what is possible in the circumstances for ensuring the … safety of the dam? They then need to consider whether it is reasonable, in the circumstances to do all that is possible. This means that what can be done should be done, unless it is reasonable in the circumstances for the appointed person to do something less. …

10

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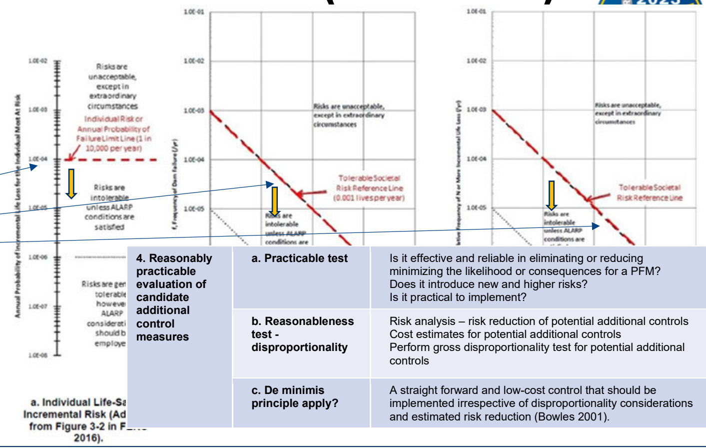
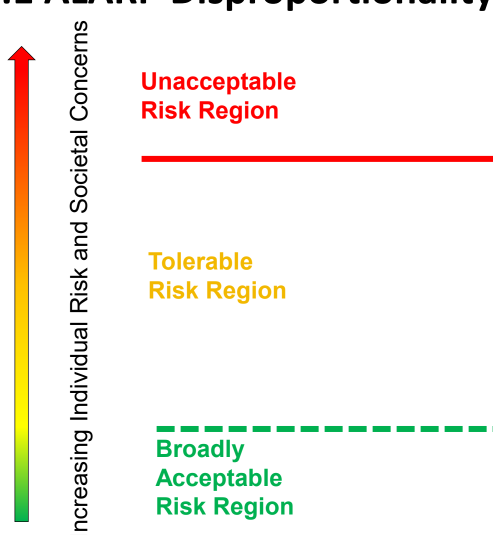


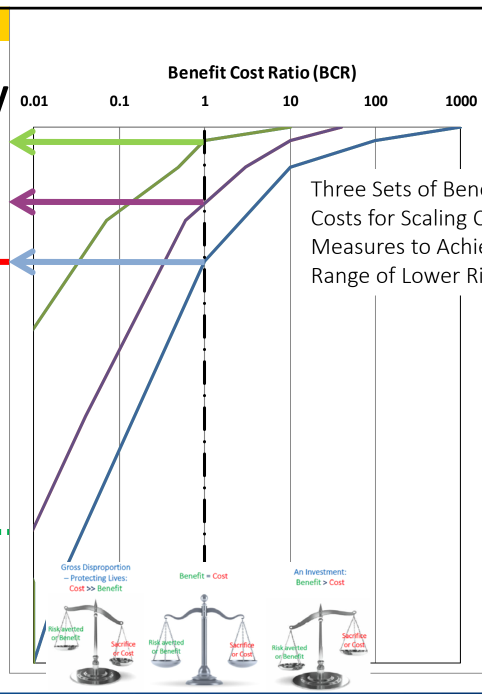
4. Reasonably practicable evaluation of candidate additional control measures	**a. Practicable test**	Is it effective and reliable in eliminating or reducing minimizing the likelihood or consequences for a PFM? Does it introduce new and higher risks? Is it practical to implement?
	b. Reasonableness test - disproportionality	Risk analysis – risk reduction of potential additional controls Cost estimates for potential additional controls Perform gross disproportionality test for potential additional controls
	c. De minimis principle apply?	A straight forward and low-cost control that should be implemented irrespective of disproportionality considerations and estimated risk reduction (Bowles 2001).

Reasonably practicable. Definition adapted from Department of Mines, Industry Regulation and Safety (2022), Government of Western Australia - our context is dam safety branch rather than industry/mine health and safety:
*… a registered manager or other statutory **appointed person** (Accountable Executive/Board) must meet the standard of behaviour expected of a reasonable person in that position. There are **two elements to 'what is reasonably practicable'**. The **appointed person** needs to **first consider what can be done – that is, what is possible in the circumstances for ensuring the … safety of the dam?** They **then** need to **consider whether it is reasonable, in the circumstances to do all that is possible. This means that what can be done should be done, unless it is reasonable in the circumstances for the appointed person to do something less.** …*

11

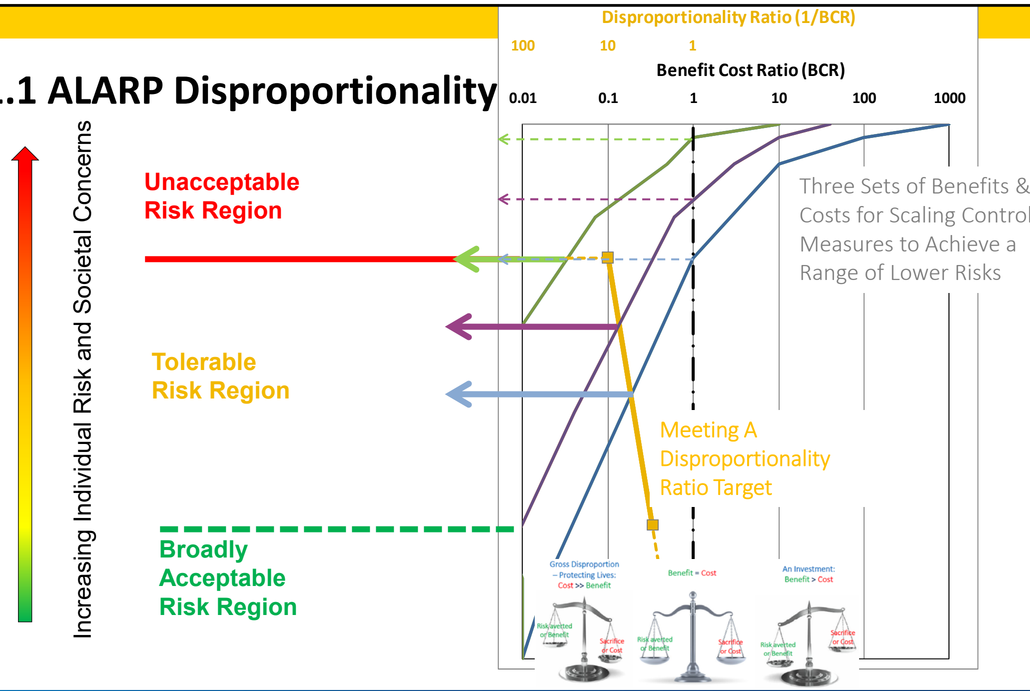
1.1 ALARP Disproportionality





12

1.1 ALARP Disproportionality

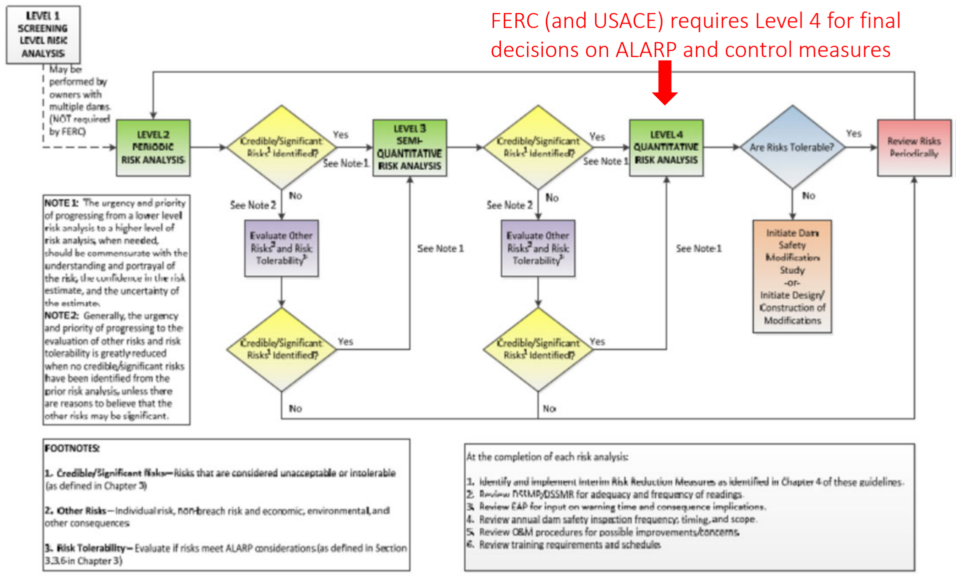


1.1 Risk Assessment Level

- **Selection depends on:**
  - **Risk assessment objectives, including desired types of outcomes and level of confidence/defensibility**
  - Fit for purpose, decision-driven
  - Necessary resources should be provided consistent with objectives
- Methods, tools, needed information and process for a screening assessment would differ from methods used for demonstration of ALARP and justification of risk controls
  - Supporting studies are usually needed to develop adequate information
- A staged approach is commonly used progressing to more detailed RA as justified

1.1 Risk Assessments levels (FERC 2016)

FERC (and USACE) requires Level 4 for final decisions on ALARP and control measures



1.1 Risk Assessments levels (FERC 2016)

Table 2-1. Summary of Risk Analysis Levels

Level	Description	Purpose/Outcome	Type of Risk	Typical Level of Effort	Loadings	Consequences	System Response	Uncertainty
1	Screening	- Initial prioritization of inventory - Identify dams that are potentially very high risk that require immediate attention - Not appropriate for decisions	Incremental life safety Economic (in very general terms)	Minimal effort. Lead by a single individual or small team	Rapid assessment using simple, readily available tools	Simplified methods	Common potential failure modes (PFMs) using simplified tools	Qualitative to None
2	Periodic	- Identification of all PFMs - Prioritization of additional studies - Lowest level of risk analysis for decisions - Prioritization of inventory - Tolerable risk evaluation for existing conditions	Incremental life safety Economic Other	Low to moderate effort. Lead by a single individual (Independent Consultant) or a small team	Basic tools/ methods to estimate annual exceedance probability (AEP)	Simplified methods	Common PFMs using simplified approach	Qualitative
3	SQRA	- Project-wide assessment of risks - Identification of PFMs needing further study	Incremental life safety Economic Other	Effort can vary greatly depending on PFMs and issues. Team-based, facilitated.	Basic tools/ methods to estimate AEP	Simple to intermediate methods	Comprehensive evaluation of PFMs using semi-quant. approach	Qualitative
4A	QRA	- Lowest level of issue-specific risk analyses to determine if risks are tolerable or unacceptable	Individual life safety Incremental life safety Non-breach life safety Annual Prob. Failure Economic Other	Relatively simple/ routine models. Team-based, facilitated.	Simple loadings with no challenging technical issues	Relatively simple to estimate. Straight-forward.	Simple, common PFMs	Simple approach to quantify
4B	QRA	- Intermediate level of issue-specific risk analysis	Individual life safety Incremental life safety Non-breach life safety Annual Prob. Failure Economic Other	Moderate to high level of effort. Team-based, facilitated.	Intermediate difficulty. Use of additional experts may be required.	Intermediate difficulty. Use of additional experts may be required.	Intermediate difficulty	Moderate approach to quantify
4C	QRA	- Highest level of issue-specific risk analyses to determine if risks are tolerable or unacceptable	Individual life safety Incremental life safety Non-breach life safety Annual Prob. Failure Economic Other	Intense level of effort. Sophisticated/ detailed models. Team-based, facilitated.	Complex, difficult loadings. Use of additional experts likely to be required.	Challenging and difficult. Use of additional experts likely to be required.	Complex, multiple PFMs with multi-disciplinary teams	Detailed approach to quantify

FERC (and USACE) requires Level 4 for final decisions on ALARP and control measures

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

1.1 Some GISTM Requirements

ICMM members and other owners committed to compliance with GISTM

4.4: *Select, explicitly identify and document all design criteria that are appropriate to minimise risk for all credible failure modes for all phases of the tailings facility lifecycle.*

4.7: *… determines that the upgrade of an existing tailings facility is not viable or cannot be retroactively applied. In this case, the Accountable Executive shall approve and document the implementation of measures to reduce both the probability and the consequences of a tailings facility failure in order to reduce the risk to a level as low as reasonably practicable (**ALARP**). …*

5.4: *Address all potential failure modes of the structure, its foundation, abutments, reservoir (tailings deposit and pond), reservoir rim and appurtenant structures to minimise risk to **ALARP**. Risk assessments must be used to inform the design.*

6.5: *… The change management system shall also include the requirement for the EOR to prepare a periodic Deviance Accountability Report (DAR), that provides an assessment of the cumulative impact of the changes on the risk level of the as-constructed facility. …*

7.4: *Analyse technical monitoring data at the frequency recommended by the EOR, and assess the performance of the tailings facility, clearly identifying and presenting evidence on any deviations from the expected performance and any deterioration of the performance over time. Promptly submit evidence to the EOR for review and update the risk assessment and design, if required. …*

10.1: *Conduct and update risk assessments with a qualified multi-disciplinary team using best practice methodologies at a minimum every three years and more frequently whenever there is a material change either to the tailings facility or to the social, environmental and local economic context. …*

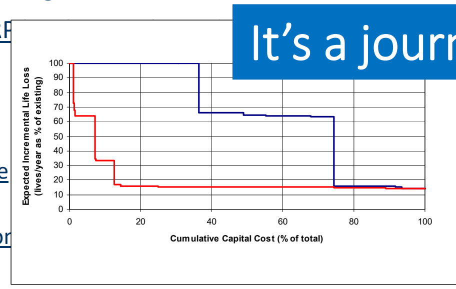
17

1.1 Accountable Executive – GISTM Definition

*One or more executive(s) who is/are **directly answerable** to the CEO on matters related to this Standard, **communicates with the Board** of Directors, and who is **accountable for the safety of tailings facilities** and for **minimizing the social and environmental consequences** of a potential tailings facility failure. The Accountable Executive(s) **may delegate responsibilities but not accountability**.*

What is the **appropriate degree of confidence and defensibility** consistent with the responsibility to be *accountable* for, *approve*, *confirm*, *certify in writing* and *document* that ALARP will be met by either a) accepting the existing controls, or b) justifying and implementing additional controls?

- By August 2023 it may not be possible to state that ALARP
- Instead, the case should be made that:
  - Given the time constraints,
  - all reasonably practicable actions have been taken
  - or are planned to be taken as soon as reasonably practicable
  - to achieve and maintain a long-term ALARP position,
  - including investigations to address knowledge gaps to demon
    confidence and defensibility.



It's a journey!

18

1.1 Adequate Confidence / Defensibility

1. People – Suitably qualified, experienced
2. Proof – Supporting evidence, Knowledge gaps
3. Process – objectively executed in a technically defensible manner with due consideration given to significant uncertainties
   - Manage elicitation/estimation biases
   - Level of detail
   - Participative review

19

Part 1.2 What is Risk?

20

1.2 What is Risk? – some definitions

- Cambridge Dictionary

The possibility of something bad happening or something bad that might happen.

- ISO 31000 (Risk Management)

Effect of uncertainty on objective.

- ICOLD B130 (2005) B194 (2022) and ANCOLD Dam Risk Assessment Guideline (2022)

Measure of the probability and severity of an adverse effect to life, health, property, or the environment.

In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequences.

Adopted for this short course

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

21

1.2 What is Risk? - Society for Risk Analysis (SRA 2018) Glossary

1. *Risk is the possibility of an unfortunate occurrence*
2. *Risk is the potential for realization of unwanted, negative consequences of an event*
3. *Risk is exposure to a proposition (e.g., the occurrence of a loss) of which one is uncertain*
4. *Risk is the consequences of the activity and associated uncertainties*
5. *Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value*
6. *Risk is the occurrences of some specified consequences of the activity and associated uncertainties*
7. *Risk is the deviation from a from a reference value (e.g., an objective) and associated uncertainties*

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

22

1.2 Risk metrics/descriptions - SRA (2018) Glossary

1. *The combination of probability and magnitude/severity of consequences*
2. *The combination of the probability of a hazard occurring and a vulnerability metric given the occurrence of the hazard*
3. *The triplet (s_i, p_i, c_i), where s_i is the i^{th} scenario, p_i is the probability of that scenario, and c_i is the consequence of the i^{th} scenario, i =1,2,…N.*
4. *Expected consequences (damage, loss). For example, computed by:*
   a. *Expected number of fatalities in a period of one year …* (AALL, Average Annual Life Loss CAUTION)
   b. *P(hazard occurring) x P(exposure of object | hazard occurring) x E[damage | hazard and exposure] i.e., the product of the probability of the hazard occurring and the probability that the relevant object is exposed given the hazard, and the expected damage given that the hazard occurs, and the object is exposed (the last term is a vulnerability metric …)*

23

Part 1.3 What is probability?

24

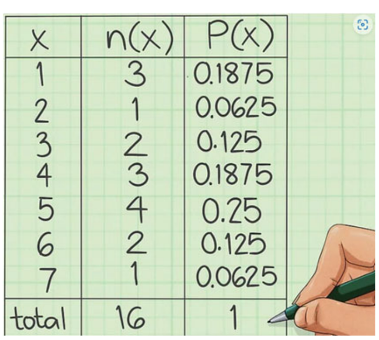
1.3 Probability – classical interpretation (SRA 2018)

… applies only in situations with a finite number of outcomes which are equally likely to occur (a priori known probability):

- *The probability of A is equal to the ratio between the number of outcomes resulting in A and the total number of outcomes, i.e.*
    - *P(A = 3) = Number of outcomes resulting in A = 3/Total number of outcomes = 1/6*

1.3 Probability – frequentist interpretation (SRA 2018)

A frequentist probability of an event A, denoted P_f (A), is defined as the limiting fraction of times the event A occurs if the situation considered were repeated (hypothetically) an infinite number of times.



x	n(x)	P(x)
1	3	0.1875
2	1	0.0625
3	2	0.125
4	3	0.1875
5	4	0.25
6	2	0.125
7	1	0.0625
total	16	1

- *The propensity interpretation holds that the probability is to be thought of as a physical characteristic; a propensity of a repeatable experimental set-up which produces outcomes with limiting relative frequency probability P_f (A).*
- Not applicable to one-off events – e.g., dam failures.
- How is the frequency of dam failures around the world related to a specific dam?

1.3 Subjective probability

In ordinary conversation the word probability is applied not only to variable phenomena but also to propositions of uncertain veracity.

- *The truth of any proposition concerning the outcome of an experiment is uncertain before the experiment is performed.*
- *Many other uncertain propositions cannot be defined in terms of repeatable experiments.*
- *An individual can be uncertain about the truth of a scientific theory, a religious doctrine, or even about the occurrence of a specific historical event when inadequate or conflicting eyewitness accounts are involved.*
- *Using probability as a measure of uncertainty enlarges its domain of application to phenomena that do not meet the requirement of repeatability.*
- *The concomitant disadvantage is that probability as a measure of uncertainty is subjective and varies from one person to another.*

https://www.britannica.com/science/probability-theory/An-alternative-interpretation-of-probability

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27

1.3 Probability – Bayesian interpretation

- Bayes (1763) defined subjective probability as:
  - *The probability of any event is the ratio between the value at which an expectation depending on the happening of the event ought to be computed, and the value of the thing expected upon its happening.*
- *Bayesian probability is an interpretation of the concept of probability, in which, instead of frequency or propensity of some phenomenon, probability is interpreted as reasonable expectation representing a state of knowledge or as quantification of a personal belief.*
- *Bayesian probability belongs to the category of evidential probabilities;*
  - *to evaluate the probability of a hypothesis, the Bayesian probabilist specifies a prior probability.*
  - *This, in turn, is then updated to a posterior probability in the light of new, relevant data (evidence).*
  - *The Bayesian interpretation provides a standard set of procedures and formulae to perform this calculation.*

Wikipedia Bayesian Probability Accessed June 1, 2023, 3:14 pm MST.

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28

1.3 Objective and Subjective Probability in Dam Safety RA

Objective = a real-world attribute of an object, event, etc.

- Classical and frequentist interpretations
  1. Flood frequency is an example of frequentist interpretation
  2. Reliability of a backup generator is an example of frequentist interpretation

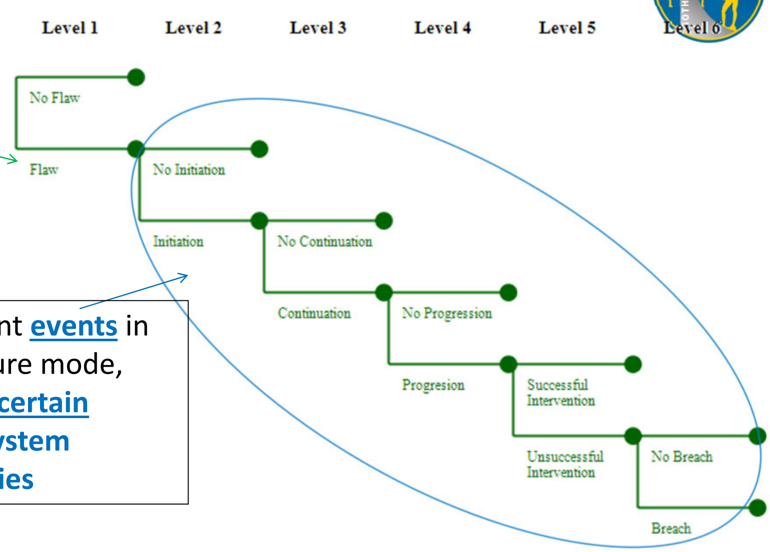
Subjective = judgmental, evidence-based, not a real-world attribute

- Bayesian interpretation, e.g.:
  1. A measure of the likelihood that a failure event will occur if a given loading condition occurs as estimated by a subject matter expert (SME) based on the evidence
     - A conditional probability – conditioned on occurrence of the loading event
     - Reality is that it will or will not occur if the loading condition occurs
  2. A measure of the uncertainty that a flaw (state of nature) exists in the core of a dam as estimated by a SME based on the evidence
     - Reality is that it does or does not exist

29

1.3 Example Internal Erosion Sub Event Tree

This branch is **not an event** - it represents **uncertainty in the "state of nature"** – i.e., that a flaw exists in the dam core



These branches represent **events** in the internal erosion failure mode, which dependent on **uncertain attributes of the dam system ~ conditional probabilities**

30

1.3 Objective and Subjective Probability in Dam Safety RA

Combinations of the frequentist and Bayesian (subjective) interpretations:

1. Probabilistic Seismic Hazard Analysis (PSHA) and Probabilistic Flood Hazard Analysis (PFHA)
2. Reliability of a backup generator adjusted for an operating environment that differs from the environment of the generators for which the reliability was calculated

ICOLD (2005) Bulletin 130, ICOLD (2022) Bulletin 194 and ANCOLD (2022) Guidelines on Risk Assessment definition of probability:

- ***Measure of the degree of confidence in a prediction, as dictated by the evidence, concerning the nature of an uncertain quantity or the occurrence of an uncertain future event.***

Adopted for this short course

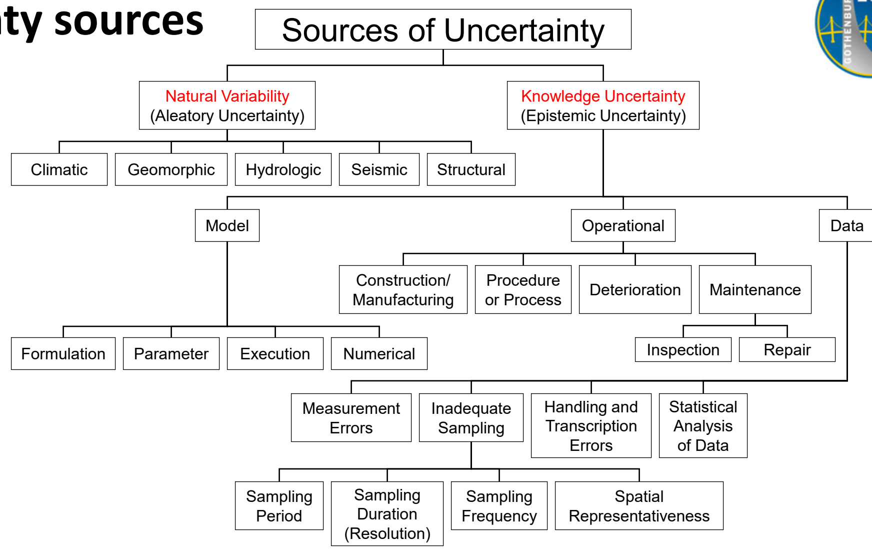
1.3 What is Uncertainty? (NAP 2000)

… a lack of sureness about something or someone, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome

Three types of uncertainty relevant in dam safety risk assessment:

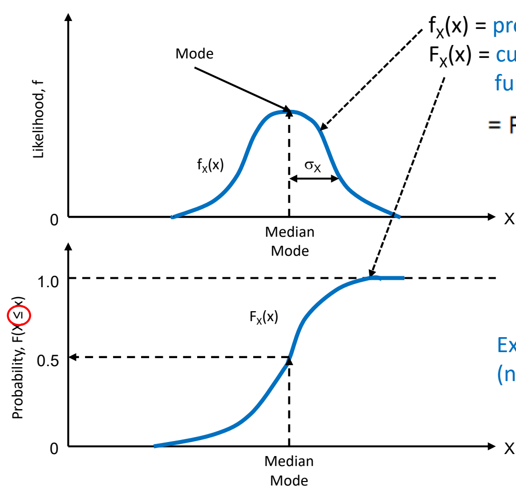
1. Uncertainty with respect to **occurrence of a natural phenomena** (**natural variability - aleatory**) means that an outcome is unknown or not established and is therefore in question
   - Irreducible, although estimates may be improved with more data
   - E.g., Temporal variability in loading events and exposure of people to a dam failure
2. Uncertainty with respect to a **belief** (**knowledge uncertainty - epistemic**) means that a conclusion is not proven or is supported by questionable information
   - May be reduced through investigations, testing, analyses, etc., but may reach a point of practically irreducible knowledge uncertainty – but control measures should reduce this uncertainty
   - E.g., Conditional/system response probabilities (fragilities)
   - Considered using sensitivity analyses and uncertainty analyses
3. Uncertainty with respect to **a course of action** (**policy uncertainty**) means that a plan (potential control measures) is not determined or is undecided
   - Best considered through "what if" or sensitivity studies

1.3 Uncertainty sources



adapted from Tung and Yen (2005)

1.3 Non-Exceedance Probability Distribution



$f_X(x)$ = probability density function (PDF) for X

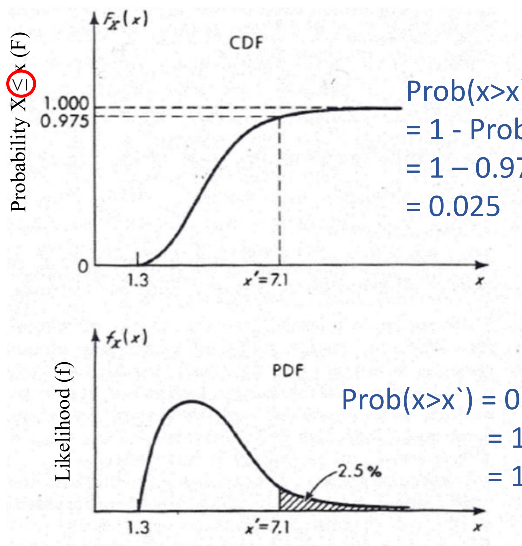
$F_X(x)$ = cumulative probability distribution function (CDF) for X

$= P(X \le x) = \int_{-\infty}^{\infty} f_X(x)dx$

Example: particle size distribution
(natural variability in particle sizes)

1.3 Obtaining Probabilities from Continuous Distributions

EXAMPLES:
- Inflow flood magnitude
- Peak ground acceleration
- Spillway discharge
- Warning time



Prob(x>x`)
= 1 - Prob(x≤x`)
= 1 – 0.975
= 0.025

Prob(x>x`) = 0.025
= 1 in 1/.025
= 1 in 40

1.3 Obtaining Probabilities from Continuous Distributions

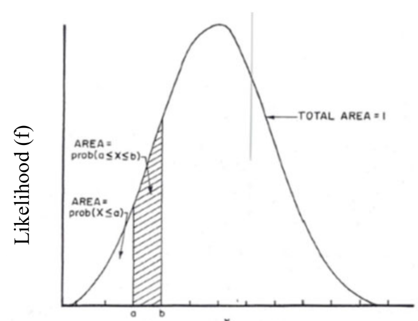


Fig. 2.10. Probability density function.

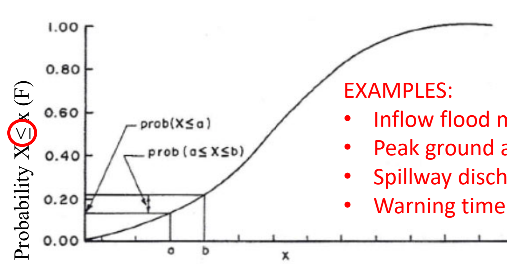
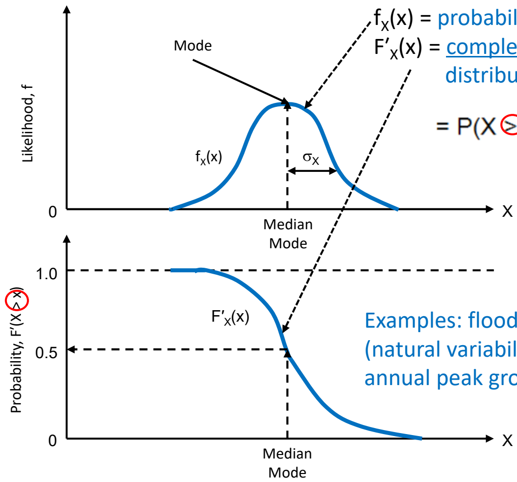


Fig. 2.11. Cumulative probability distribution function.

EXAMPLES:
- Inflow flood magnitude
- Peak ground acceleration
- Spillway discharge
- Warning time

1) Prob(X<a) = 0.15
2) Prob(X=a) = 0
3) Prob (a≤X≤b) = Prob (X≤b) – Prob (X≤a) = 0.22 - 0.15 = 0.07

1.3 Exceedance Probability Distribution



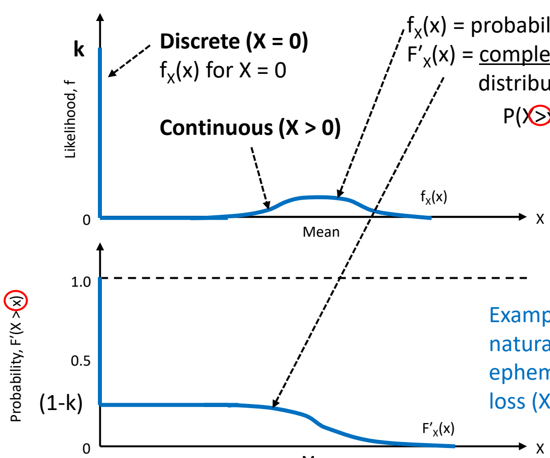
$f_X(x)$ = probability density function (PDF) for X
$F'_X(x)$ = complementary cumulative probability distribution function (CCDF) for X

$$= P(X > x) = 1 - \int_{-\infty}^{\infty} f_X(x)dx$$

Examples: flood frequency and seismic hazard (natural variability in annual peak flow rates or annual peak ground acceleration)

37

1.3 Mixed Probability Distribution



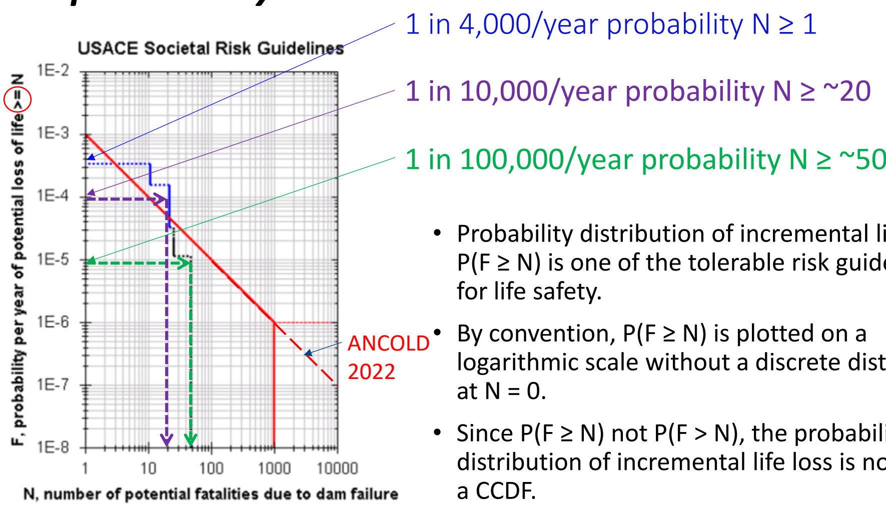
$f_X(x)$ = probability density function (PDF) for X>x
$F'_X(x)$ = complementary (exceedance) cumulative probability distribution function (CCDF) for X>x

$$P(X > x) = k + (1\text{-}k)\int_0^x f(x)dx$$

Examples: snow water equivalent (SWE) on May 1 and natural variability of SWE; flood-frequency for an ephemeral stream; debris plugging; incremental life loss (X = N)

38

1.3 Example of societal tolerable risk guidelines and F-N plot: *A "complementary" cumulative mixed distribution*



- Probability distribution of incremental life loss P(F ≥ N) is one of the tolerable risk guidelines for life safety.
- By convention, P(F ≥ N) is plotted on a logarithmic scale without a discrete distribution at N = 0.
- Since P(F ≥ N) not P(F > N), the probability distribution of incremental life loss is not strictly a CCDF.

Part 1.4 Combination of triplets of scenario, probability, and consequences?

1.4 Risk as triplets of scenarios, probability & consequences

Risk is the combination of N triplets (s_i, p_i, c_i), where s_i is the i^{th} scenario, p_i is the probability of the i^{th} scenario, and c_i is the consequence of the i^{th} scenario

1. A set of failure event – exposure scenarios

- **Failure event**
  - Failure modes
    - Breach characterizes
    - Detection - Notification - Warning – Mobilization - Evacuation timeline
- **Exposure scenario**
  - Day/night, Season of year, etc.

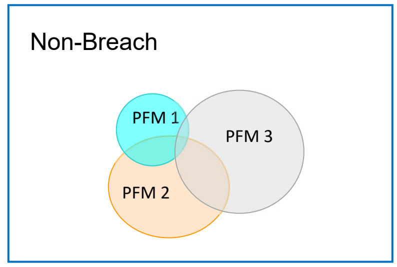
2. Probability of each scenario occurring

3. Consequences of each scenario

- Incremental consequences in the case of floods

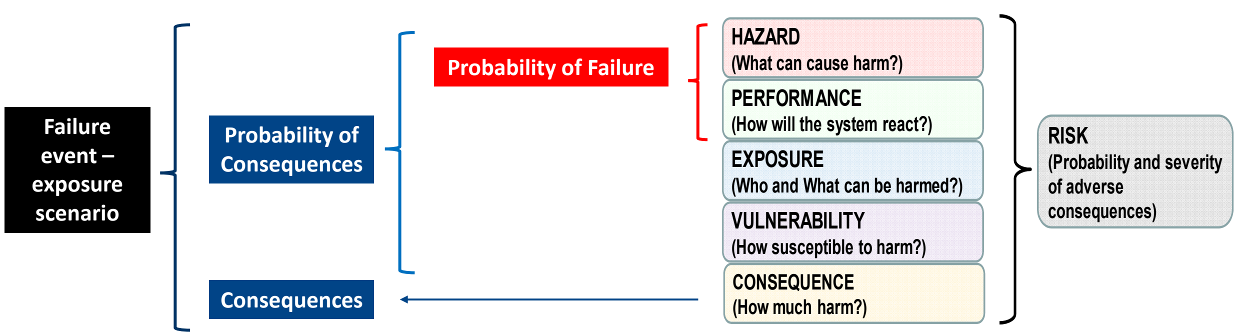
Combining probabilities of the set of scenarios

- Non-mutually exclusive failure modes, dominance
- Correlated failure modes



41

1.4 Risk as triplets of scenarios, probability & consequences



42

1.4 Consequences – depends on decision context

Life Loss

- Key consideration in tolerable risk guidelines
- Simulation approaches have an advantage over empirical approaches because:
  - provide insights into causation and
  - mitigation (control) measures

Economic

- Accruing at national, regional or local levels?
- Involve an economist

Financial

- Owner's liability

Environmental, heritage, reputation etc.

1.4 Dam failure scenario– two-dimensional view

Two dimensions of dam safety risk:

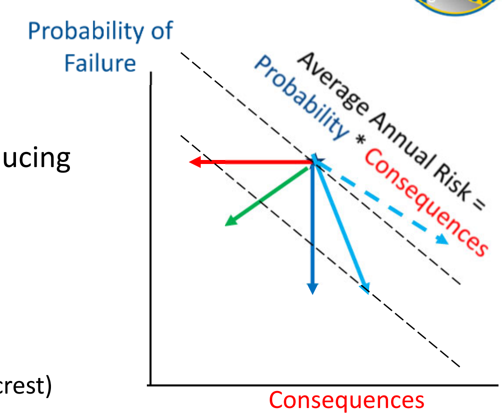
- Probability
- Consequences

Important to identify opportunities (controls) for reducing

- Probability
- Consequences dimensions of dam failure risk, or
- Both

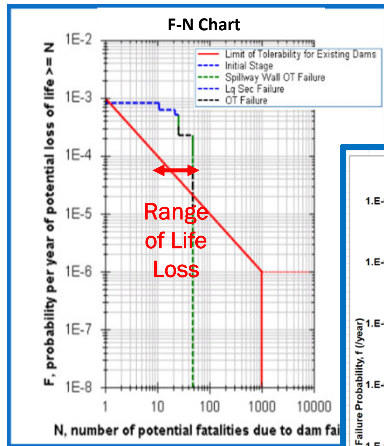
Some dam safety risk controls can

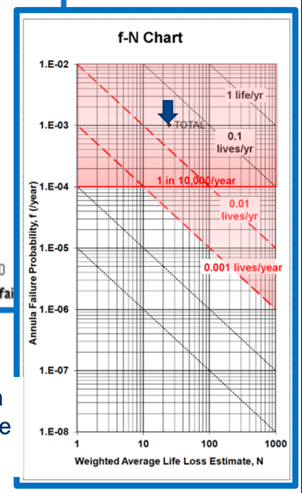
- increase consequences (e.g., dam raise)
- increase non-breach risk (e.g., lowering/widening spillway crest)
  - "Do No Harm"



1.4 Portrayal of dam failure risk

- "Probability of life loss" is not the probability of a single magnitude of life loss,
  - but a **probability distribution of a range of life loss magnitudes: F-N Chart**
- Many factors make the magnitude of life loss variable,
  - e.g., time of day, failure mode and location.





Single Value for Life Loss is a Weighted Average over Range of Life Loss: f-$\bar{N}$ Chart

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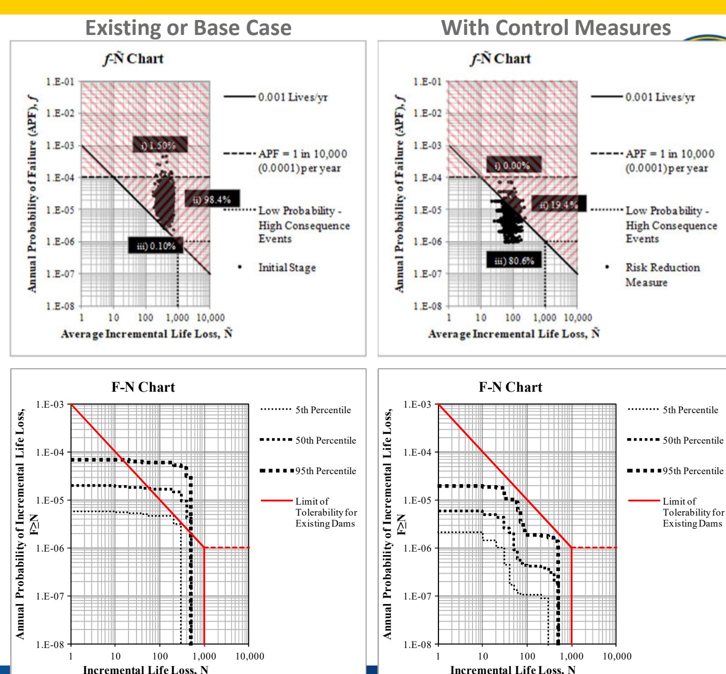
45

1.4 Portrayal of dam failure risk with uncertainty

f-$\bar{N}$ Charts:
Annual Probability of Failure (APF, f) vs Weighted Average Life Loss ($\bar{N}$)

F-N Charts:
Annual Probability of Life Loss ≥ N (F) vs Life Loss (N)



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46

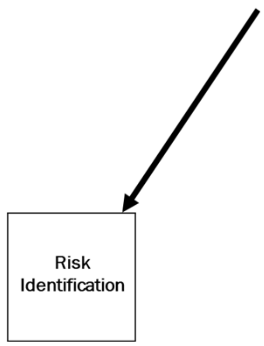
Part 1.4 Combination of triplets of scenario, probability, and consequences

Risk Assessment Process

1.4 RA Process: Scoping – *Often Overlooked*

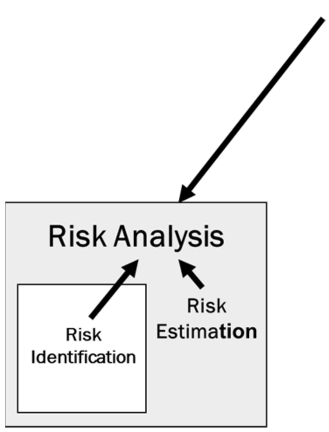
- System to be analyzed, including existing controls
- Risk assessment purpose(s)
- Decision context
- Decision bases, including outcome types
- Additional information to be obtained
  - Schedule and cost
- If insufficient resources are provided for the RA this may lead to:
  - Less than desired level of confidence in RA outcomes
  - Poor decisions that will likely be more costly than investing more in the RA

1.4 Process: Risk Identification – Evidence based



- Hazards
- Current practice assessment
- Failure modes (what can go wrong, why and how)
  - Systematic (e.g., FTA, FMEA) and brain storming approaches
  - Existing controls
  - Failure modes screening:
    - Credible – physically plausible
    - Significant – contribution to total risk
  - System interdependencies and human factors
  - Knowledge gaps - iterative
- Exposure and consequences types
- Candidate additional controls

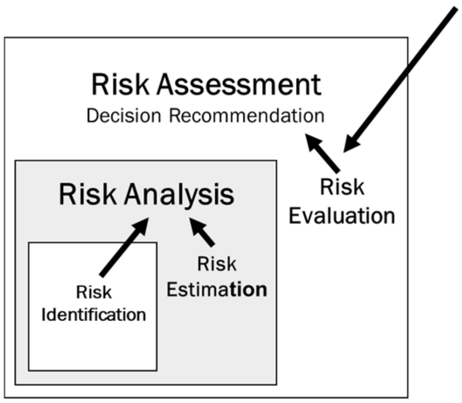
1.4 Process: Risk Analysis – Evidence based



- Process of understanding the nature, sources and causes of the identified risks to estimate the level of risk
- Quantifying probabilities and consequences for all credible and significant failure modes
- Level of detail and rigour of risk analysis and quality of inputs (evidence) should be decision-driven

Details provided in Part 3

1.4 RA Process: Risk Evaluation



- Examining and judging the significance of the estimated risk.
- Evaluating whether the risk is ALARP
- Considering cultural, economic, social, environmental, cost and other factors.
- Informing decision recommendations in reference to "tolerability" of estimated risk.
- Informing judgement over what additional risk controls are **reasonably practicable**.

Details provided in Part 1.5 and Part 4

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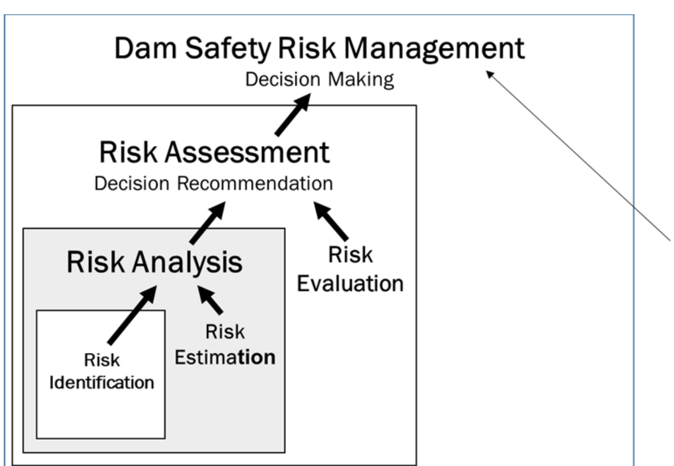
51

1.4 RA Process - Risk Management



The systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, evaluating, controlling (decisions) and monitoring risk.

Details provided in Part 4.4 and 4.5

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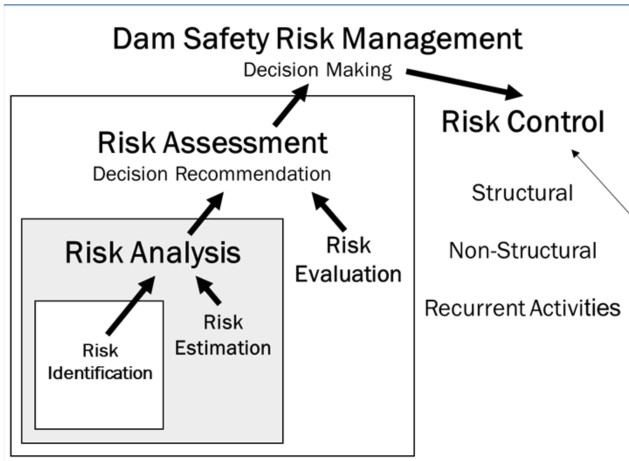
52

1.4 RA Process: Risk Control Implementation

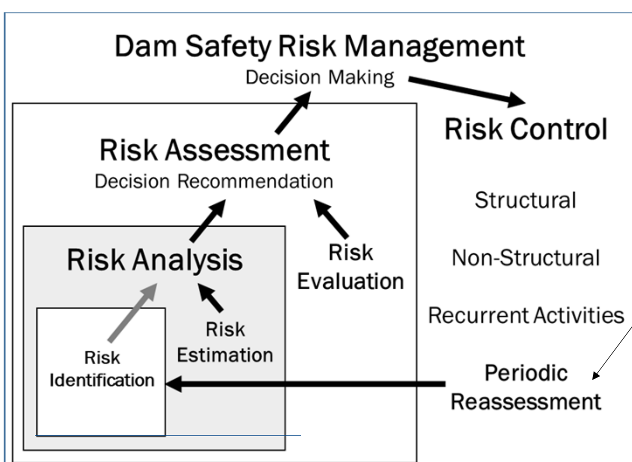


The selective application of appropriate control measures and management principles to reduce/manage the likelihood of failure, its adverse consequences, or both

Details provided in Part 4.2

53

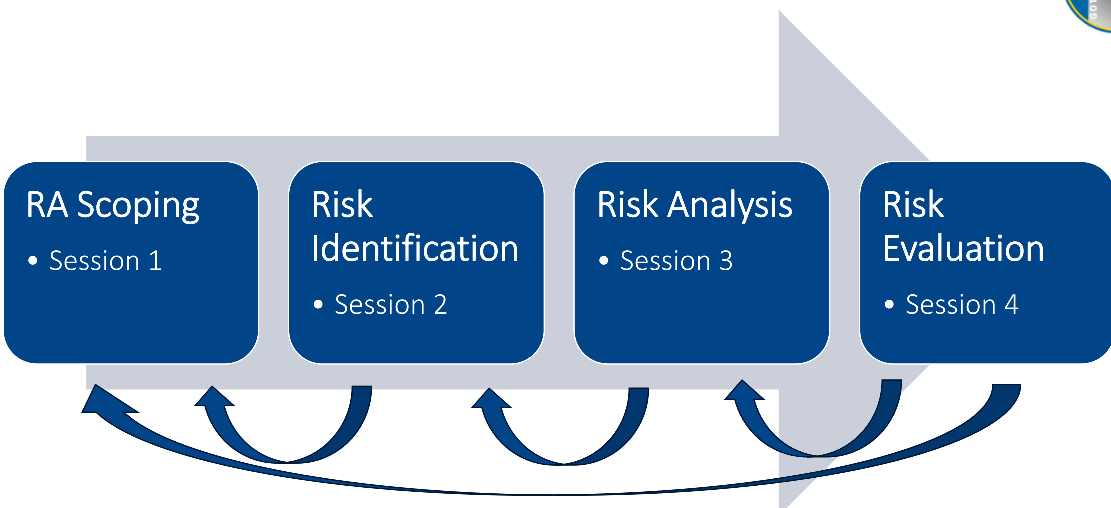
1.4 RA Process: Risk Control Verification



- Systematic process of verification of risk control effectiveness
- Monitoring performance and reassessing the risk

54

1.4 Risk assessment process



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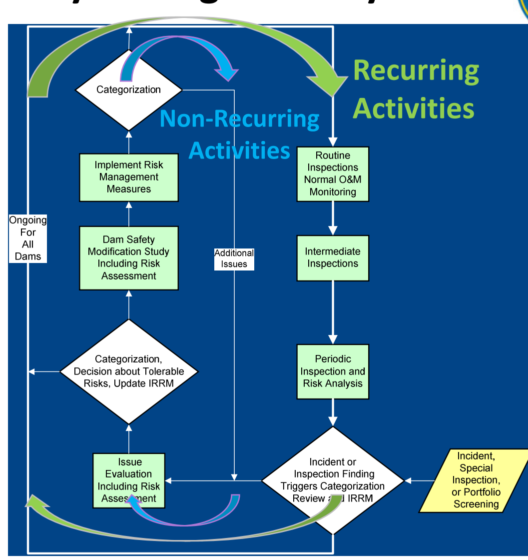
55

1.4 Integration of Risk in Dam Safety Management System

- Mature risk-informed dam safety systems use RA and risk thinking (culture) throughout the Recurring and Non-Recurring dam safety processes
- Prioritization and queues are necessary due to resource limitations and the desire to reduce overall portfolio risk as efficiently as possible.
  - Priority - the order in which things should be done
  - Urgency - how soon things should be done
- Prioritization is an iterative process that is updated as new information is obtained and RAs are completed or revised.

More details provided in Section 4.5



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56

Part 1.4 Combination of triplets of scenario, probability, and consequences

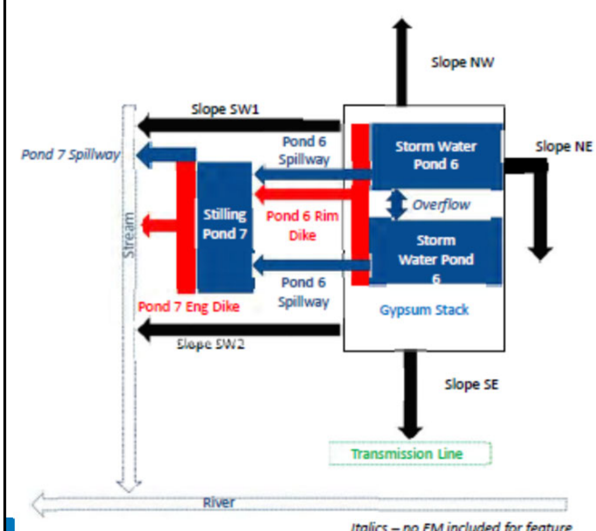
EXAMPLE:

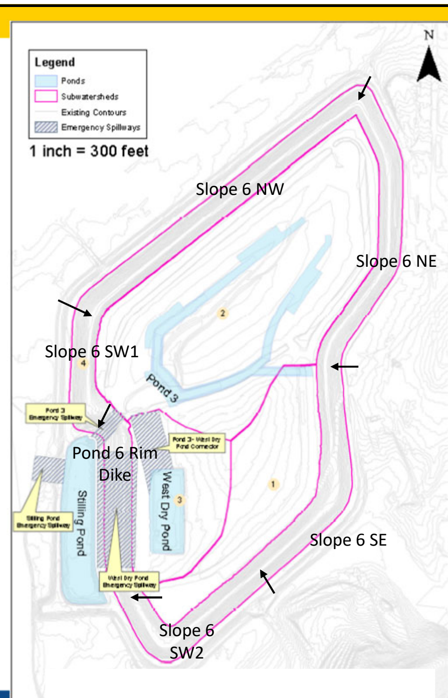
Risk Assessment of Coal Ash Impoundments/Stacks

~ Parallel System

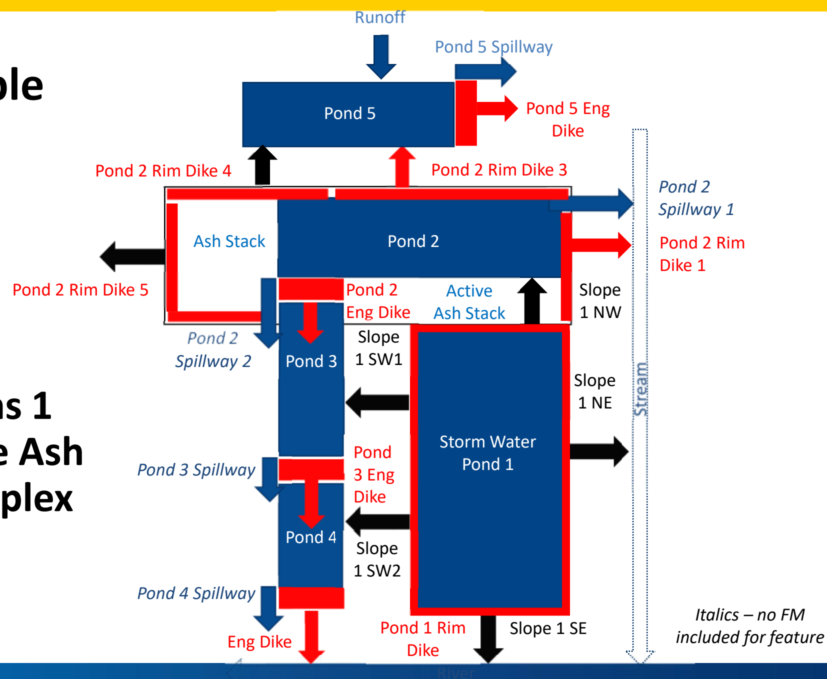
57

1.4 Subsystem 3 - Gypsum Stack Example





1.4 Example



Subsystems 1 & 2: Active Ash Stack Complex

59

1.4 Example Hierarchy of System Components

				Slopes	
System	Subsystem 1	Pond 1	1.1	Rim Dike	
			1.2	Rim Dike	
			1.3	Rim Dike	
			1.4	Rim Dike	
			1.5	Rim Dike	
	Subsystem 2	Pond 2	2.1	Rim Dike	
			2.2	Engineered Dike	
			2.3	Rim Dike	
			2.4	Rim Dike	
			2.5	Rim Dike	
		Pond 3	2.6	Engineered Dike	
		Pond 4	2.7	Engineered Dike	
		Pond 5	2.8	Engineered Dike	& Spillway
	Subsystem 3	Pond 6	3.1	Rim Dike	
			3.2	Rim Dike	
			3.3	Rim Dike	
			3.4	Rim Dike	
			3.5	Rim Dike	
			3.6	Slope	
		Pond 7	3.7	Engineered Dike	& Spillway

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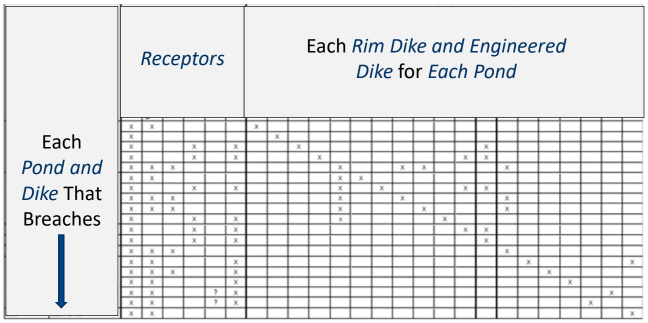
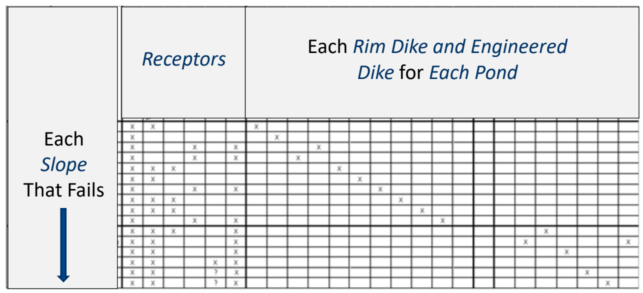
60



Receptors – Pond Breaches

Receptors – Slope Failure



61

1.4 System Considerations

A pond with multiple dikes

- Common cause adjustment, which accounts for one dike preempting the failure of other dikes by draining the pond

Ponds in series

- Assigned consequences associated with downstream pond breaches initiated by an upstream pond breach to the upstream pond
- No change in probability of downstream pond breach if the potential for its breach is caused by the upstream pond breach

Length effects

- Increase in probability of failure with increasing length of slopes/rim dikes

Combining probabilities of slope failure or pond breach over:

- Subsystems or entire system
- Assuming statistical independence of failures/breaches at different locations except in the case of multiple dikes on the same pond

Combining probabilities of slope failure and pond breach with the same consequences rating

- Avoid double counting of consequences for slope failures that involve rim dike failure that leads to a pond breach

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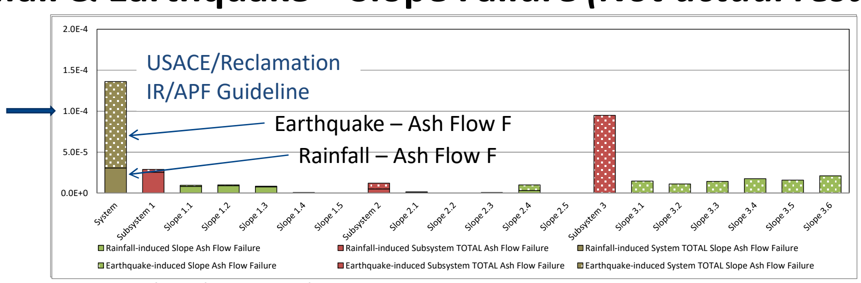
62

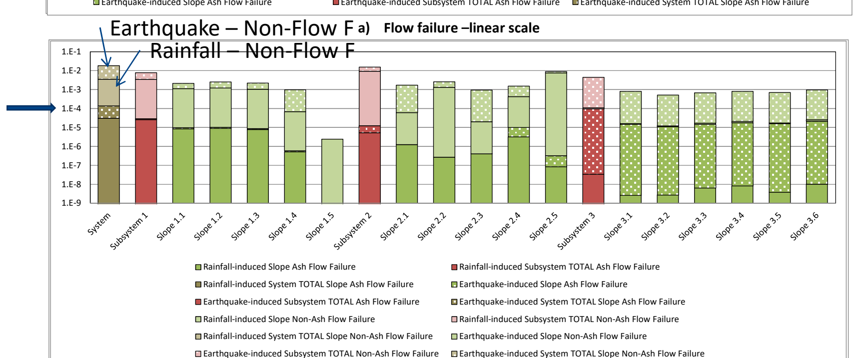
1.4 Static liquefaction & Ash Flow Failure

- Including static liquefaction in RA in many cases is not feasible because of the difficulty in all predicting all potential trigger events.
  - Can include a “preventative” control measure for tailings flow (e.g., berms) in a Base Case RA.
- In example only slope instability, overtopping failure, and piping failure were considered as triggers.
- To estimate the probability of an ash flow failure associated with static liquefaction one must estimate:
  1. the probability of a **trigger event** occurring (Ptrg)
  2. the **conditional probability that static liquefaction occurs given that the trigger event** occurs (Psl/trg)
  3. the **conditional probability that an ash flow failure occurs given static liquefaction** occurs (Pff/sl)

1.4 Rainfall & Earthquake – Slope Failure *(Not actual results)*



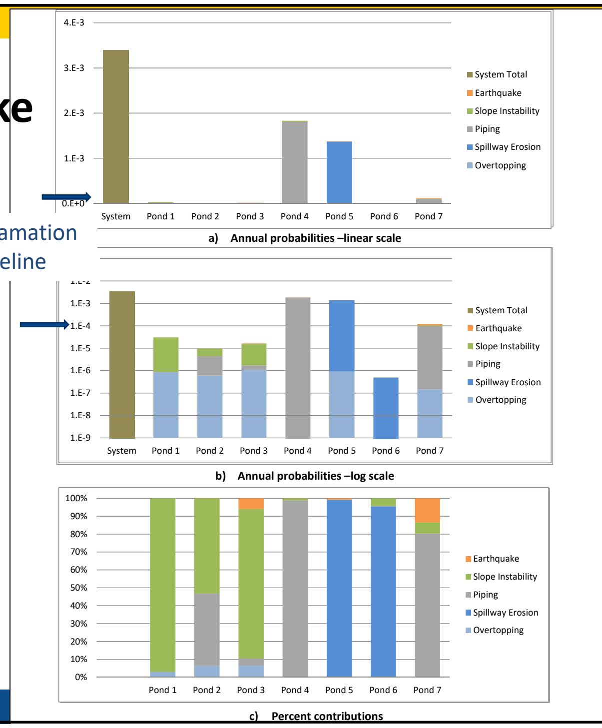
a) Flow failure –linear scale



b) Flow and slope non-flow failure –log scale

1.4 Rainfall & Earthquake – Pond Breach
(Not actual results)

USACE/Reclamation IR/APF Guideline



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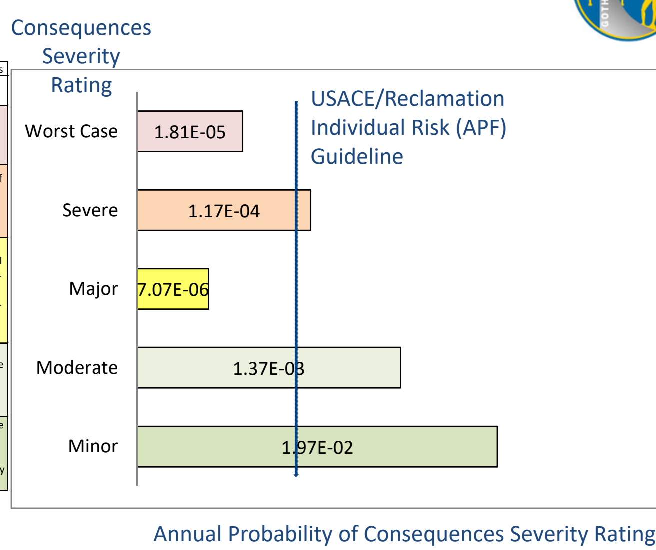
1.4 Enterprise risk consequences severity ratings
(Not actual results)

Severity Scale Rating		Customer Public Image	People Safety	Financial Cash Flow Impact	Assets and Operations Damage to Environment
5	Worst Case	International media attention nearly unanimous public criticism	Fatalities	>$1B	Widespread offsite impacts [1]
4	Severe	National media attention: federal, state officials, and customers publically critical	Permanent Disability	$500 - $1B	Significant quantity of hazardous material discharged: multiple offsite impacts [2]
3	Major	Regional/Local media attention: customers voice concern	Lost Work Time: Hospitalization	$100 - $500M	Significant localized offsite environmental impacts/damage [3], or Significant threat to human health and/or the environment on TVA property only
2	Moderate	Minimal media attention: letters/emails to executive leadership voicing concern	Lost Work Time: Non-Hospitalization	$25 - 100M	Minor localized offsite environmental impacts/damage [4]
1	Minor	No media attention: sparse criticism	First Aid	<$25M	Minor localized offsite environmental impacts/damage effecting TVA property only



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1.4 Some closing thoughts

A central role for risk assessment to demonstrate ALARP as recommended in GISTM

Limited experience exists with applying risk analysis to TSFs
- Many unique challenges
- But the same principle/process applies as for WSFs

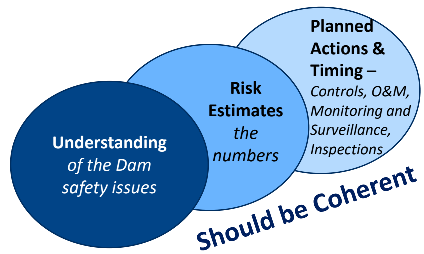
Level of detail should be decision driven

ALARP demonstration - Ultimately a matter of judgment supported by evidence with consideration of the options and uncertainties
- More than just disproportionality
- Confidence is a critical requirement

It's a journey – reduce risk as soon as reasonably practicable

One accepts options, not risks (Fischhoff et al. 1981)

A Coherence test for RAs:



67

Part 1.5 Risk tolerability questions

Risk Assessment Short Course - Session 4.5

68

Part 1.5 Risk tolerability questions

The issue to be addressed ….

Is a line on F-N plot defendable and does it meet the equity criteria?

- ***.. line on F-N plot defendable?… it depends!***
- ***..meet equity criteria.. to a degree!***
  - ***But to what degree? … it depends!***

<u>Perspective and many other things come into play in all aspects of risk and safety</u>

69

1.5 Safety Criterion (1967)

Safety Criterion was postulated as the logical basis for a method of assessing the safety of nuclear reactors by Mr. F.R. Farmer, Director of the Safety and Reliability Directorate of the UK Atomic Energy Authority in Vienna (1967).

Although originally only intended for the assessment of nuclear reactors the concept is so broad that it can be applied to the quantitative evaluation of the acceptability of any risk situation.

Provided of course a wide range of contextual pre-conditions are met

70

1.5 Safety Criterion (1967)

orders of magnitude.

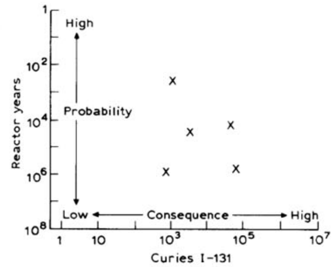
The position of the line will reflect three main considerations:

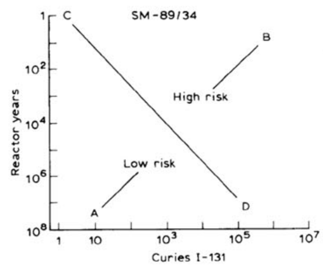
(i) possible public reaction after an accident;

(ii) the estimated number of casualties likely to arise in the population affected by the release;

(iii) the increased risk incurred by any individual.

In order to establish the collective risk (ii) or individual risk (iii), it is necessary to define a population distribution. In view of the growing need for flexibility in reactor siting, the population chosen for the present study is typical of that around suitable industrial sites in or near large cities in the U.K. Details are presented in the Appendix from which a standard site is chosen having a uniform population density of about 13,000 per square mile in all directions from about ½ mile to 10 miles from the site. This site is thus surrounded by 4,000,000 people.





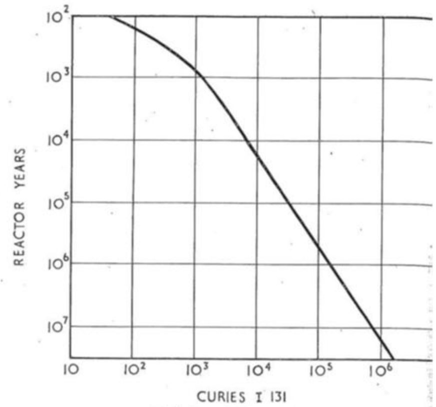


Fig. 12. Proposed release criterion.

1.5 Quantitative statement of Farmer Criterion

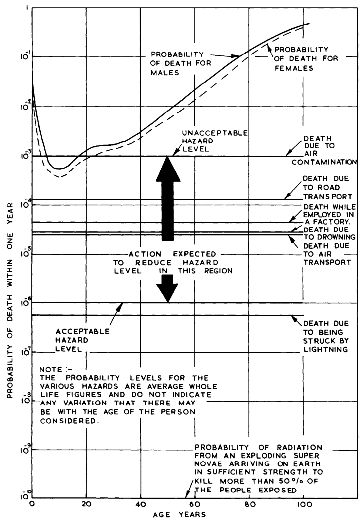
In its very simplest form, the criterion could be stated as follows:

The acceptability of particular risks associated with the activity of interest should be evaluated in quantitative terms and the consequences of the whole spectrum of risks compared with levels of risk that are known to be generally acceptable. If the level of risk is higher than can be accepted then the engineering of the activity must be improved to bring the risk to an acceptable level.

Hazard Control Policy in Britain (Chicken, 1975)

The matter of the assumption of the "general" applying to the "particular" is a questionable assumption given what we know to-day.

1.5 Hazard Control Policy in Britain (up to 1973)



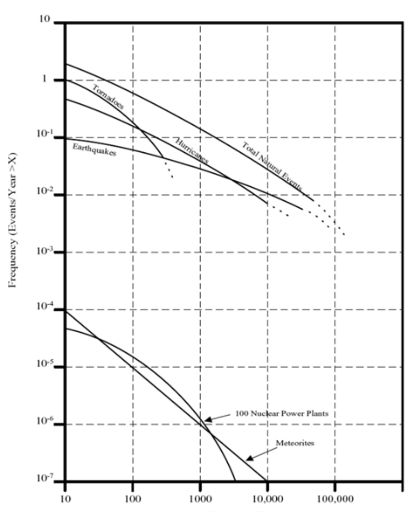
A COMPARISON OF HAZARD LEVELS.

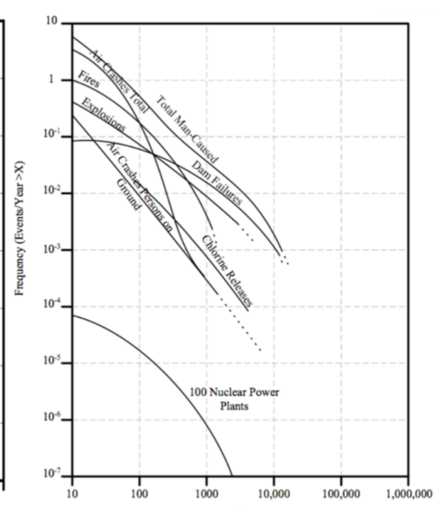
From Fig. 1 it is possible to infer that:

- unacceptable hazards are those which have a probability of causing death within a year greater than 10^{-3}
- acceptable hazards are those with a probability of death within a year of less than 10^{-6}
- if the hazard has a probability of between 10^{-3} and 10^{-6}, then it is expected that some steps would be taken to reduce the hazard to an acceptable level.

73

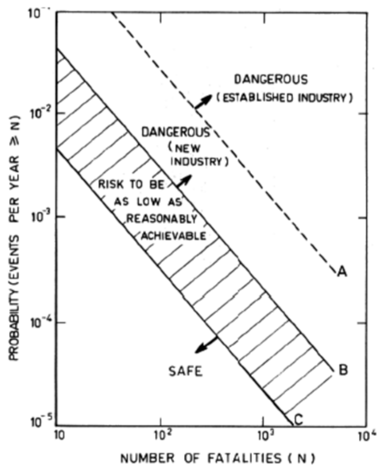
1.5 Reactor safety study (USA, 1975)



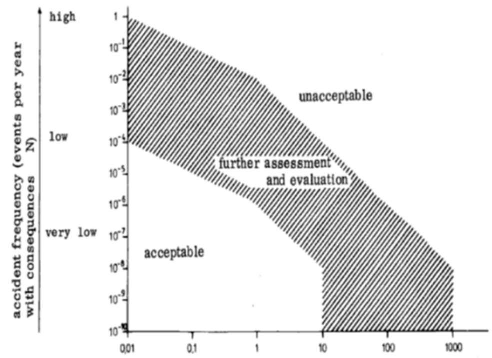


74

1.5 Generalised criteria for other industries



Proposed criteria for dangerous industries based on UK and USA nuclear safety (Australia 1978)



Quantitative scale for damage to public health (in equivalent fatalities)

Evaluation diagram for the evaluation of group risks

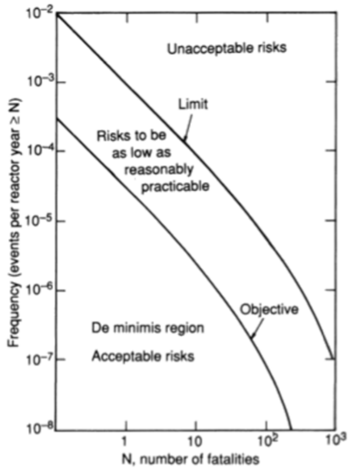
Criteria for Risk related to Dangerous Goods (Netherlands 1979)

1.5 Sizewell B Nuclear Inquiry (UK, 1986)

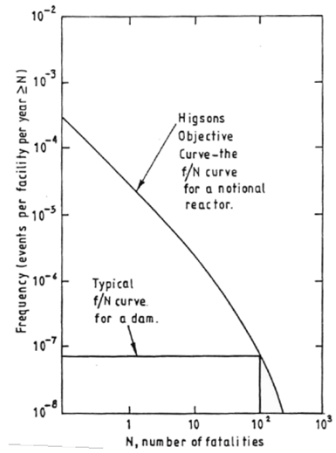
2.98 Many opinions on tolerable risk were put in evidence. There was no authoritative guidance from the Government or Parliament on what a level of tolerable risk from a new nuclear power station might be, nor on how it should be determined [36.84].

2.99 In the absence of authoritative guidance, I have had to reach a judgment on the basis of the relevant evidence from the CEGB and other parties. I conclude that a level of individual risk of death of the order of once in a million years is likely to be broadly tolerable if justified by associated benefits. On this basis, the CEGB's target of restricting the probability of an uncontrolled release of radioactive materials to once in a million years, and its targets for design basis accidents, are reasonable [36.85].

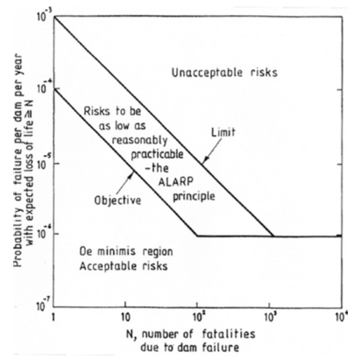
1.5 From reactors to dams....



Proposed Nuclear Safety Assessment Criteria (Higson 1990)

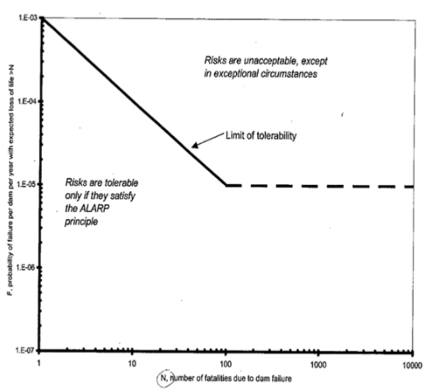


ANCOLD (1994)

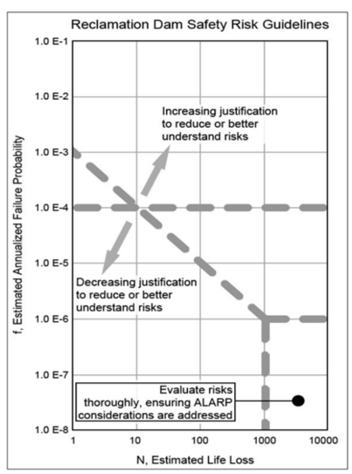


Fell and Hartford (1997)

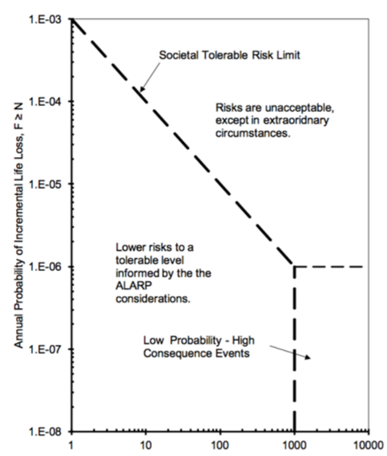
1.5 Societal criteria for dams



ANCOLD (2003)



USBR (2011)

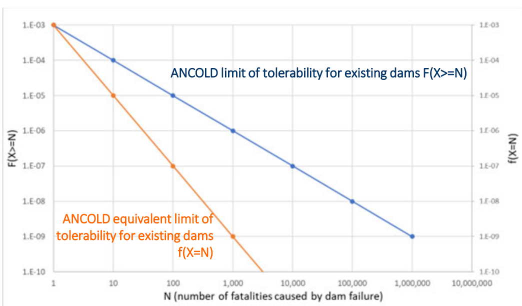


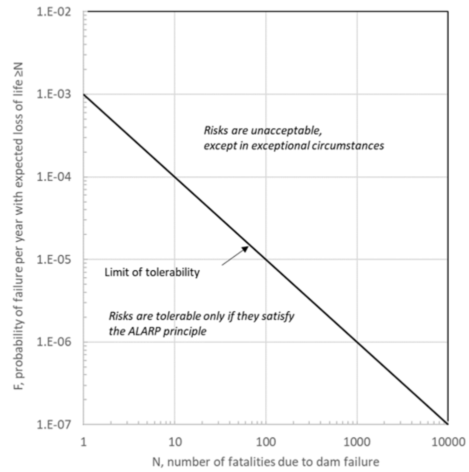
USACE (2014)

1.5 Societal criteria for dams cont.

Basic mathematics of F-N and f-N plots

- ANCOLD (2022) tolerability line for existing dams, F (X≥N) $= (\frac{1}{N}) \times 10^{-3}$, complementary cumulative distribution function
- Equivalent probability distribution function f(X=N) $= (\frac{1}{N^2}) \times 10^{-3}$, negative derivation of complementary cumulative distribution F(N)





ANCOLD (2022)

1.5 What is risk neutral position?

- **FN ≠ *fN***

fN is very different to FN

- FN line with a slope of -1 in log-log space represents the magnitude of risk aversion
- fN slope of minus one presents a risk neutral position where f(N) x N = f(N-1)x(N-1) = 1 x 10-3
- FN with a present a risk averse position with fN slope of minus two
- One debate in the dams industry is which approach satisfies the equity principle of everyone's safety being treated fairly?
- **But perhaps this is the wrong debate! – Unless the objective is to base the decision on a risk curve – and replace a deterministic standard with a risk standard**
  - **to the exclusion of a case-by case analytic-deliberative approach within a democratic environment.**

1.5 Is risk tolerability defendable?

- Has been used in various industries for over fifty years
- Useful tool in decision making and prioritization
- After the event, it is difficult to argue that the realised loss of life was tolerable or acceptable
- If associated with the background "natural risk" the tolerability criteria vary significantly
- Not recognized in legal frameworks
- Consequence assessments don't provide X>=N but simply N (inconsistency with FN)
- Is the risk averse appropriate given our experience and background risks?
- Tolerability criteria ignore the benefit of the risk being present.
- Requires full quantification of probability and consequence of failure.

81

1.5 Outline

Part A: What are we talking about?

- Evaluation - To judge the significance of "something":
  - Need to be clear about what "something" is
    - Not so simple in the domain of risk analysis in any context
    - Even more difficult in the domain of **<u>risk evaluation in the safety context</u>**

Part B What does risk evaluation entail?

- Dimensions of risk evaluation
  - In the general safety context
  - In the context of the safety of dams
- Principles or Criteria?
  - What type?
  - Who sets them?
  - How are they set?

82

1.5 ICMM on Risk Evaluation (ICMM, 2019)

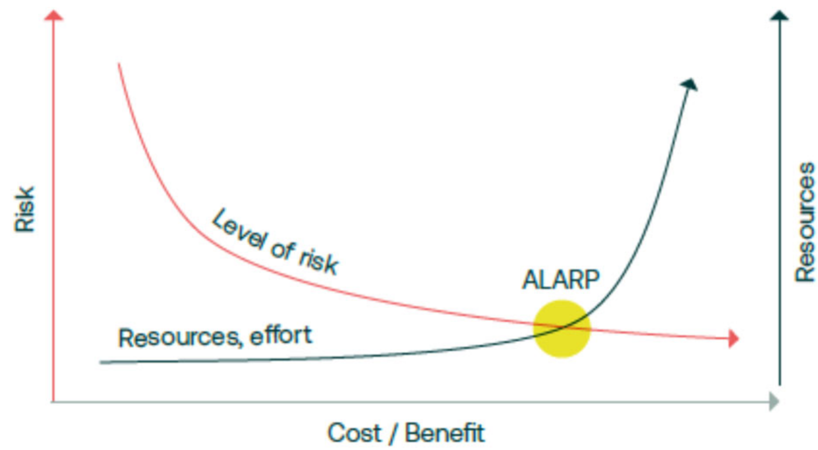
Risk evaluation compares the outcomes of risk analysis for existing conditions to determine if risks are within acceptable limits, whether present risk measures and controls are adequate, and what additional alternative risk reduction measures could be considered. The process typically considers the following, among other aspects: robustness of design, past and future performance monitoring, site context, and practicality of any remediation considered. Guidelines from regulatory agencies, governing bodies, other industries associated with tailings facility safety, and corporate governance should all be reviewed to determine what risks are within normal operating limits. Understanding environmental, social, cultural, ethical, political, and legal considerations should also be included in risk evaluation. The team typically considers risk mitigation alternatives at this stage. The outcome of the risk assessment includes recommendations for actions deemed justified by the team.

1.5 ICMM ALARP

ICMM has its own interpretation of ALARP:

- *As low as reasonably practicable (ALARP): ALARP requires that all reasonable measures be taken* ***with respect to 'tolerable' or acceptable risks*** *to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit. [based on the definition provided in the Standard]*
- *For those risks that cannot be eliminated or avoided, a key concept in risk-informed decision-making is reducing identified risks (likelihood and/or consequence) to levels that are ALARP. As defined in the Standard, ALARP requires that all reasonable measures be taken with respect to 'tolerable' or acceptable risks to reduce them even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit.*

1.5 ICMM "ALARP Calculation"



1.5 But what if….?

…. all of the stakeholders do not see Tolerability of Risk and ALARP world through the eyes of ICMM or ICOLD or its national Committees or any organization championing the probabilistic approach

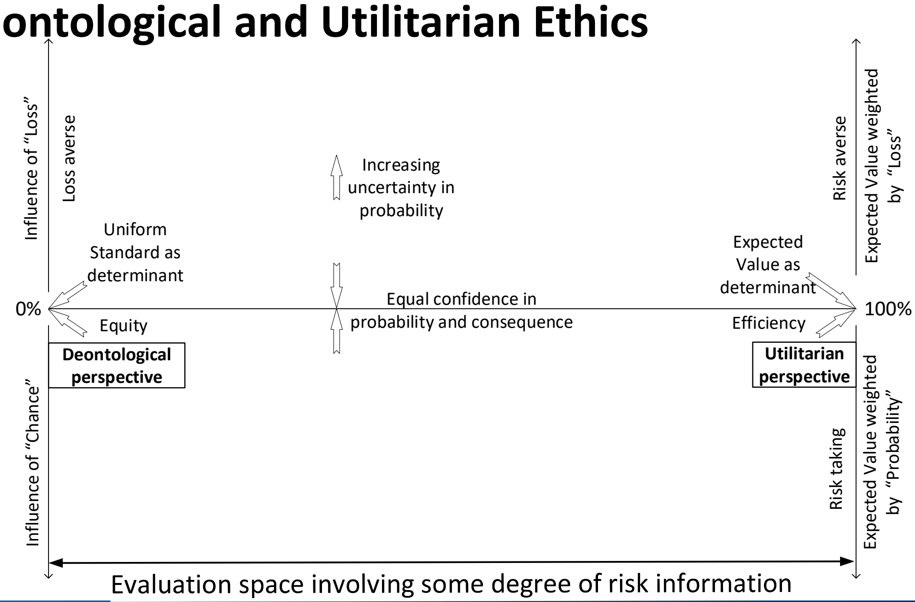
1.5 Ethics

The arguments on which decisions especially those involving the probability of death are made are rooted in ethical principles:

- Deontology - includes the ethical theories of Kant (1788)
  - The precautionary principle can be called deontological, if formulated as a deontological type of principle like; one should not do anything, or expose anyone to risk, if one does not have enough knowledge to make an informed decision to do otherwise.
- Utilitarianism - Economists and philosophers Bentham (1789) and Mill (1861)
  - Decisions made on the principle of utilitarianism should bring the *"maximum amount of happiness"*

… often considered to be mutually incompatible

1.5 Deontological and Utilitarian Ethics



1.5 Risk Evaluation …..2000's forward

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- Hxurshdq Hqylurqphqw Djhqf|
  - Odvw grzqordghg Dsulo4< 5356

Wkh surfhvv ri ghwhuplqlqj wkh ydoxh0edvhg frpsrqhqw ri pdnlqj d mxgjphqw rq ulvn

- Uhqq/ R1 +533;, Ulvn Jryhuqdqfh1 Hduwkvfdq

1.5 Issue 1: Relationship between risk and safe

In many technical contexts safety is defined as the antonym of risk

- Safe = 1-Risk

But is Safety/Safe simply the antonym of Risk in a wider societal context

- If yes, then discussion about safety can be carried out in terms of risk

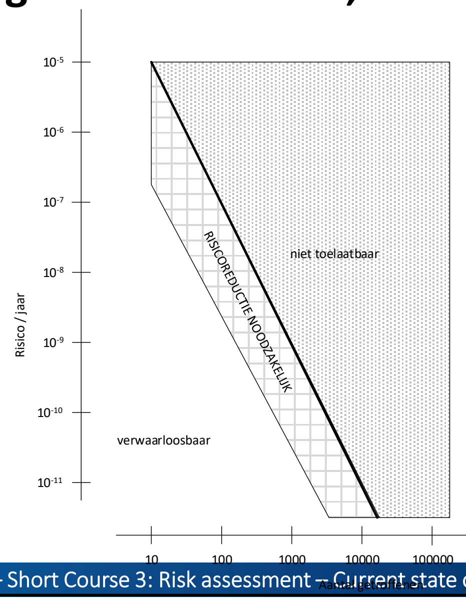
However, in common usage, "safe" is often considered to be "free from harm or risk"

None of this is "settled" in the wider societal sense

- **The fact is that public may not consider that risk provides an appropriate way to characterize the state of safety.**

The relationship between risk and safety frames how judgements concerning the significance of risk influence safety decisions.

1.5 VROM (NL), Omgaan met Risico's, 1989



1.5 It has been shown that…

In particular situations

- Graphical risk criteria can be established for safety assessment
- Societies as a whole can have confidence in safety decisions based on risk assessments

1.5 Information and perspectives

Steps towards generalizing the particular

93

1.5 The importance of words

Probability, chance, odds and likelihood are primary examples where precise definition can be important.

- In the "normal" use of language these words are used as synonyms.
- In mathematics they have precise and distinct definitions.

Unfortunately, these exact definitions present decision makers and those who philosophize about risk with some serious problems.

Probability can be defined as the number of a particular outcome (often called success) divided by the total number of tries, if the number of tries is infinite.

- In the real world the number of tries cannot be infinite.

94

1.5 Inevitability of accidents as frequencies

If the particular outcome is an accident, if one looks carefully enough, no accident is really the same, nor are the circumstances.

More often than not, the "probability" is really a frequency.

- It is the number of occurrences in a certain timeframe, usually a year.
- Even if events do not occur every year, the cumulative number over a longer period can rise to a number above 1, which violates the mathematical rule about probability that it is a number between 0 and 1 by definition.

When a frequency is nonzero the relevant question is no longer whether the event can happen, but when it will happen, making the probability equal to 1, thus fulfilling Murphy's law.

95

1.5 Subjective and Intersubjective probability

Probability also has gained extended meaning beyond the mathematical definition.

It can also mean the subjective estimate of a chance given the information available to the assessor

Risk and probability can even be defined as a social construct

- But in safety, even inter-subjective agreements between "experts" on subjective probabilities may not be sufficient in the context of "safe enough" in the public domain.

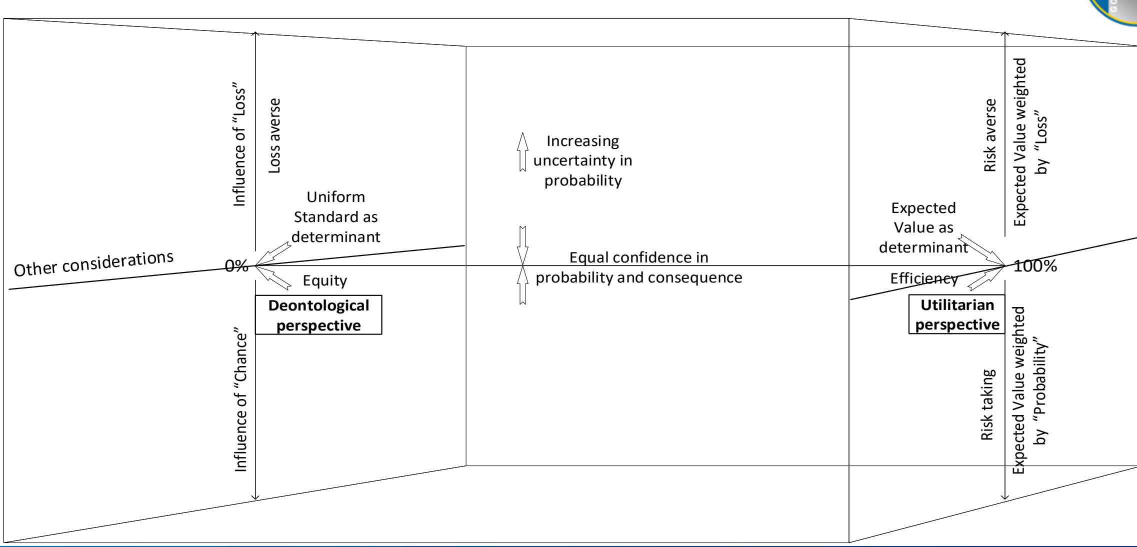
96

1.5 A final word…on the meanings of the words

All definitions by means other than mathematical formulae tend to be imprecise and often circular, such as the definition that probability is the likelihood, or chance.

For decision makers the philosophy around terminology may not be exciting, but it is important to know whether any number or wordy expression about chance is a probability, a frequency or whether it has any such meaning at all.

1.5 Risk evaluation space



1.5 So why not use available risk criteria for dams?

Will be covered in the next session

- Along with considerations concerning what risk evaluators need to consider

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99

Part 1.6 Steps in risk assessment

Risk Assessment Short Course - Session 4.5

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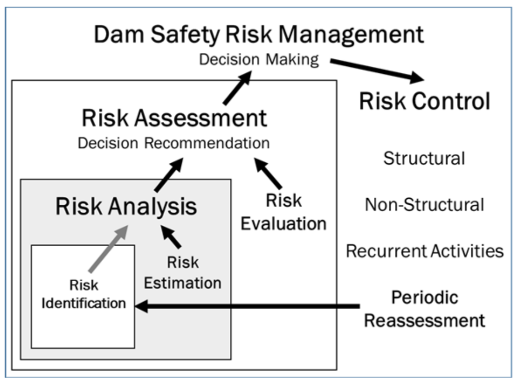
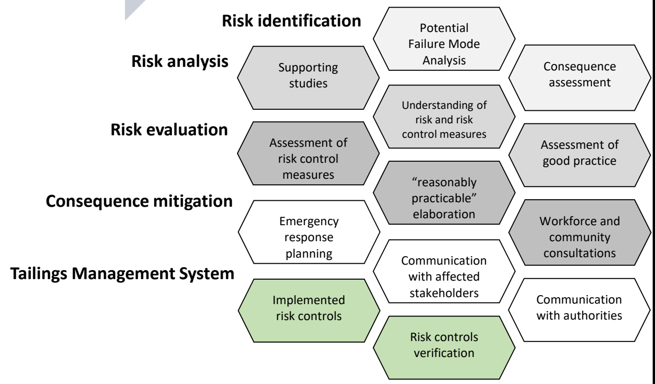
100

Part 1.6 Steps in risk assessment





1.6 What is covered in current guidelines

B130 (2005)

- Comparison of RA practices from numerous countries (2005)
- Outline of RA process including identification, analysis and evaluation
- Current applications (2005)

B194 (2022)

- Overview of risk assessment and management for tailings dams, aligned with terminology and principles of B130

ANCOLD (2022)

- Focus on quantitative risk analyses and risk tolerability principles
- Provides guide for risk assessment planning

1.6 What is not covered in current guidelines

- Linking risk assessment with Tailings Management System
- Linking risk assessment with monitoring and surveillance
- Presentation of basic legal requirements
- Decision making process
- What can be considered as reasonably practicable

103

Part 2 Risk Identification

Part 2	Risk Identification	Presenter
2.1	**Piping assessment - owner's practice**	**Dom**
2.2	**Dam description and definition of problem - potential piping through the dam body**	**Ryan**
2.3	**Group activity 1 - Development of piping failure mode - event tree, fault tree, bowtie**	
2.4	**Identification of risk controls**	**Jiri**

104

Part 2.1 – Piping assessment - owner's practice

2.1 Bureau of Reclamation overview

- An agency of the U.S. Department of the Interior
- 338 reservoirs with a total storage capacity of 173 billion m^3
- Second largest producer of hydropower in U.S.
  - 53 powerplants, annual average of 40 billion kilowatt-hours
  - Primary mission is water supply
- Self-regulated and self-insured

2.1 Disclaimer #1

Reclamation does not operate any tailings dams

107

2.1 Disclaimer #2

The presenter does not have any professional experience with tailings dams, either as an engineer or as a risk analyst

108

2.1 Disclaimer #3

Neither the presenter nor the Bureau of Reclamation are recommending or suggesting that you use the approaches outlined in this presentation

The content of this presentation is "for information only"

109

2.1 Typical Reclamation embankment dam

- Built between 1930 and 1970
- Well constructed, but compacted dry of optimum
- Zoned, but with no designed filter
- Impervious core composed of low to moderate plasticity soils
- Well maintained
- Lightly instrumented

110

2.1 Notable incidents and accidents

- Fontenelle Dam, 1965
- Teton Dam, 1976
- A.V. Watkins Dam, 2006

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111

2.1 Risk management strategy

Dam Safety Office

- Functions as an independent internal “regulator”
- Mission: *To ensure Reclamation dams do not present unreasonable risk to people, property, and the environment*

Risk informed decision making

- Likelihood of future adverse performance must be taken into account, among other things, when making spending decisions
- Not just looking for design deficiencies (→ standards based approach)

Comprehensive Reviews

- Every 8 years regardless of the estimated risk

Performance monitoring, inspections, maintenance, higher level studies...

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112

2.1 Outline of Comprehensive Review process

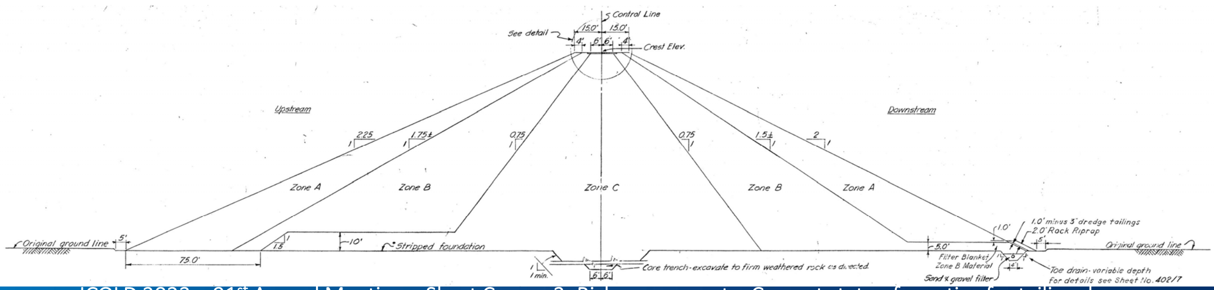
- Review design and construction information
- Review previous analyses and investigations
- Review current performance and condition
- Identify key susceptibilities
- Develop potential failure modes
- Estimate failure probabilities (QRA)
- Interpret the risk estimates with respect to agency guidelines
- Develop a compelling written argument (dam safety case) in favor of/against action to reduce or better understand the risk at present time

2.1 Example dam

Large reservoir retained by a concrete gravity dam and multiple embankment structures, including the right wing dam

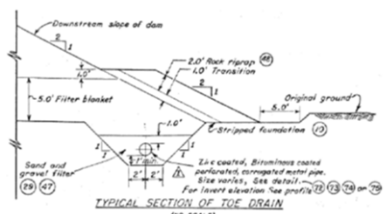
2.1 Example dam

- Constructed in the 1950s using borrow materials sourced from within the reservoir area
- Zoned embankment with sandy/clayey core (Zone C), sandy/gravelly transition zones (Zone B), and dirty rockfill shells (Zone A)
- Structural height up to 45 m, with a length of over 2000 m



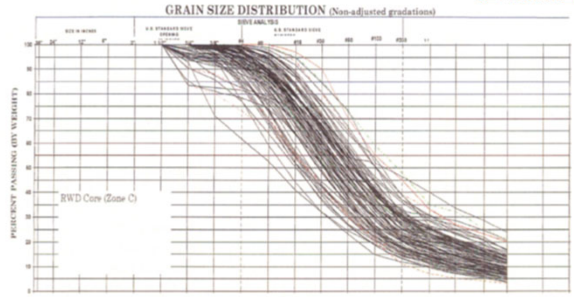
2.1 Construction info

- Constructed entirely on rock (decomposed granite)
- Very thick lifts (up to 3.5 m) used for outer zones
- 15-30 cm lifts + sheepsfoot roller used for much of Zone C, but 45 cm lifts + rubber tire roller used in some areas
- Zones B and C are generally filter compatible, but not in all areas
- 2000 m long toe drain



2.1 Earth materials info

- Standard penetration testing (SPTs) and Becker penetration testing (BPTs) of downstream zones
- Gradation samples from test pits and borrow areas
- Observation of Zone C core during upper embankment filter installation
- Motivated by hydrologic internal erosion concerns



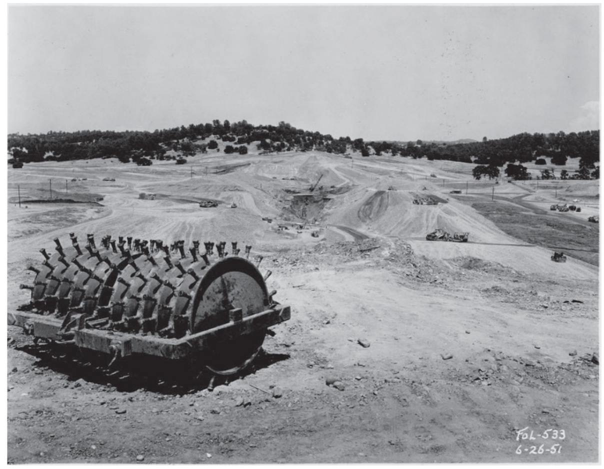
2.1 Performance info

- Toe drain appears to move sediment when flushed out by large rainfall events
  - Source of the sediment cannot be determined due to length

- Embankment piezometers are responsive to reservoir but do not show any abrupt changes in behavior
- Embankment measurement points do not show any recent settlement
- One area of relatively minor seepage along the toe of the dam
  - Later discovered to be the site of an abandoned CMP conduit

2.1 Factors suggesting that internal erosion of the embankment may be a critical PFM

- Stripping to rock below core and outer zones (no realistic potential for foundation internal erosion)
- Weathered granite foundation (no open joints or voids)
- Variability in embankment placement techniques
- Muddy flows in toe drain

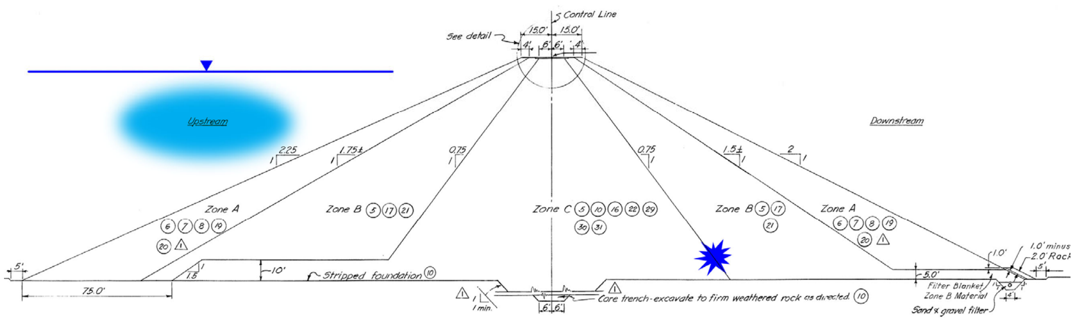


2.1 Factors suggesting that backward erosion (piping) may be the critical mechanism

- Low plasticity core
- Potential for filter incompatibility
- Some evidence of poorly compacted Zone C material
- No evidence of cracking when the upper Zone C was exposed
- No significant differential settlement since construction
- No evidence of other flaws

2.1 Where is the PFM likely to initiate?

- Likely near the maximum section, where the driving head is greatest
- Likely along the lower portion of the Zone B/C interface, where the differential head/local gradient could be highest



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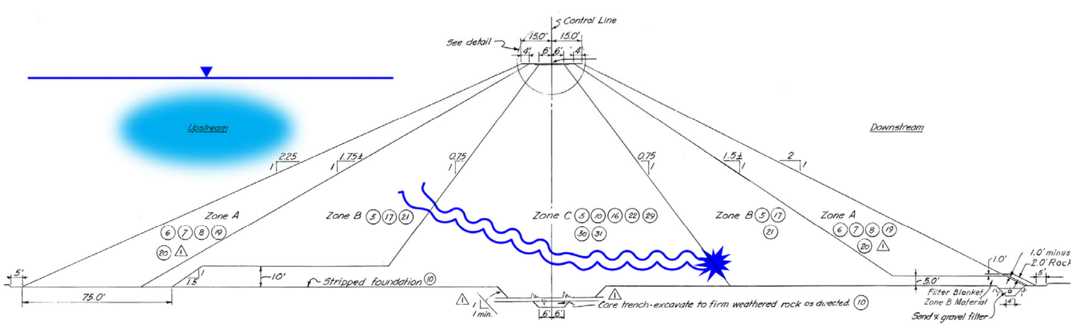
121

2.1 How would the PFM likely progress?

- By working upstream (without collapse) in the direction of the gradient
- By eventually connecting up with the more pervious upstream shell, resulting in more direct access to reservoir water



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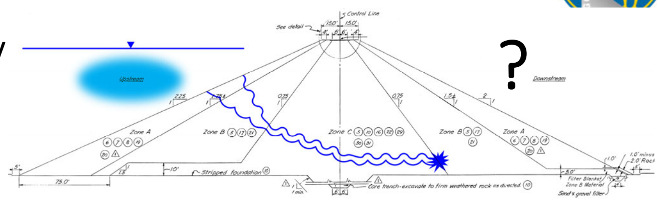
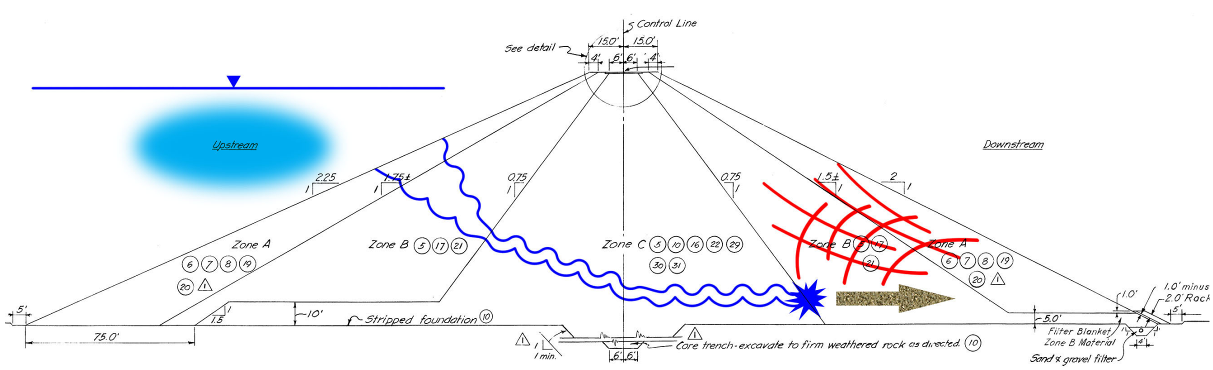
122

2.1 What is the most plausible breach mechanism?



- An upstream sinkhole is unlikely to compromise the crest
- The unfiltered exit is fairly deep within the dam, so gross enlargement (tunnel formation) is not the most likely breach mechanism
  - No direct access for reservoir water to downstream face
- The downstream shell is relatively pervious, so a large-scale stability failure or static liquefaction are unlikely
- The most plausible breach mechanism for this scenario is sloughing (i.e., progressive slope failure)

2.1 Develop a sketch of the PFM



2.1 Develop a PFM description

As the reservoir reaches a critical elevation, internal erosion of the Zone C core initiates by backward erosion piping, near the maximum section, along the lower third of the Zone C to Zone B interface. Eroded materials are transported through a continuous coarse layer of Zone B material and into the Zone A, which serves as a repository or as a path to the toe drain. The fines content of the Zone C is high enough for a roof to be maintained, and internal erosion progresses because the upstream Zone B does not provide a sufficient source of crack stoppers (at the elevation where it is intercepted) and because there are no flow limiting features present. Due to the ongoing issues with the toe drain, the problem is not detected in a timely manner, and intervention fails because an effective downstream filter cannot be constructed or because the reservoir is not drawn down quickly enough. As the upstream Zone A begins to implode over the nascent sinkhole, flows intensify, pore pressures within the downstream shell increase, and seepage breaks out onto the face of the dam. The downstream slope begins to unravel, sloughing progresses upslope, and the crest of the dam is undermined resulting in negative freeboard and an uncontrolled release of the reservoir.

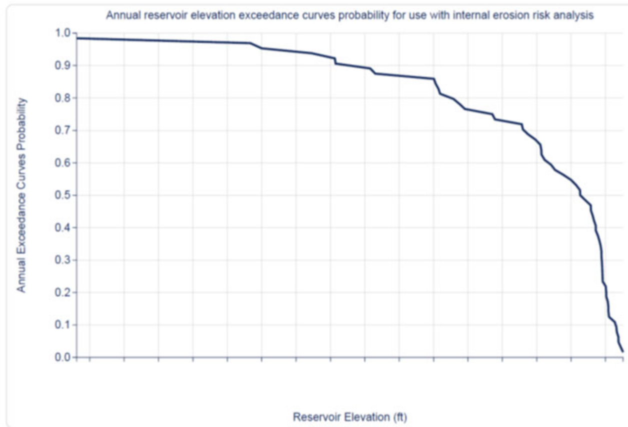
2.1 Discretize the PFM into individual events whose probabilities can be estimated

"Standard" 8-event decomposition used by Reclamation

- Event 1: Critical reservoir threshold exceeded in a given year
- Event 2: Internal erosion initiates
- Event 3: An unfiltered exit exists (continuation)
- Event 4: Erosion pathway remains open (progression #1)
- Event 5: No flow-limiting ability (progression #2)
- Event 6: No self-healing ability (progression #3)
- Event 7: Intervention fails
- Event 8: A breach occurs

2.1 How individual event probabilities are estimated

- Using frequency data (e.g., for the probability that the reservoir will exceed the critical elevation in a given year)
- Using subjective probability estimation ("expert elicitation")



127

2.1 How does Reclamation approach subjective probability estimation?

- Start with an *uninformed prior* probability
  - 0.5 for most events
  - ~1E-3 for the initiation event – see Engemoen 2017
  - Use of a 0.5 uninformed prior for the initiation event would imply a much higher number of internal erosion incidents than are actually observed
- Consider more likely/less likely factors for each event
- Based on the strength and significance of the more/less likely factors, adjust the uninformed prior up or down to obtain a *best estimate* (qualitative Bayesian inference)

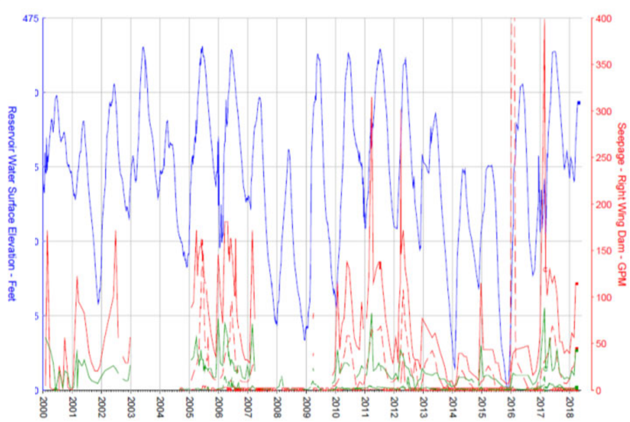
128

2.1 Disclaimer #4

- Neither the presenter nor the Bureau of Reclamation are recommending or suggesting that you use an uninformed prior of 1E-3 for the initiation event
- A base rate of approximately 1E-3 internal erosion initiation events per dam year may be appropriate for our inventory but may not be appropriate for other types of dams

2.1 Trigger event: key considerations

- Single threshold elevation usually selected for static PFMs
- Selecting a pool that is not frequently experienced could result in an artificially low risk estimate
- Are there changes in seepage at certain reservoir elevations?



2.1 Initiation event: key *more likely* factors considered for the example dam

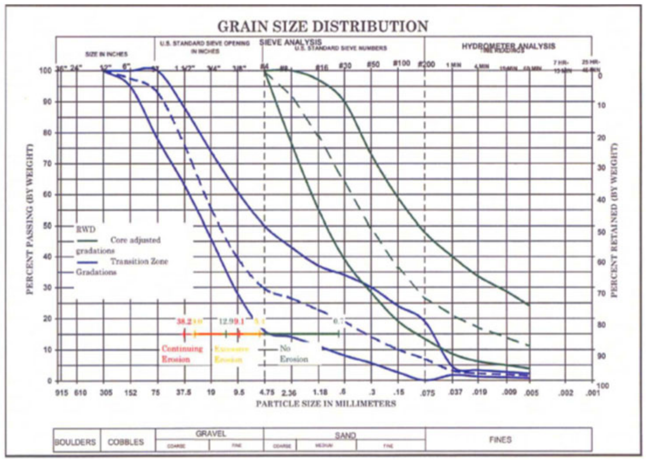
- Non-plastic Zone C may be erodible under the estimated 0.5-1.0 average gradient (or under potentially higher exit gradients)
- Embankment was compacted dry of optimum, making it more erodible
- Apparent pattern of increasing drain flows over last few years, which could potentially be associated with this PFM
- Use of 45-inch lifts + pneumatic tire roller could have resulted in poor compaction in some areas
- Low BPT blow counts recorded in upper Zone C, suggesting poor compaction near the Zone B interface

2.1 Initiation event: key *less likely* factors considered for the example dam

- Wide Zone C, the majority of which should be well compacted
- Many Zone C density tests performed during construction, with good relative compaction/density indicated
- Excavated Zone C slopes held a 0.75H to 1V cut during the upper embankment filter modification, indicating consistently dense material
- Most SPT blow counts in the range of 30-70, indicating dense material
- Shear wave velocities in the range of 300-500 m/s, increasing with depth
- Zone C gradations do not indicate any potential for internal instability, but with a high enough C_u to suggest erosion resistance

2.1 Unfiltered exit event – how filter criteria come into consideration

- Qualitatively (as a more likely or less likely factor)
- Gradations usually vary across the interface
- Backward erosion initiates at a point of filter incompatibility, so the fact that there is filter compatibility in most areas does not mean p(event) = 0



133

2.1 A roof is sustained – example of how the Fell "toolbox" is used

- Qualitatively
- p(event) would not simply be taken as the roofing probability from the toolbox table
- Rather, the fact that the toolbox suggests, e.g., a 0.9 probability for moist SC would be listed as a more likely factor
- But the potential for areas of coarser material to exist along the seepage path could be listed as a less likely factor

"Fell et al (2008) Table 8.1" – Probability of a soil being able to support a roof

Soil Classification	Percentage Fines	Plasticity of the Fines	Moisture Condition	Likelihood of Supporting a Roof
Clays, sandy clays (CL, CH, CL-CH)	> 50%	Plastic	Moist or saturated	0.9+
ML or MH	>50%	Plastic or non-plastic	Moist or saturated	0.9+
Sandy clays, Gravely clays, (SC, GC)	15% - 50%	Plastic	Moist or Saturated	0.9+
Silty sands, Silty gravels, Silty sandy gravel (SM, GM)	> 15%	Non plastic	Moist Saturated	0.7 to 0.9+ 0.5 to 0.9+
Granular soils with some cohesive fines (SC-SP, SC-SW, GC-GP, GC-GW)	5% to 15%	Plastic	Moist Saturated	0.5 to 1.0 0.2 to 0.5
Granular soils with some non plastic fines (SM-SP, SM-SW, GM-GP, GM-GW)	5% to 15%	Non plastic	Moist Saturated	0.05 to 0.1 0.02 to 0.05
Granular soils, (SP, SW, GP, GW)	< 5%	Non plastic Plastic	Moist and saturated Moist and saturated	0.0001 0.001 to 0.01

Notes: (1) Lower range of probabilities is for poorly compacted materials (i.e. not rolled), and upper bound for well compacted materials.
(2) Cemented materials give higher probabilities than indicated in the table. If soils are cemented, use the category that best describes the particular situation.

134

2.1 Progression events – what kinds of things are considered

- Flow limiting is usually considered only when the source of the seepage is a foundation fracture network, when there is an upstream liner, or when there is an u/s zone that can't be eroded
- Self-healing would be considered if there were a coarser-grained upstream zone with the potential to flow into the active erosion area and stop or slow seepage
  - Examples: Balderhead Dam, Matahina Dam Suorva Dam, Uljua Dam

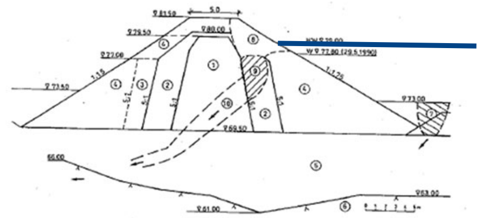


Fig. 3
Cross section of dam failure

(1) Core of glacial till
(2) Filter of sandy gravel
(3) Coarser filter
(4) Supporting rockfill
(5) Glacial till
(6) Weathered bedrock
(7) Crater
(8) Sinkhole
(9) Cement and grouting equipment
(10) Gravel tube

2.1 Intervention fails event

- The ability to detect a problem condition in a timely manner is usually a key consideration
- The ability to quickly draw down the reservoir is usually a key consideration

- For the example dam, the reservoir is large, but there is an auxiliary spillway with an unusually high capacity

2.1 Breach event

- Most plausible breach mechanism is sloughing (progressive slope failure)
- Breach event covers everything between progression and the point where the reservoir is released (not just "after" intervention fails)
- Some PFMs are inherently unlikely to result in a breach
- In this case, the Zone A rockfill is dirty enough to suggest that if water is continuously fed into it, sloughing would be a realistic possibility

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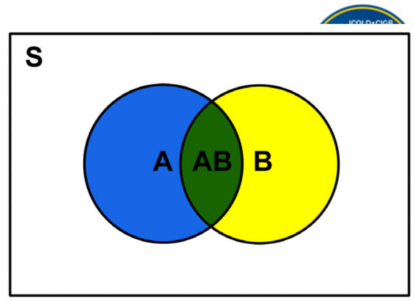
137

2.1 Annualized Failure Probability

- Mathematical model: The probability of failure is the probability of the intersection of the events that make up the PFM
- Annualized Failure Probability or AFP ≡ p(PFM) = p(Event 1 ∩ Event 2 ∩ ... ∩ Event 8)
- Use the conditional probability formula: p(AB) = p(A)*P(B|A)
- If the subjective probability estimates are distributions, Monte Carlo can be run through the formula to obtain an AFP distribution



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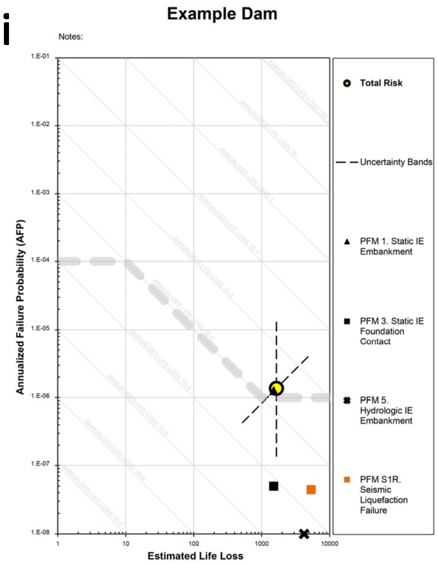
138

2.1 Annualized Failure Probabili

Individual event best estimates

- Event 1: Trigger (0.7)
- Event 2: Initiation (2.2E-3)
- Event 3: Continuation (0.006)
- Event 4: Progression #1 (0.65)
- Event 5: Progression #2 (0.95)
- Event 6: Progression #3 (0.67)
- Event 7: Intervention fails (0.35)
- Event 8: A breach occurs (0.95)

Best estimate AFP = 1.3E-6



2.1 Dam Safety Case

- The numbers are not considered exact
- The numbers may not reflect the actual probability that the dam will fail by this PFM in a given year
- The numbers alone are not used to make the case for action
- The *dam safety case* is a compelling written argument that reconciles the risk estimates with the performance and condition of the dam, discusses the potential impact of uncertainty, and intuitively explains why the recommended course of action is appropriate and makes sense

2.1 Dam safety case paragraph 1

There is a dam safety case for action to reduce or better understand the risks associated with the right wing dam, whose performance is just as vital to reservoir retention as that of the concrete gravity dam. The controlling PFM for this structure is associated with normal (in the sense that they are routinely experienced) operating conditions, and the impervious core of the right wing dam is composed of non-plastic, erodible materials. Sediments are being flushed out of the toe drain by rainfall runoff, which could be evidence of a problem with the toe drain or a even potential failure mode in progress (though this is not currently considered likely), with impacts to the monitoring ability regardless. The downstream population is not only large but located very close to the dam, and life loss in the event of a sudden failure would be catastrophic. The estimated risks are above guidelines, but with low confidence* in the overall portrayal of risk.

2.1 Dam safety case paragraph 2

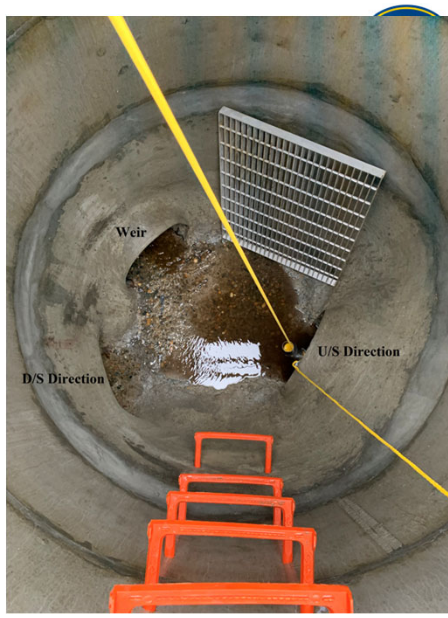
The risks of the controlling PFM (as well as other less significant PFMs) could be significantly reduced through the construction of a full downstream filter (extended to the base of the dam and weighted to prevent against blowout). However, a major structural modification of the wing dam is not justified at this time for several reasons. First, the dam is understood to be in relatively good condition, and a dam safety modification has already been performed to address the critical hydrologic internal erosion PFMs. Second, as noted, confidence in the interpretation of risk is low, and high confidence would be required for another major modification to be recommended. Third, the risks can likely be reduced by some amount without a major structural modification. This is where the ALARP principle* comes into play. A large amount of money has been spent to date on the facility, and in particular to reduce the risks of overtopping failure (previously a controlling PFM for both of the wing dams). Spending hundreds of millions more to address the residual risks would likely move project expenditures beyond the point of ALARP disproportionality.

2.1 Dam safety case paragraph 3

In contrast, the (anticipated) relatively modest expenditure associated with monitoring improvements can be justified not only under ALARP, but also by the greater confidence that the implementation of repairs, more frequent readings, and other physical changes to the monitoring system would result in. As discussed, the ability to detect a failure mode in progress before a seepage breakout occurs would help ensure that the generous spillway discharge capacity can be taken full advantage of. Without any changes to the conditional probabilities of the remaining events, updated *intervention fails* estimates below the current estimate range could result in the risks of the controlling PFMs ending up below guidelines. This, in turn, could allow outstanding recommendation 2007-SOD-J to be considered complete with respect to the wing dams. In addition, performing a Value Engineering study could help ensure that all avenues of monitoring enhancement are explored, and that due attention is paid to the efficiency of the modification. The Area Office has first hand knowledge of some of the issues involved, and their involvement in the process will be essential.

2.1 Recommended action

2018-SOD-A. Develop, evaluate, and design monitoring enhancement options to improve the ability for early detection of an incident.



Part 2.2 Example dam description

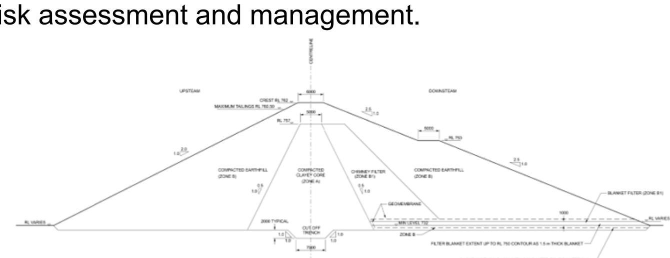
Risk Assessment Short Course - Session 4.5

2.2 Example dam description

Example TSF provided in pre-read documentation.

The facility and level of information and data is representative of TSFs for which owners have asked that a quantified risk profile be developed.

Example facility will be used in several group activities throughout the day to cover the processes within risk assessment and management.



Part 2.3 Group activity 1

2.3 Potential Failure Mode Analysis

Produce a Potential Failure Mode Analysis using suitable tools, such as event trees, fault trees or bow-ties for an **embankment piping failure mode**.

The Potential Failure Mode Analysis should include the **cause and steps to the development of uncontrolled release of stored material**.

Note: It may help to first define the system and sub-system of the TSF relevant to this failure mode.

Part 2.4 Identification of risk controls

2.4 Identification of risk controls

- PFMA formulates a narrative of dam failure
- Opportunity to identify controls to contradict the narrative
- Defense in depth principle (consider everything)
- Assists in decision making (decisions can be made progressively)

Part 3 Risk Analysis

Part 3	Risk Analysis	Presenter
3.1	Estimation of system responses	Malcolm
3.2	Estimation of probability of occurrence	Malcolm
3.3	Group activity 2 - Estimate of failure probability of embankment piping	Ryan

- RA Scoping
  - Session 1
- Risk Identification
  - Session 2
- **Risk Analysis**
  - **Session 3**
- Risk Evaluation
  - Session 4

151

Part 3.1 – Estimation of system responses

Risk Assessment Short Course - Session 4.5

152

3.1 Seven Habits of Highly Effective Dam Risk Assessors

HABIT 1. Commit to the process (Be Proactive)

HABIT 2. Decide on the level of review and investigation needed (Begin with the End in Mind)

HABIT 3. Ensure you have the right information (Put First Things First)

HABIT 4. Ensure good facilitation (Think Win/Win)

HABIT 5. Understand engineering judgement (Seek First to Understand, Then to be Understood)

HABIT 6. Act as a team (Synergize)

HABIT 7. Focus on continuous improvement (Sharpen the Saw)

Dr Malcolm Eddleston (ASDSO Journal of Dam Safety Vol 13 Issue 11, 2015)

153

3.1 Life is complicated and so is Risk Assessment

"The hardest thing in the world to understand is the income tax" - *Albert Einstein*

Things are not always what they appear to be - Look and Think

- If people don't think, they don't learn;
- When people think they learn;
- When you discover something for yourself, you own it.

154

3.1 Risk Analysis Concept

Structured process aimed at estimating probability of failure of the dam or dam components and extent of the consequences of failure

Estimate of risk is not a physical property of the dam but is a mathematical representation of the state of knowledge of the dam and confidence in its future performance

Risk Analysis is a **decompositional process**, which involves:

- Separating the system into its component parts and functions
- Identifying the functional failure mechanisms
- Analysing each part of the failure mechanism in isolation including the **failure** and **consequences** and then
- Recombining all of the parts in accordance with basic physical principles and laws of physics

Outputs are expressed as probability distributions

Goal of risk analysis is quantification of probability and consequences of system failure which is the system risk.

3.1 Questions to be answered by the Risk Analysis Team

What are the hazards? (the potential sources of harm, such as flood or earthquake or human factors, or an internal vulnerability with the potential to initiate a failure mode, such as geological conditions in the foundation);

What can go wrong? (failure modes/scenarios);

What is the **likelihood** that it will go wrong? (loading conditions and system response - frequency/probability);

What are the **consequences** if it does go wrong? (loss of life, dollar losses, incommensurable and intangible impacts);

What are the **risks**? (The combinations of scenario, likelihood and consequences).

3.1 Example of a spatial model of the "system of interest"

- System should include dams in cascade where appropriate
- System is a group of interacting, interrelated and interdependent elements that form the complex as a whole
- Failure means cessation of proper functioning or performance or non-performance of the system as a whole

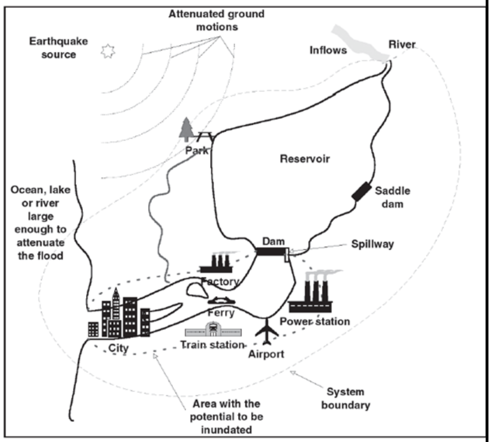
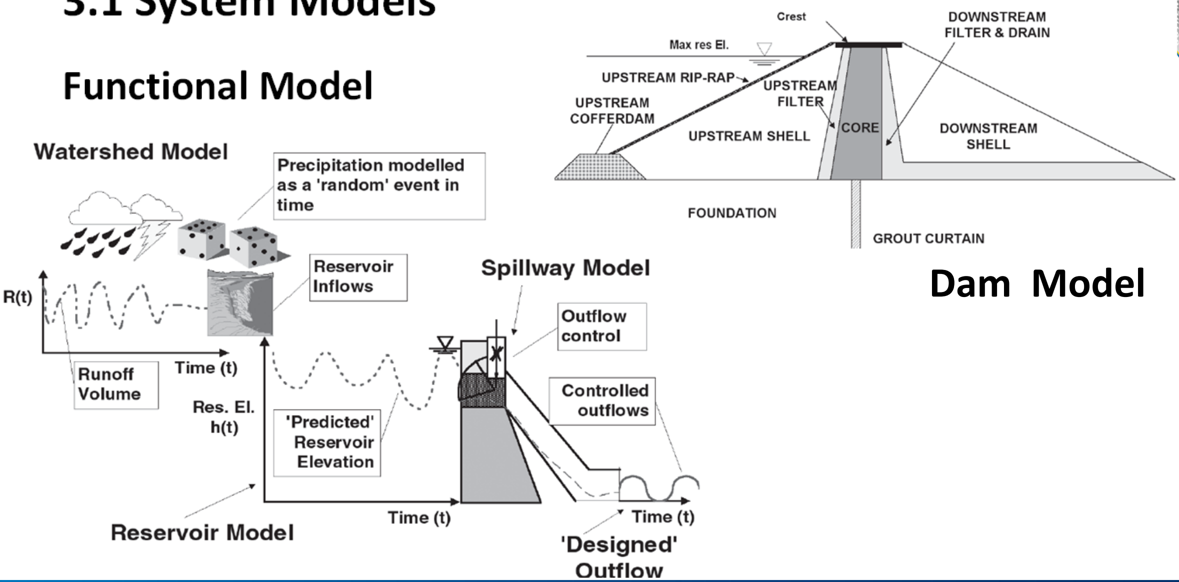


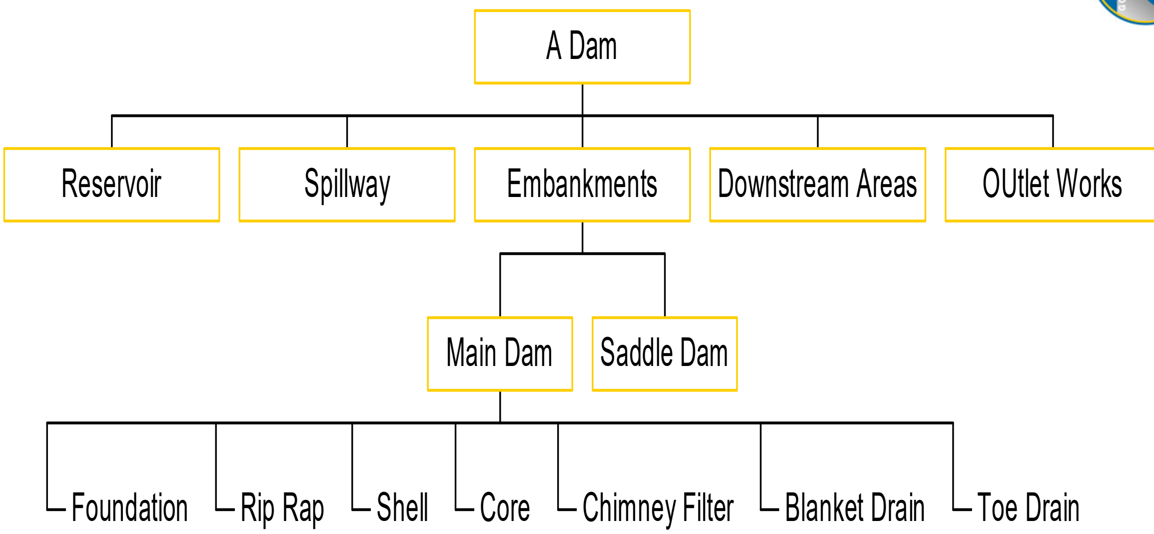
Fig. 3.2
Example of a Spatial Model of the "System of Interest"

3.1 System Models

Functional Model



3.1 Definition of a Dam Sub-System



3.1 Example Component Definition - Spillway

SYSTEM	
EXAMPLE DAM	

SUB SYSTEMS	
1	**Spillway**
2	**Embankment**
3	**Outlet Works**
4	**Reservoir Rim**

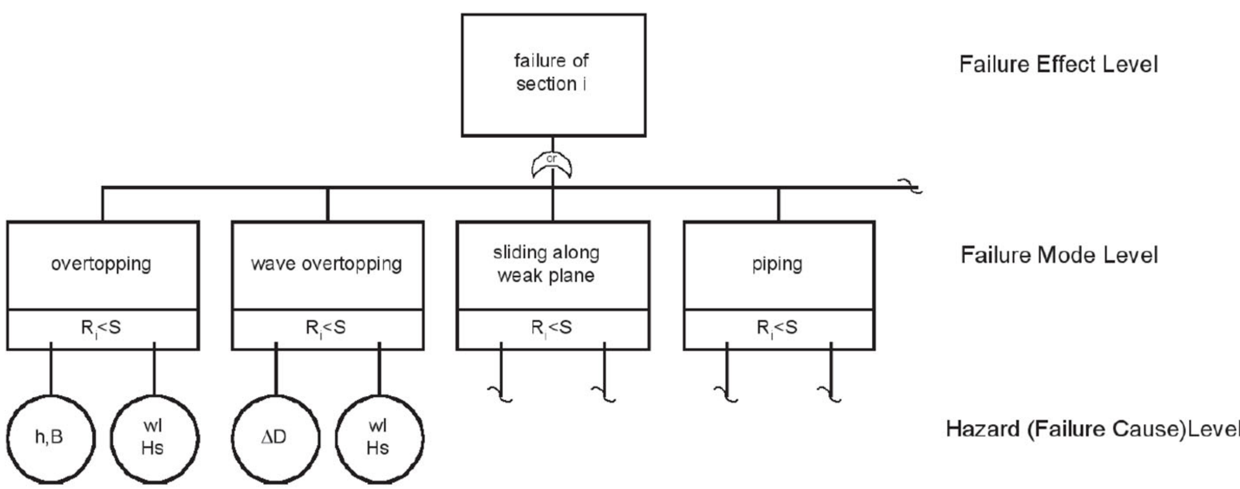
COMPONENTS

1	SPILLWAY					
Components	**Number**	**Sub Components**	**Number**	**Identification Number**	**Primary Function**	**Auxiliary Functions**
Foundation	1	Grout Curtain	1	1.1.1	Seepage Control	
		Rock/Weathered rock Right Bank	2	1.1.2	Structural support	Seepage Control
Retaining Walls	2	Concrete	1	1.2.1	Embankment retaining Flow Channel	
		Reinforcement	2	1.2.2		
		Joints	3	1.2.3		
		Drainage	4	1.2.4		
		Foundation	5	1.2.5		
Ogee	3	Concrete	1	1.3.1	Flow Control	Storage
		Reinforcement	2	1.3.2		
		Joints	3	1.3.3		
		Shear Key	4	1.3.4		
		Drainage	5	1.3.5		
Upstream Apron	4	Concrete	1	1.4.1	Erosion protection	Seepage Control
		Reinforcement	2	1.4.2		
		Joints	3	1.4.3		
Spillway Bridge	5	Deck & Beams	1	1.5.1	Access	
		Bearing Pads	2	1.5.2		
		Pier	3	1.5.3		
		Concrete	4	1.5.4		
		Reinforcement	5	1.5.5		
Chute	6	Floor	1	1.6.1	Flow Control	
		Walls	2	1.6.2		
		Concrete	3	1.6.3		
		Reinforcement	4	1.6.4		
		Joints	5	1.6.5		
		Anchors	6	1.6.6		
		Aeration Slots	7	1.6.7		
		Drainage	8	1.6.8		
Flip Bucket	7	Concrete	1	1.7.1	Energy Dissipation	Erosion Control
		Reinforcement	2	1.7.2		
		Joints	3	1.7.3		
		Anchors	4	1.7.4		
		Splitters	5	1.7.5		
Plunge Pool	8	Upstream Protection	1	1.8.1	Energy Dissipation	Erosion Control
		Rock	2	1.8.2		

3.1 Component Definition Example 2

- Reservoir and reservoir slopes,
- Dam
- Discharge facilities
  - Spillway approach channel
  - Spillway control structure
    - Foundation
    - Drainage system
    - Concrete invert
    - Abutments
    - Piers
    - Radial gates
    - Gate guides
    - Gate hoists
    - Bulkhead gates
    - Gantry crane
    - Control equipment
  - Discharge chute and stilling basin
  - Low level outlet
  - Sediment release facility
- Power or irrigation intakes
- Power conduits or irrigation canals
- Access routes
- Downstream river channel

3.1 Failure Effect, Modes and Hazards Fig 3.5 ICOLD B 130



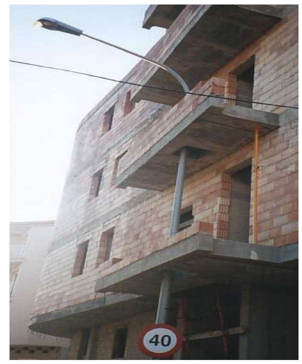
3.1 Winston Churchill

"True Genius resides in the capacity for the evaluation of

uncertain,

hazardous and

conflicting



Information"

3.1 What is a System response

Given a flood or earthquake, the conditional probability of dam failure is an example of the confidence in an outcome meaning of probability. The critical points about this type of probability are:

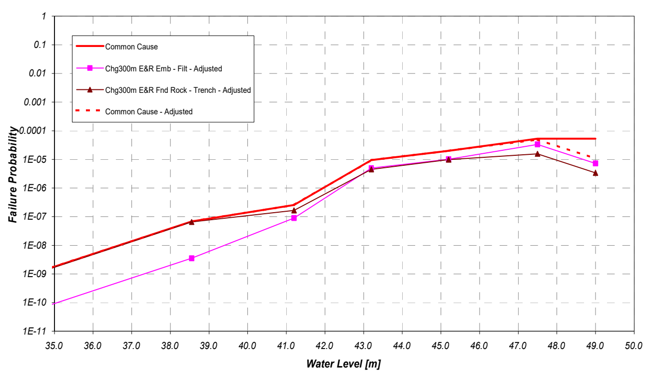
- Estimated probability is the analysis team's degree of confidence in an outcome;
- The degree of confidence is based on the evidence; that is, the knowledge and information available at the time;
- Estimated probability may change as knowledge and information changes.

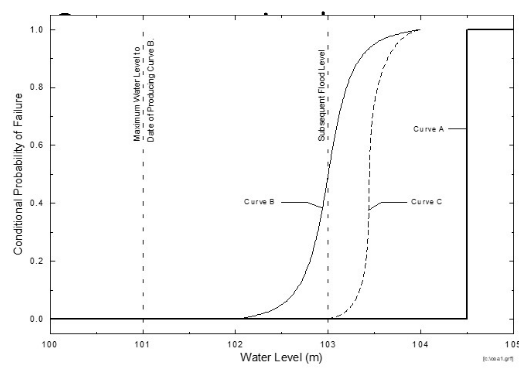
This type of probability is not a property of the dam, but a reflection of the best understanding of the analysis team, given the available knowledge and data concerning the question at issue (Kaplan, 1997).

The understanding of the confidence in an outcome type of probability can be illustrated by reference to the "made-up" example below.

3.1 What is a System response

The conditional probability of dam failure between zero and 1.0 of allied loads and concurrent conditions (fragility curve)?





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165

3.1 Concrete Gravity Dam System components

Component	Sub-Component	Function
Gravity Section	Mass Concrete Waterstop Shear keys Concrete Drains	Stability Prevent seepage at joints Block interlock stability Uplift control
Foundation	Rock Grout curtain Foundation drains	Stability Shear Seepage control Uplift control

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166

3.1 Disaggregation for system response analysis

Disaggregation of failure processes into their elements is an aid to judgement in the assignment of estimated probabilities for System response curves

In order to disaggregate, it is necessary to define the logic of the failure mechanism. The usual tools for doing this are event trees and fault trees.

Ensure that the analysis process is logically correct and used for communicating an understanding of the mechanism.

Normally an event or fault tree is produced for each failure mode, unless the failure process is unusually direct and simple.

Where appropriate, allow for the possibility that intervention may arrest and control the failure mechanism. In such cases, event trees need branches to examine the likelihood of a successful intervention.

Wherever practicable, it is useful to have the outcome of traditional deterministic analyses as a guide to the selection of probability values

3.1 Concrete Gravity Dam Example of Disaggregation

Waterstop Fails
- Loss of seepage control at joints
- Seepage flow into concrete drains

Loss of Uplift Control
- Drains overwhelmed
- Horizontal Joint Pressurisation

Critical Reservoir load
- Uplift change initiates cracking
- Cracking results in overturning or sliding instability

Concrete Dam failure
- Adjacent Blocks unstable
- Shear keys inadequate toi transfer load
- Failure mechanism formed
- Dam Failure

Foundation seepage mineralisation
- Mineralisation of foundation water
- Joints into drains blocked

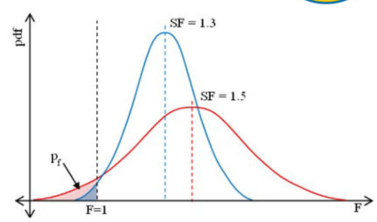
Loss of Uplift Control
- Foundation grouting ineffective
- Drains unable to relieve pressure
- Foundation joints pressurised

Critical Reservoir load
- Uplift change initiates cracking
- Cracking results in overturning or sliding instability in foundation

Concrete dam Foundation Failure
- Adjacent gravity blocks unstable
- Failure Mechanism formed
- Dam Failure

3.1 Analysis Methods

- Structural Reliability Analysis – Reliability theory Demand and Capacity using Monte Carlo simulation. Be aware of the need to truncate unbounded probability density functions.
- Human Reliability Analysis – human reliability
- Component performance data bases – Appropriate for mechanical electrical systems
- Historic Performance of Dams – Not generally used but can aid in judgement: e.g., overtopping.
- Expert Engineering Judgement – Be aware of biases and use as much probabilistic and/or traditional analysis as practicable



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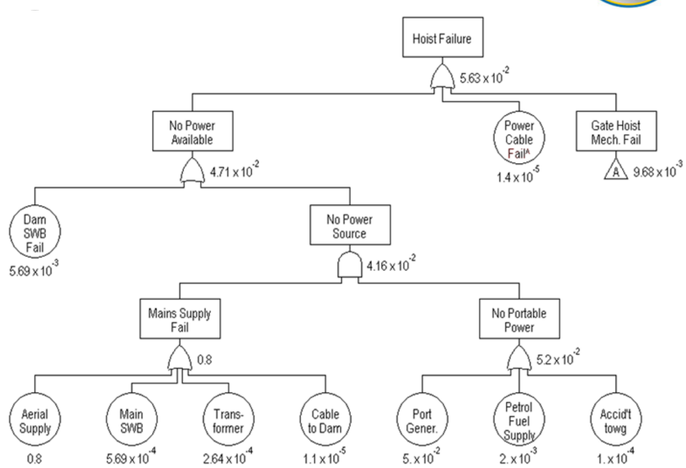
169

3.1 Analysis Methods Contd.

Spillway Gate Reliability

- Makes use of the methods described above.
- Barneich not suitable but rather use component failure rate data
- Follows strict laws for development e.g.
  - Top down development
  - Immediate cause
  - No miracle rule
  - Common cause of failure - Switchboard
  - Common mode of failure - Bearings



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170

3.1 Analysis Methods Contd.

- Probability Mapping Schemes - conditional probabilities are related to verbal descriptors of likelihood.
- Questionable for very low probabilities but can be useful in event trees. Be aware of verbal descriptors having different meaning for people
- Database is not limited to an individual's experience.
- Scenario descriptors useful

TABLE 8.1 MAPPING SCHEME AFTER BARNEICH ET AL. (1996)

Description of Condition or Event	Order of Magnitude Probability Assigned
Occurrence is virtually certain	1
Occurrences of the condition or event are observed in the database	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

3.1 Analysis Methods Continued

- Length and Number Effects
- Usually small in relation to other uncertainties
- Embankment lengths > 1 to 2km
  - Divide into representative embankment and/or foundation sections
  - Use different sections where consequences vary
  - Use De Morgan's rule for combining conditional probabilities before use of annual probabilities
- Number of blocks for gravity dams – May be significant if factors of safety differ significantly and interlocking of blocks is likely

3.1 Analysis Methods Contd.

Common Cause and Common Mode Failures

- Common Cause - All failure scenarios modelled by event trees and emanating from natural events such as flood or earthquake are common cause failures
- All conditional failure probabilities are adjusted using De Morgan's rule
- Common mode failures - These are multiple, concurrent and dependent failures of identical equipment that fail in the same mode

3.1 Concrete gravity dam uncertainty (ANCOLD 2022)

Analysis of the Concrete gravity section considering components and sub-component interaction

The real system response curve for the concrete gravity dam is a vertical line; which in the example is at water level "104.5" and is marked "A"

The line "A" is unknowable to the analysis team unless the water level at which failure takes place is observed

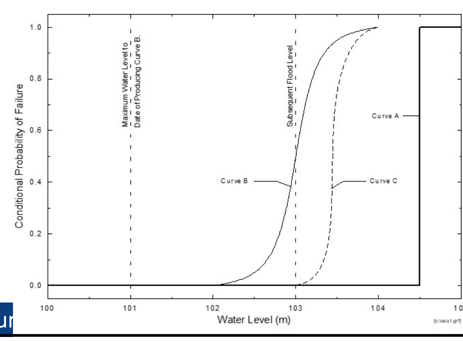
Team does analysis using Maximum Water Level 101m to date

Probability density functions (pdf's) and Monte Carlo simulation system response B

Curve B is analysis team's degree of confidence in the dam's safety at various reservoir water levels

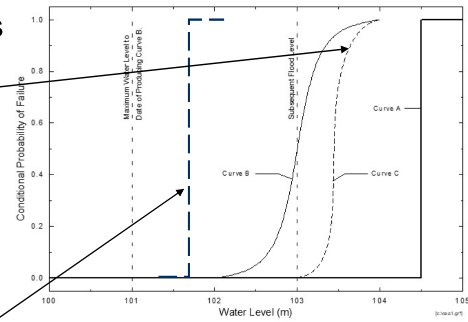
Subsequent Flood reaches 103m without failure

Probability of failure is now Zero for WL < 103m



3.1 Concrete gravity dam uncertainty (ANCOLD 2022)

Experience has now shown that some combinations of material properties, uplift pressures and loads are out of contention. A new system response curve marked "C" is produced



The deviation of the analysis team's system response curves ("B" and "C") from the true system response curve ("A") has two components:

- uncertainties in the properties of the dam, and in the loads – Accounts for horizontal span of system response curve
- unknown errors in the analysis team's analysis model – Conservatism but Curve A could also be to the left of Curve B

175

3.1 System Response Curve Comment

The example illustrates the understanding of subjective probability as the degree of confidence in an outcome, given the evidence and knowledge available to the analysis team.

The question of whether subjective probabilities are correct or not, is not one of whether they properly reflect reality (they do not), but whether they properly reflect the known uncertainties. Given the same description of the uncertainties (the various probability density functions) and analysis model, any number of analysts should arrive at the same subjective probability values

176

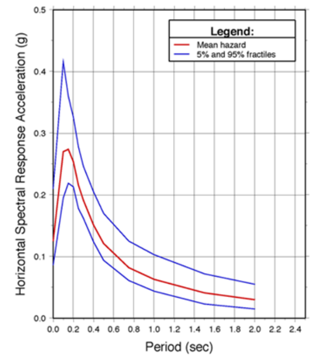
3.1 Seismic Uncertainty and System Response Curves

Sources of uncertainty may result in a wide range of loads as shown in the Figure

It is particularly important to take account of these uncertainties where the system response of the dam to the loading is non-linear. For example

- Foundation of a dam subject to liquefaction at 0.2g PGA
- Mean estimate PGA is 0.14g so liquefaction would not occur at a 1 in 10,000 AEP earthquake
- 5% fractile PGA is 0.23g, so there is about a 0.1 probability liquefaction.

In practice seismic hazard curve (AEP vs PGA) extend to 1 in 50,000 AEP.



Mean, 5% and 95% fractiles for a 1 in 10,000 AEP Seismic event

3.1 Earthquakes after shock and System response

If a structure is significantly damaged by the main seismic event it may be vulnerable to disproportionally greater damage from after-shock loading than it would for the same load pre the main seismic loading.

CFRD face slab is damaged, and the zoning is such that the fill becomes partly saturated. The net force on the face slab under the after-shock load will be much less than for the initial loading, however, other failure modes may result from the damage to the slab.

Tailings slope stability

- Liquefiable material below the piezometric surface with partly saturated material above.
- Earthquake leads to liquefaction and increased saturation above the phreatic surface.
- Strength parameters for the saturated zone reduce to shear normal function.
- Aftershock failure may occur
- Requires additional disaggregation (breakdown) of the failure mechanism pathway

3.1 Damaged Dam analysis

If a dam has been damaged, for example by an earthquake, but has not suffered a prompt failure, it may be vulnerable to a subsequent event, such as a flood or aftershock, in the period before repairs can be completed.

Event trees need branches to examine the estimated probability that the dam may be failed by a subsequent event (each branch of a specified representative loading magnitude) within the period required for repair.

Note that this probability is dimensionless, the probability per annum being that of the damaging earthquake.

179

3.1 Some general cautions

- The mathematics of probability must be correctly applied in making quantitative estimates of the probability of failure.
- The methods used in estimating probabilities should be documented
- The reasoning that supports all of the probability values should be documented
- The meaning of probability, as given in these guidelines, should be outlined in the study report
- There should be a summary statement of the reliance that can be placed on the probability values, and their defensibility, in the context of the purpose of the study and the resources available for its completion
- There should be a separate report from an independent reviewer(s) that includes specific comment on the reliance to be placed on the probability values
- All basic probability values, drawn from databases, should be referenced
- Where a particular PFM dominates the risk and is dependent on one parameter or component, it may be worthwhile investing more time and effort into refining the result

180

3.1 Common Cause Adjustment for failure modes

Common cause Adjustment

Failure Modes Not Mutually Exclusive Unimodal Bounds theorem

$$\max_i [p_i] \le p_f \le 1 - \prod_{i=1}^{k} (1 - p_i)$$

or

$$p_f^l \le p_f \le p_f^u$$

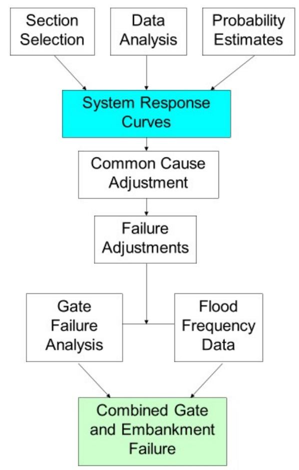
Adjustment of all probabilities

$$p_i^u = p_i (p_f^u / p_f)$$

Where:

p_i = branch failure probability

p_f = total probability of failure



181

3.1 Hazard Analysis

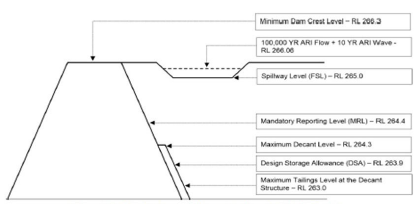


Figure 3-1: TSF Design and Reporting Levels (Not to Scale)

Seismic Hazard (85percentile dashed l

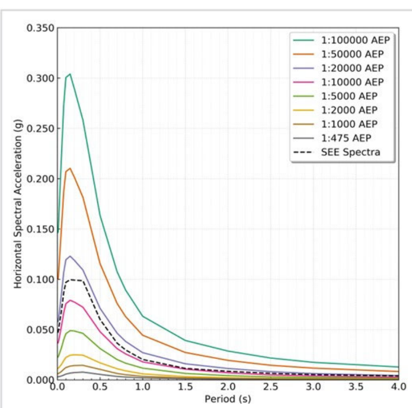
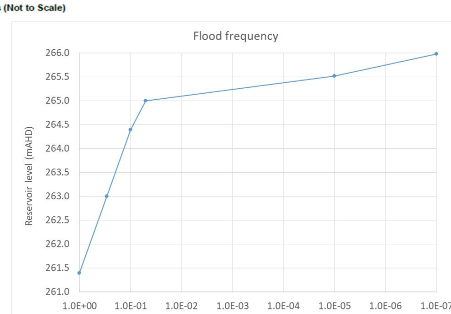


Figure E-1. Mean uniform hazard response spectra at the Blackwater NCPP TSF site for a set of return periods, 5% damping, horizontal component of ground-motion. The NCPP TSF SEE spectrum (85th fractile, 1:10,000 AEP) is plotted with the dashed curve.



Flood Hazard

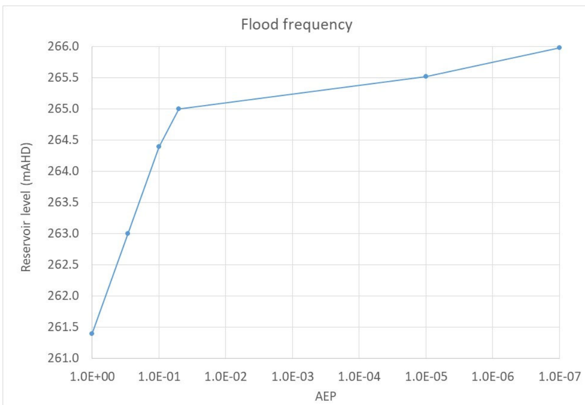
Include Seasonality of floods where required

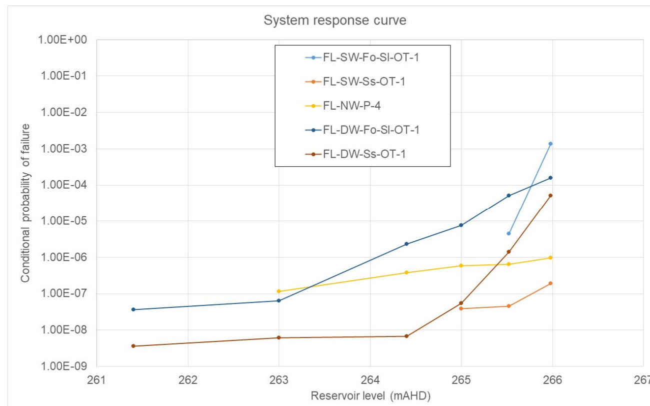
Frequent floods use statistical analysis

182

3.1 What do we do with System response curves?

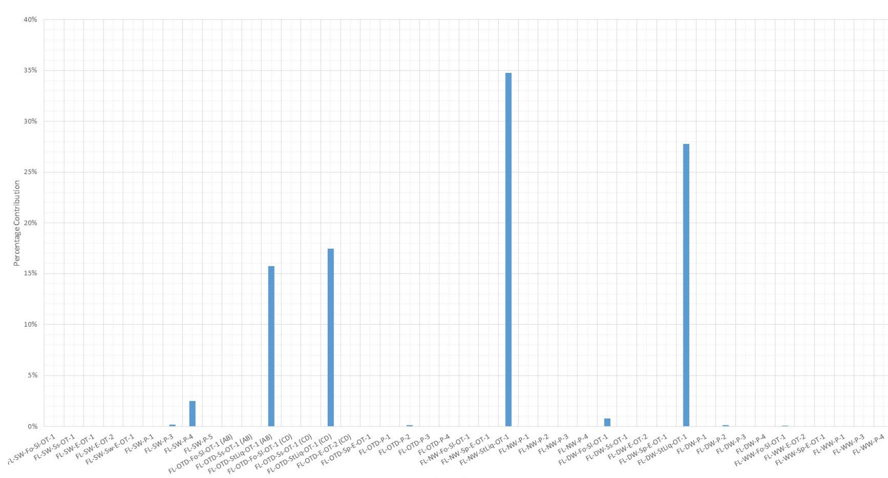
Integrate them with appropriate Hazard curves to get probability of Occurrence





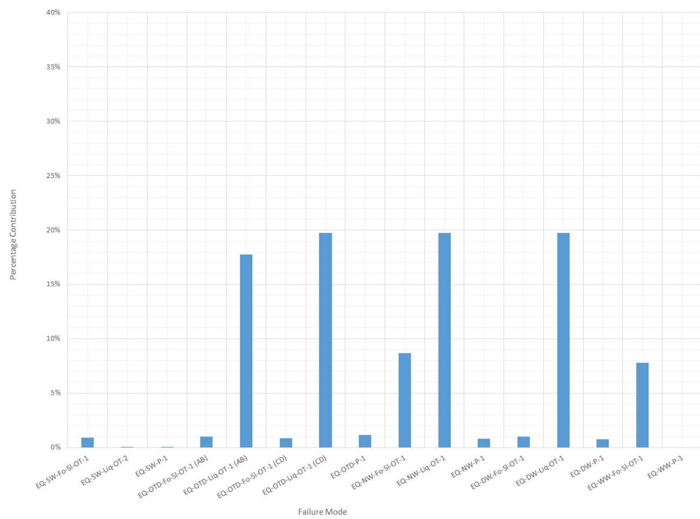
183

3.1 Failure Probability results (Hydrology)



184

3.1 Failure Probability results (Seismic)



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185

Part 3.2 Estimation of probability of occurrence

Risk Assessment Short Course - Session 4.5

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186

3.2 Examples of Methods for estimating Probability of Failure for embankment Dams

Load Condition	FAILURE MODE	METHODS: Screening and Preliminary Assessments	Detailed Assessment	Very Detailed Assessment
Normal operating	Embankment instability settlement and loss of free board	Event tree analysis coupled with judgement supported by stability analyses (2)	Event tree analysis coupled with judgement (2), supported by stability analysis and estimated post failure deformations	Event tree analysis coupled with judgement, supported by stability analysis and estimated post failure deformations. Probabilistic analysis if sufficient data are available and conditions warrant it.
	Internal erosion and piping in the embankment, foundation, and embankment to foundation	Event trees for all critical failure paths using published guides to estimating probabilities(1)	Event trees for all failure paths supported by engineering assessments for each mechanism of internal erosion	Event trees for all failure paths supported by engineering assessments (e.g. cross valley stresses and strains for concentrated leak erosion).
	Spillway wall instability	Analysis plus judgement	Analysis plus judgement	Analysis plus judgement. Probabilistic analysis if sufficient data are available and conditions warrant it.

3.2 Examples of methods for estimating Probability of Failure for embankment Dams

Load Condition	FAILURE MODE	METHODS: Screening and Preliminary Assessments	Detailed Assessment	Very Detailed Assessment
Flood	Embankment overtopping	Flood level AEP usually estimated without modelling prior reservoir water level if applicable. Historic performance plus judgement to assess depth of overtopping giving failure	Flood level AEP modelled with prior reservoir water level if applicable, and allowance for gate reliability. Historic performance plus judgement to assess depth of overtopping vs probability of failure	Flood level AEP modelled with prior reservoir water level if applicable, and allowance for gate reliability. Historic performance plus calculation and judgement to assess depth of overtopping vs probability of failure. May model wave and setup effects probabilistically.
	Embankment instability settlement and loss of freeboard	Covered in normal operating load calculation	Analysis coupled with judgement; supported by stability analysis and estimated post-failure deformations	Event tree analysis coupled with judgement supported by stability analysis and estimated post failure deformations. Probabilistic analysis if sufficient data available and if warranted.
	Internal erosion and piping in the embankment, foundation, and embankment to foundation	Event trees for all critical failure paths using published guides to estimating probabilities (1)	Event trees for all failure paths supported by engineering assessments for each mechanism of internal erosion	Event trees for all failure paths supported by engineering assessments (e.g. cross valley stresses and strains for concentrated leak erosion).
	Spillway and spillway energy dissipator scour and overtopping of spillway chute walls	Hydraulic analysis, results of hydraulic modelling if available, scour analyses, and judgement	Hydraulic analysis, results of hydraulic modelling if available, scour analyses and judgement	Hydraulic analysis, results of hydraulic modelling, scour analyses, and judgement

3.2 Examples of methods for estimating Probability of Failure for embankment Dams

Load Condition	Failure mode	METHODS: Screening and Preliminary Assessments	Detailed Assessment	Very Detailed Assessment
Earthquake	Embankment instability, settlement and loss of freeboard for dams not subject to liquefaction	Earthquake AEP of peak ground acceleration. Simplified deformation analysis, or judgement. Reservoir assumed at full supply level(3)	Earthquake AEP of peak ground acceleration. Simplified deformation analysis is sufficient in almost all cases. If critical, more advanced numerical modelling may be used. Prior reservoir level modelled(3)	Earthquake AEP of peak ground acceleration. Simplified deformation analysis is sufficient in almost all cases. If critical more advanced numerical modelling using selected time histories may be used. Prior reservoir level modelled. (3)
	As preceding but for dams subject to liquefaction	Earthquake AEP of peak ground acceleration, single design magnitude. Simplified liquefaction analysis e.g. AEP of liquefaction occurring (3)	Earthquake AEP of peak ground acceleration, with magnitude contributions. Detailed liquefaction analysis including post-liquefaction deformations. Prior reservoir level modelled(3)	Earthquake AEP of peak ground acceleration and selected time histories, with magnitude contributions. Detailed liquefaction analysis including post-liquefaction deformations. Prior reservoir level modelled. (3)
	Internal erosion and piping in the embankment, foundation and embankment to foundation	Deformations assessed as above, with failure paths assessed allowing for deformations and cracking and probabilities by judgement. Reservoir assumed at full supply level	Deformations assessed as above; cracking estimated empirically; event trees for all failure paths. Prior reservoir level modelled	Deformations assessed as above, cracking estimated empirically or/and by numerical analysis; event trees for all failure paths. Prior reservoir level modelled.
	Spillway wall instability	Earthquake spectral analysis, pseudo-static analysis plus judgement	Earthquake spectral analysis, pseudo-static analysis plus judgement	Earthquake spectral analysis, pseudo-static analysis plus judgement. Probabilistic analysis if sufficient data exist and if warranted.
Reservoir Rim Instability	Overtopping of dam by waves induced by landslide in the reservoir	Judgement based on topography, geomorphological mapping, and historic landsliding	Landslide hazard assessed by air photo interpretation, inspection, and geomorphological mapping, and history and mechanics of sliding. Wave heights calculation from volume and velocity of slide	Landslide hazard assessed by air photo interpretation, inspection, and geomorphological mapping, and history and mechanics of sliding. Wave heights calculation from volume and velocity of slide.

189

3.2 Internal Erosion and Piping

Event tree methods coupled with expert judgement have become the most commonly adopted method for estimating the probability of failure by internal erosion and piping.

These are described in Fell et al. (2008), Fell et al. (2015) and USACE and USBR (2015).

Model

- Initiation - Flaw present, hydraulic gradient initiation with material type
  - Continuation - Unfiltered or inadequately filtered exit exists
    - Progression - Continuous stable roof and/or sidewalls or Constriction or upstream zone fails to limit flows or No self-healing by upstream zone
      - Possible intervention unsuccessful
        - Breaching

Fault Tree analysis provides clear logic leading to a failure

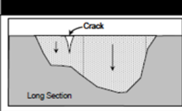
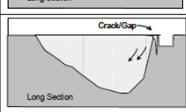
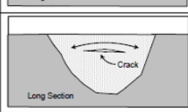
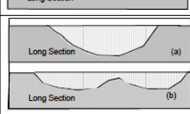
190

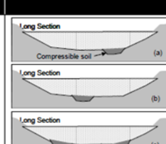
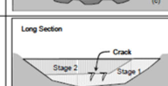
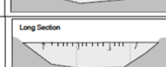
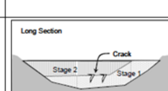
3.2 Internal Erosion Failure modes

- Generally characterised by physical location of the erosion pathway
- Internal erosion through the embankment
- Internal erosion through the foundation
- Internal erosion of the embankment into the foundation, including along the embankment/foundation contact
- Internal erosion into/along embedded structures such as conduits or spillway walls
- Internal erosion into drains

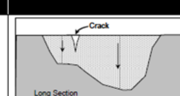
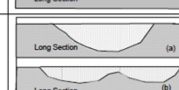
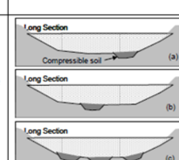
3.2 Piping Initiating Mechanisms

Upper Embankment

Initiating Mechanism	Sketch of Failure Mode
IM1 Transverse cracking due to cross valley differential settlement	
IM2 Transverse cracking due to differential settlement adjacent a vertical cliff at the top of the embankment	
IM3 Transverse cracking due to cross valley arching	
IM4 Transverse cracking resultant on cross section settlement	

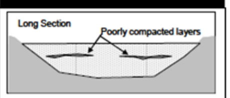
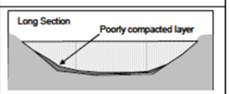
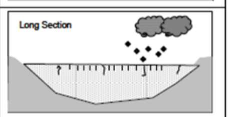
Initiating Mechanism	Sketch of Failure Mode
IM5 Transverse cracking due to differential settlements in the foundation beneath the core	
IM6 Transverse cracking resulting from differential settlements due to embankment staging	
IM7 Cracking in the core near the crest due to desiccation by drying	
IM8 Cracking on seasonal shutdown layers during construction and staged construction surfaces due to desiccation by drying	

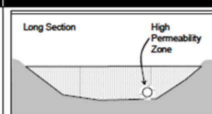
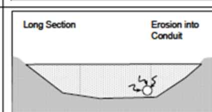
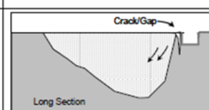
Middle and Lower Embankment

Initiating Mechanism	Sketch of Failure Mode
IM9 Transverse cracking due to cross valley differential settlement	
IM10 Transverse cracking due to differential settlement causing arching of the core onto the shoulders of the embankment	
IM11 Transverse cracking or hydraulic fracture in the lower part of the embankment due to differential settlement in the foundation under the core	
IM12 Transverse cracking at the foundation contact due to small scale irregularities in the foundation profile under the core	

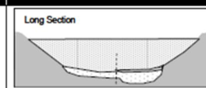
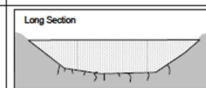
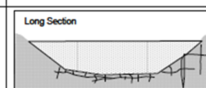
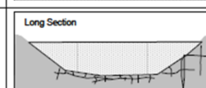
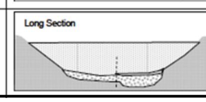
3.2 Piping Initiating Mechanisms Contd.

High Permeability Zones

Initiating Mechanism	Sketch of Failure Mode
IM14 Poorly compacted or high permeability layer in the embankment	
IM15 Poorly compacted or high permeability layer on the core-foundation contact	
IM16, IM17 Cracking in the crest or seasonal shutdown layers during construction due to desiccation by freezing	

Initiating Mechanism	Sketch of Failure Mode
IM18 High permeability zone around a conduit through the embankment	
IM19A Erosion into a (non-pressurized) conduit IM19B Erosion into a (non-pressurized) conduit leading to erosion along the conduit	
IM20, IM21, IM22 Poorly compacted or high permeability zone, crack/gap associated with a spillway or abutment wall	

In and Into Foundation

Initiating Mechanism	Sketch of Failure Mode
IM24 Backward erosion in a cohesionless soil foundation Suffusion in a cohesionless soil in the foundation	
IM25 Erosion in a crack in cohesive soil in the foundation	
IM26 Erosion in open or in filled defects in a rock foundation	
IM27 Internal erosion of the embankment into or at a rock foundation	
IM28 Internal erosion of the embankment into or at a soil foundation	

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193

3.2 Piping event Tree example (IM1)

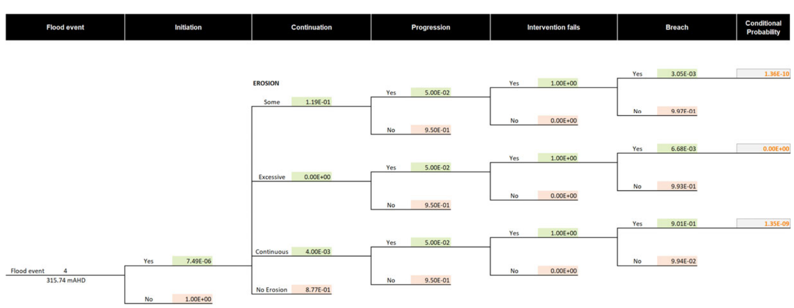

Table B.6.3: Conditional probability commentary for failure mode RE-FL-PI(IM1)-1

Flood event	Initiation	Continuation	Progression	Intervention fails	Breach
Selected flood event are used to develop a system response curve for this failure mode.	Evaluate using Piping Toolbox. IM1 Table 5.2 gives LFxRF=10 No cracks observed on dam crest during site investigation. Estimated crack at crest for evaluation = 2 mm Use Table 5.32 for material in and above the core (CL).	Zone 2B is not compatible with Zone 1 and continuous erosion could occur. Zone 2B can be found up to the dam crest. Probability assigned are as shown below. Base case data uses DTMR (2008) Zone 2B upstream gradings and sensitivity uses specification gradings. (columns: DTMR (2008) / Sensitivity) Some: 0.119 / 0.397 Excessive: 0.00 / 0.196 Continuous: 0.004 / 0.0272 No filter above top of core. $P_{CE} = 1.0$ $P_{NE} = 0$	Table 11.1 - Material is CL type Adopt likelihood of supporting a roof to be 1.0 Table 11.2 - Central and earth with gravel shoulders - Adopt 0.5 below top of core and 1.0 above core. Table 11.3 - Upstream filter 2A and 2B (both <15% fines), gradient across upstream zone <1 Adopt 0.1. Note road base material similar to Zone 2B. Below core: Pr(progression)=1x0.5x0.1=0.05 Above core: Pr(progression)=1x1x0.1=0.1	Unsure if piping will be detected and outlet work is capable of releasing sufficient water to reduce reservoir level. Gates would be able to decrease reservoir level however this is only applicable for non-flood scenarios as gates opened is part of SOP for flood events. There is no suitable equipment to intervene the piping process if it occurs hence conditional probability of intervention fails is 1.0.	Evaluated following Piping Toolbox, Table 13.1. Include: Gross enlargement. Slope instability and Sinkhole development Exclude: Sloughing Evaluated Gross enlargement using Section 13.2. Evaluated Slope instability using Section 13.3. Evaluated Sinkhole development using Section 13.5. Gross enlargement dominates giving a max Pr(breach) = 0.95.

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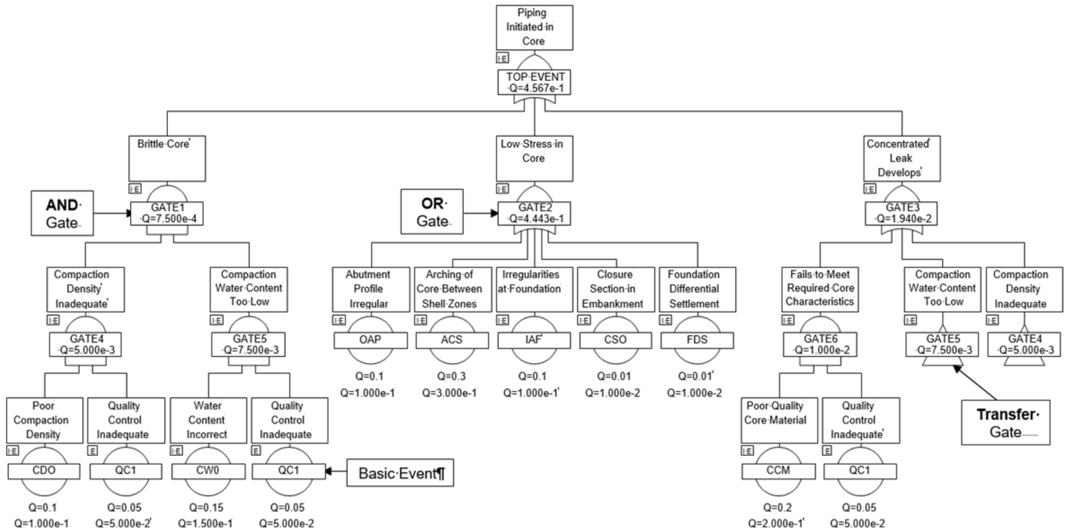
194

3.2 Fault Tree Piping Example



3.2 Embankment Overtopping

Probability of failure versus depth of water over the dam crest is developed for the dam.

The system response curve is developed by expert elicitation taking account of factors such as

- height of embankment,
- downstream slope,
- zoning,
- downstream slope material type,
- compaction.
- The actual crest level and how it varies across the dam should be taken into account
- Duration of overtopping

Case histories using similar dam crest configuration

Guidance Powledge et al. (1989) and Maslin and Rodd (2016), USBR (2015)

3.2 Embankment instability under seismic loading

Loss in freeboard for dams not subject to liquefaction model :-

- The probability of reservoir level;
- The probability of the earthquake ground motion;
- Dam deformation for the earthquake ground motions

Loss of freeboard for dams subject to liquefaction model :-

- The probability of the reservoir level;
- The probability of the earthquake ground motion;
- The probability of occurrence and extent of liquefied zones, given the earthquake loading, and the residual undrained strength of the liquefied zones;
- The post-liquefaction factor of safety, and estimated deformations;
- Comparison of the deformations and freeboard to see how much freeboard is lost

3.2 Internal erosion and piping through earthquake induced cracking

Earthquakes commonly induce settlement and cracking of a dam.

Mostly longitudinal cracking but scarps formed can be paths for concentrated leaks or damage to filter zones

Methods for estimating cracking based on magnitude Fell et al. (2008), Fell et al. (2015) and ICOLD (2017)

3.2 Calculate overall Probabilities

Combine the estimated annual probabilities of load states/scenarios or failure initiation with the conditional probabilities of failure to obtain the estimate of overall annual probability of failure.

Mutually exclusive failure modes or independent events – additive

Not mutually exclusive failure modes – De Morgans Theorem before multiplying by annual likelihood of being in load state

Check logic of the event tree to ensure dimensions are correct for the failure calculations

199

3.2 Evaluate Consequences

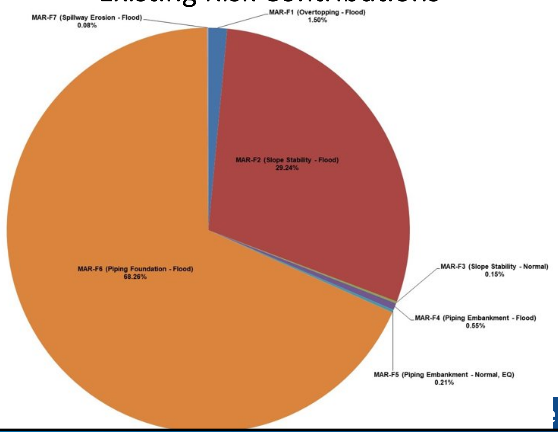
- Identify Breach locations
- Determine breach parameters
- Evaluate concurrent downstream flows
- Perform breach analysis for identified scena
- Estimate PLL with and without breach
- Calculate incremental PLL for scenarios
- Interpret PLL for all failure scenarios

200

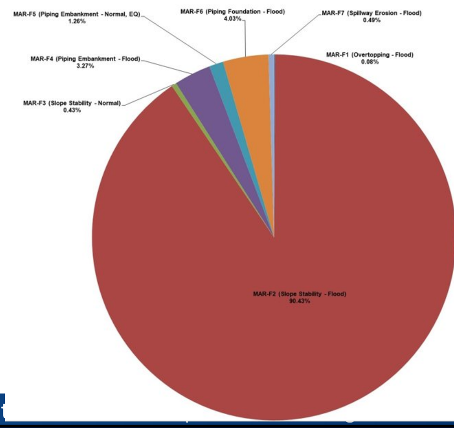
3.2 Calculate the Risk

Integrate the system response curve data with the Consequence data to obtain the risk

Existing Risk Contributions



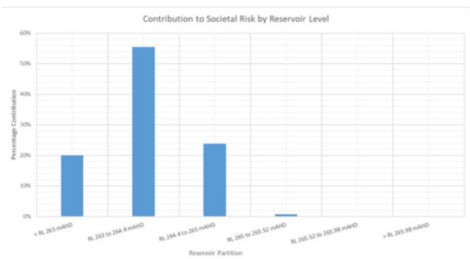
Upgrade Risk Contributions

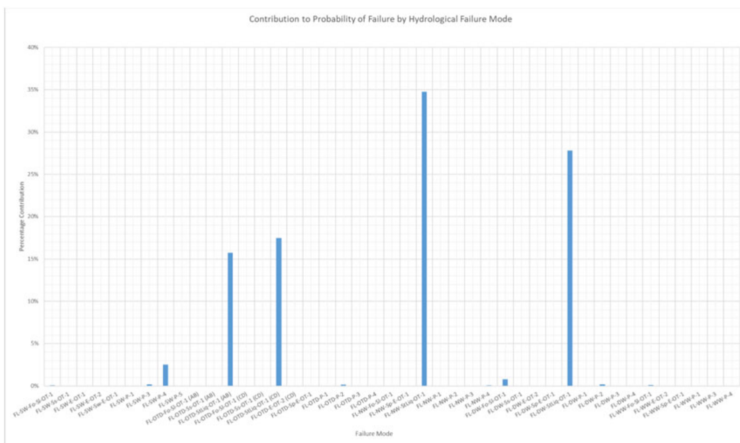


3: Risk assessment

201

3.2 Risk Contributions





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202

Part 3.3 Group activity 2

Risk Assessment Short Course - Session 4.5

203

3.3 Embankment piping probability estimation

Estimate the probability of piping through the embankment due to a poorly compacted layer in the embankment clay core.

Please refer to the calculation spreadsheet. Key steps in the calculation have been removed.

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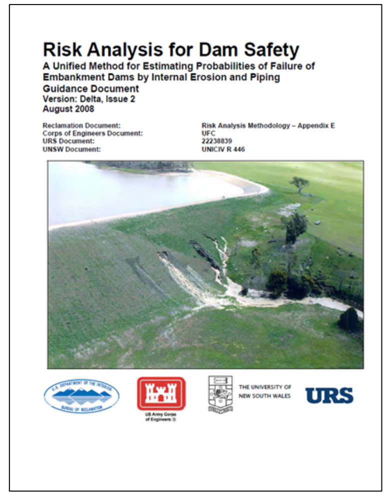
204

3.3 Embankment piping probability estimation

Methodology and workflow has been adopted from **Risk Assessment for Dam Safety A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping (BoR, USACE, UNSW, URS, 2008)**


Risk Analysis for Dam Safety
A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping
Guidance Document
Version: Delta, Issue 2
August 2008

Reclamation Document:	Risk Analysis Methodology – Appendix E
Corps of Engineers Document:	UFC
URS Document:	22238839
UNSW Document:	UNICIV R 446

205

Part 4 Risk Evaluation

Part 4	Risk Assessment Overview	Presenter
4.1	Defensible decision making - basic requirements	Jiri/Joel
4.2	Assessment of risk controls to assist in decision making (what is ALARP)	Moderated panel discussion
4.3	Group activity 3 - selection of controls to be implemented to mitigate risk of piping	Moderated group activity
4.4	Societal confidence in dam risk assessments	Des
4.5	Architecture of Dam Safety Management Systems	Jiri/ ails owner?

206

Part 4.1 Defensible decision making – basic requirements

4.1 Dam failure = change of paradigm

Dam failure with life loss

Question	After dam failure with life loss
Risk classification?	A priori risk classification irrelevant
Dominant failure mode? Probability of failure ?	Failure mode known (almost) Probability of failure = 1
Consequences?	Consequences realised
Is the risk acceptable / tolerable?	Consequences are never acceptable and hardly tolerable (not defined in law)
Is the risk ALARP?	All reasonably practicable actions completed with respect to the known event?

4.1 What may happen post the dam failure?

Investigation of:

- **Decision making**
  - Process
  - People
  - Reasonableness
- **Guidance material and industry standards (at the time)**
- **Correspondence between parties**
- **Meeting notes**
- **Inspection reports**
- **Expert evidence**

Greg Smith (T&MW, 2022)

209

4.1 Were all reasonably risk controls in place?

What is reasonably practicable?

Anything that ought to be in places under given circumstances

The words "reasonably practicable" have, somewhat surprisingly, been the subject of much judicial consideration. It is surprising because the words "reasonably practicable" are ordinary words bearing their ordinary meaning.

… the question whether a measure is or is not reasonably practicable is one which requires no more than the making of a value judgment in the light of all the facts.

Slivak v Lurgi (Australia) Pty Ltd [2001] HCA 6

Reasonably practicable is not limited to design decision-making! It applies to the whole process!

As a legal risk management principle, reasonably practicable requires you to demonstrate that you had:

- **proper systems to manage the relevant risk**
- **adequate supervision/assurance to understand if those processes are implemented and effective**

Greg Smith (T&MW, 2021)

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210

4.1 Were all reasonably risk controls in place?

*You start with what can be done and **only do less when** it is **reasonable** to do so.*

Key considerations:

- Hierarchy of risk controls (1. eliminate if RP and if not reduce as far as RP)
- Current practice
- Availability and suitability of ways to eliminate or minimise the risk
- Ability to verify the effectiveness of the risk reduction measure
- Failure likelihood and degree of harm that might result from the hazard or the risk
- Risk introduced by the risk mitigation measure
- Loss of opportunity to reduce other risks
- The cost associated with available ways of eliminating or minimising the risk, including whether the cost is grossly disproportionate to the risk

(Based on WHS in AU)

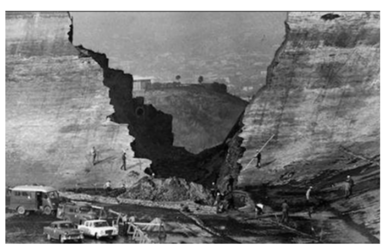
211

4.1 Were all reasonably risk controls in place?

(Paradigm shift)

Focus and investment prior to failure:

Politics (regulations – F-N, ALARP etc.) and compliance (internal and external guidelines incl. GIST)



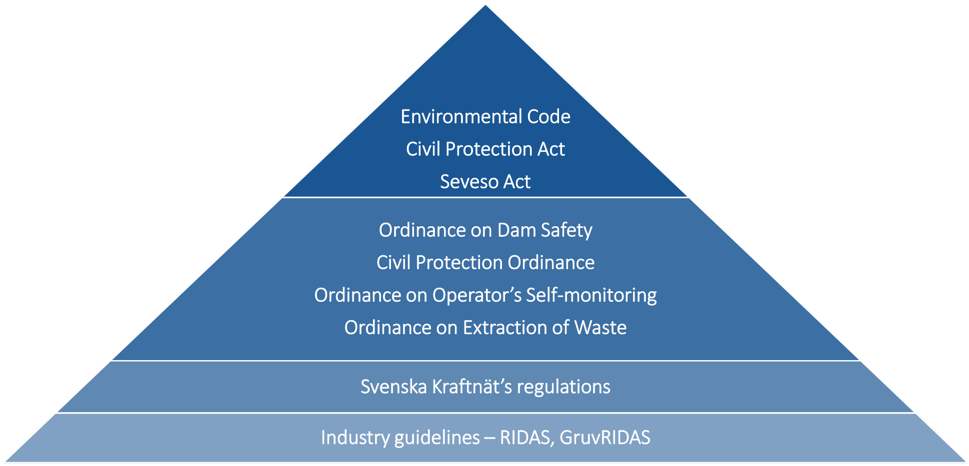
Focus after failure:

Legal defense – reasonably practicable risk controls implemented in a reasonably practicable risk management framework by reasonable people

- Defendable Risk Assessment must start with addressing legal requirements.
- This does not prevent use of conventional RA techniques.
- Focus on risk controls rather than risk magnitude, classification, tolerability, etc.
- Talk to your legal advisor before it is too late!

212

4.1 The Swedish regulation of dams



213

4.1 The Swedish regulation of dams

- Operator / dam owner
- County Administrative Board: supervisory authority (Environmental Code)
- Municipality: rescue service and supervisory authority (Civil Protection Act)
- Svenska Kraftnät: Supervisory guidance on dam safety
- The Civil Contingencies Agency (MSB): Supervisory guidance (Civil protection Act)

214

4.1 A dam owner's general responsibilities in Sweden

- Know the operations – burden of proof, self-monitoring
- Precautionary principle
- Best available technology
- Maintain the dam
- Assess consequences of dam failure (if >5m and >100,000 m^3)

215

4.1 Types of dams in Sweden

Dam safety classification

- depending on consequences
- classes A-C (or U)

Dangerous activities

Risk facility (mining waste)

Seveso facility

216

4.1 Swedish Dam safety management

- Dam safety report – annually
- Overall dam safety assessment – every 10 years
- Safety management system, prevention policy, internal emergency plan
  - scope determined by type of dam
- Personnel for emergency situations
- External information

217

4.1 Dam failure

- Strict liability for damage caused by dam failure
- Duty to inform
- Duty to act

218

Part 4.2 - Assessment of risk controls

Moderated Panel Discussion

Risk Assessment Short Course - Session 4.2

219

Part 4.3 - Selection of RP controls to mitigate piping risk

Moderated Group Activity

Please submit potential controls for the piping risk assessment analysed and the panel will discuss their thoughts and considerations on whether the controls are **reasonably practicable**

Risk Assessment Short Course - Session 4.3

220

Part 4.4 – Societal confidence in risk assessment

4.4 Why not use available risk acceptance criteria?

Several are available!

Why not just choose one of them, or,

Create a hybrid using several available criteria

Because, in part:

The establishment of risk acceptance criteria is strongly determined by historical, moral, ethical, legal, environmental, economic, social and political contexts.

Justification just on the basis that *“another agency does it the same way”* is morally insufficient especially if the relationship between safety and risk is a matter of perspective.

Decision makers should realise that their decisions over life and death should be justified commensurate with the weight that they carry.

4.4 Acknowledgement for guidance and advice

Prof. Dr. BJM Ale (Netherlands)

- Regulatory responsibility: Chemical Industry, Transport of Chemicals and Aviation and head of National External Safety Centre

Dr. JM LeGuen OBE [Dec] (United Kingdom)

- Former Head of Risk Assessment Policy Unit of UK Health and Safety Executive and principal author of *Reducing Risks, Protecting People* (UK HSE, 2001)

Dr. J. McQuaid CB (United Kingdom)

- Former Chief Scientist and Director of Science and Technology of UK Health and Safety Executive. Chair of UK Government's Inter-Governmental Liaison Group on Risk Assessment

Prof. J. Reason (United Kingdom)

- Formerly Professor of Psychology University of Manchester and author – Human Error.

Mr. JD Rimington CB

- Former Director General of the United Kingdom Health and Safety Executive. Principal architect of Tolerability of Risk and ALARP approach and author of *Tolerability of Risk from Nuclear Power Stations* (UK HSE, 1988)

4.4 Societal confidence in dam risk assessments

In general terms confidence on the "whole" depends on confidence in the parts

- And then a great deal more
  - Who
  - How
  - How it is being used

Confidence is based on trust

- Which needs to be earned and is best based on experiential knowledge

The subject matter of this session is one of psychology

4.4 Safety is a dynamic non-event

James Reason (personal comm.): and based on the observation that reliability is a dynamic non-event (Karl Weick (2011))

- It is dynamic because safety is preserved by timely human adjustments; it is a non-event because successful outcomes rarely call attention to themselves.

This means that there is little or no feed-back from safe outcomes

This coupled with the fact that dam failures are "rare events" means that there is virtually no experiential feed-back

This might be construed as a case where *"There is no evidence that risk assessment does not work well"…. but*

4.4 Dealing with the implications of "*no* feed-back"

Consider that we employ an expert to assign a probability to some rare event dam safety risk analysis.

The expert considers the problem and returns with the assessment, "The chance of this rare event is, in my opinion, **one in a thousand**."

Since this is an eminent consultant, we assign a high *a priori* confidence to the opinion; say the probability of the expert's being correct $Pr(H0) = 0.99$.

4.4 Bayes Theorem applied to "confidence"

If the rare event occurs, the probability that the expert's assignment of probability is correct is

$$Pr(H_0|\mathbf{z}) = \frac{Pr(H_0)\hat{p}}{Pr(H_0)\hat{p} + (1 - Pr(H_0))(0.5)}.$$

If the rare event does not occur, the probability that the expert's assignment is correct becomes

$$Pr(H_0|\mathbf{z}) = \frac{Pr(H_0)(1-\hat{p})}{Pr(H_0)(1-\hat{p}) + (1 - Pr(H_0))(0.5)}.$$

4.4 And unfortunately the dam fails….

$$Pr(H_0|\mathbf{z}) = \frac{(0.99)(10^{-3})}{(0.99)(10^{-3}) + (1-0.99)(0.5)} = 0.165.$$

The à priori probability of the expert being correct is assigned as 0.99
That is $P_r(H_0)$ =0.99

The lesson is: Our degree of confidence in the "expert" drops precipitously

4.4 On the other hand – nothing happens

$$Pr\left(H_0 \middle| \mathbf{z}\right) = \frac{(0.99)\left(1-10^{-3}\right)}{(0.99)\left(1-10^{-3}\right)+(1-0.99)(0.5)} = 0.995.$$

Our degree of confidence in the "expert" hardly changes

The lesson is that: Multiple non-occurrences of rare events do little or nothing to reinforce the "confidence" in the expert assessment

4.4 The implications for confidence

No feedback means no change in the pre-existing perspective of the degree of confidence in the dam safety risk assessments.

If there has been one failure then confidence will be reduced precipitously.

If there have been several failures, then confidence collapses completely.

Part 4.4 Building trust in risk assessments and safety decisions

4.4 Transparency, Objectivity and Challenge

Explain what is being done and why it is being done in generally understandable terms

- Which is not F-N curves, Expected Values or opaque "Engineering Judgments"
- Inform the public about the "analysis" of the facts, the assumptions and the opinions

Anchor the assessments in reality

- Risk is an abstract concept – it doesn't exist in the real world
- Relate the assessment to solutions that have been proven to work

Invite challenge

- Accept feed-back from the public and politicians
- Re-assess and be prepared to modify the assessment
  - Without adjusting the risk analysis, but broadening the risk evaluation

4.4 Ethics, emotion and cognition

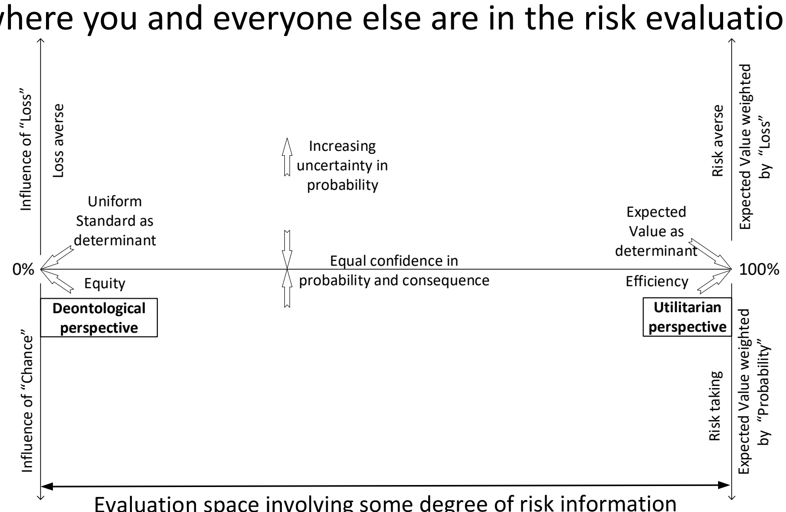
Utilitarianism and deontology are often described as opposite and mutually exclusive ends of the ethical spectrum,

However, recent research suggests that these inclinations are in fact independent and that increased moral identity increases both inclinations, be it not to the same extent.

- Deontological inclinations depend more on emotional responsivity
- Utilitarian inclinations depend more on cognitive deliberation.

4.4 Considerations in risk evaluation

Understand where you and everyone else are in the risk evaluation spectrum



4.4 Moral insufficiency and perspectives of risk

Perspective of the victim

Moral principles are usually considered from the point of view of the potential victim. Members of the public prefer to be protected by clear limits set to levels of threats. The perspective of the potential victim puts emphasis on the "As Low As" part of ALARP.

Perspective of who pays

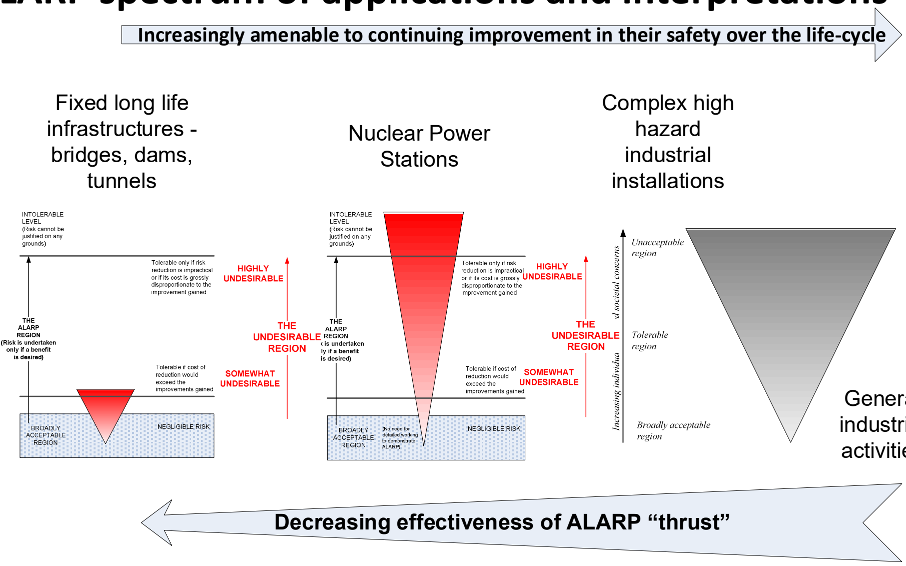
Emphasize the "Reasonably Practicable" part of ALARP

- Reduce expenditure to the minimum justified

4.4 ToR – Not quite a "one size fits all" framework

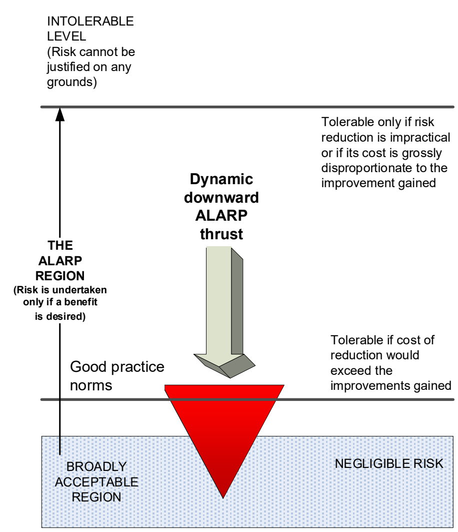
*"The TOR approach assumes a **malleable** risk situation, and indeed, most situations in industry are **malleable**. Those that are less so, for example in the case of fixed structures with a long life expectancy, and which can only be reinforced at great expense, are in principle less suited to the TOR approach. An intermediate category is that of complex, large scale operating plant, as in the nuclear industry in relation to which the TOR idea originated."*

4.4 ALARP spectrum of applications and interpretations



237

4.4 ToR and ALARP applied to dams and large fixed infrastructures



238

4.4 Rimington on SFAIRP and ALARP

The SFAIRP approach implies the existence of a powerful, well-informed and challenging regulator. "Good practice" is regarded as the minimum requirement, so that, for example, an accepted and published standard will be regarded automatically as reasonably practicable and will be enforced by the regulator.

*both SFAIRP and ALARP incorporate a **dynamic downward thrust** which seeks to ensure that avenues for risk reduction are identified at the design stage and during plant lifetime, and are undertaken if any increment of risk reduction is both technically feasible and its cost can be justified in terms of the expected reduction in risk.*

4.4 Rimington on the "dynamic downward thrust"

This downward thrust implicit in SFAIRP and ALARP is expressed in the TOR diagram. The diagram incorporates an "ALARP area" below the limit of tolerability and above the area where the risk level is negligible or generally acceptable. The process of risk reduction operates in the "ALARP" area. The diagram also takes account of a secondary idea borrowed from the legal meaning of "SFAIRP", namely that it is not enough to accept a risk on the basis simply that the cost of further improvement is likely to exceed the associated gain in safety; there should be an element of "disproportion" in favour of risk reduction.

4.4 Who evaluates societal risk?

Depends on the government and legal system and how it functions

In general, it is the duty of government to act in what it sees as the best interests of the public.

Government as a protector of its citizens from harm

Government as a provider of goods and services

- that individuals cannot provide individually for themselves and services that society deem should not be privatised

Government as an investor in citizen capabilities

- to enable them to provide for themselves in rapidly and continually changing circumstances

Government retains the overarching responsibility

241

4.4 Perhaps not use available risk evaluation guidance?

Evaluation of risk in the dam safety arena emerged in the 1990's

The general view was that "risk acceptance criteria" were the output of a deductive risk evaluation process (e.g. reviews of accident statics, economic analyses)

In reality the situation is much more complex and context specific and involves non-quantifiable aspects such as ethics.

How to make risk related decisions without quantitative risk tolerability/acceptability criteria?

242

4.4 Decision-making principles

In making decisions which lead, or may lead, to differing benefits for individuals, the decisionmaker can base their reasoning on a range of arguments such as:

- Equal benefit for all
- No harm to anybody
- Maximum benefit for a group or a society

Equivalence of costs and benefits, termed the zero-sum game - may be seen as the minimalistic application of ALARP. …… society should only stop spending money on saving the lives of those who want their lives saved, when the sacrifices are disproportionally larger than the benefits involving money, level of nuisance, health, lives, environment, life-years etc.

4.4 Not “unethical” à priori

Which way a decision goes depends on the circumstances, the decisionmaker and the decision-making process and cannot be called unethical à priori.

The initial reaction to the outbreak of COVD-19 was to protect the population and protect the health-care system to cope with the rush of patients.

- Protect the people who need protection just as you would want yourself to be protected (equity)
- There was opposition often labelled as being unethical in a face of the pandemic

But, when the consequences of COVID infection became clearer, question arose:

- Whether the sacrifice of saving the lives of patients with a relatively short remaining life expectancy were actually worth it, given the economic and other collateral damage
- The basis of the opposition became clearer

But then….

4.4 Not “unethical” à priori cont.

Emergence of vaccines raised similar issues **but** changed the ethical calculus:

The risks, in terms of probability of death and injury from the vaccine, were declared to be obviously smaller than that of catching COVID-19 for the society although it was not the case for everybody (Utilitarian perspective).

When it became clear that the side effects largely affected only healthy younger people, who otherwise would have little to fear from the disease, the official stance became Deontological: Why take the risks of these vaccines if there are other options which do not pose these risks?

4.4 Not “unethical” à priori cont.

Application to industrial risks and sacrifice for progress

In the early stages of the industrial revolution, accidents were considered as part of the game and a necessary sacrifice for the progress.

When the number of occupational accidents increased and indirect impacts (e.g. pollution) were realized, policies to reduce the number of accidents were developed and implemented.

Same process is now occurring in developing countries.

4.4 Value of a Statistical Life and Cost-Benefit Analysis

The underlying assumption in cost benefit analysis and policy making is that everything is for sale and that the price is set by the forces of the market.

But people who are exposed, or will be exposed to "third party risk" did not put their lives on sale.

Nor will the company or organization who put third parties in harm's way, normally offer them a price to buy their lives.

There also is not any form of competitiveness in the sense that people exposed to risk can sell their lives to the highest bidder. In fact, the situation is completely reversed.

A uniform value of a statistical life does not exist.

That does not preclude that citizens are treated equally under equal circumstances. It also does not preclude standard values for acceptable risk or even the VOSL in specific areas of policy.

The appropriateness of using VOSL at all in a safety analysis is a matter of perspective, without considering any second order perspectives, such as the perspective about the individual who is at risk about their own value, all of which renders the matter of a uniform value of a statistical life questionable.

4.4 Where "willingness to pay" theory breaks down

In industrial risk situations, the probability for people to lose their lives is about to be increased and they are asked what they are prepared to pay for this increase in risk to be as low as possible.

Instead of comparing this to a market, it could be more justifiably compared to a ransom or protection racket situation, in which money is demanded of people for not being damaged or killed.

In these situations, the value of life is not determined by what people would be willing to pay to have their lives saved, but what they can afford, as any would-be kidnapper understands

4.4 Proximity to the risk

Whether people choose the deontological (equity), or utilitarian (efficiency) stance, depends on their remoteness from the risk, be it in physical distance, or in time.

Institutions, which are detached from a threat, be it a threat to health, or a threat posed by industrial installations, or infrastructure, tend to reason from a utilitarian point of view.

- They set acceptability criteria and base advice and decisions on cost benefit comparisons, in which even human lives can theoretically be bought and sold at a price and dealing with threats that are only supposed to materialize in the future, can be postponed until they materialize.

When people are confronted with the reality of the consequences, they tend to choose a more deontological stance, giving preference to saving health and lives and even their businesses, regardless of the cost and without a cost benefit evaluation.

4.4 What can be defended ?

Risk tolerability approach

- Justification of a certain level of risk from any type of dam in a specific case just on the basis that "another agency does it the same way" is morally insufficient and not obviously legally defendable if failure happens.

Cost-benefit approach

- A cost-benefit analysis based purely on the comparison of QALY's (Lives, $, resources) lost or gained, or on purely economic arguments, in which human lives, environmental damage etc. are all treated as commodities, can lead to socially and politically unacceptable decisions may not be legally defendable if failure happens.

Reasonable care approach

The tested expectations of the society are provided through the law, which decision-makers must comply with. Unfortunately, the concepts of risk tolerability, acceptability and what is ALARP are not defined in most (if any) legal frameworks.

Make dam risk decisions while considering how to defend the decision after the dam has failed and when all actions are being scrutinised to ensure duty of care is met in all respects.

4.4 Equity over Efficiency

In the end, the people can be reasonably expected to prioritise a protective approach concerning matters that have the potential to affect them individually.

The argument that such a protective attitude may cost excessive resources, while reasonable in theory, needs to be considerably convincing in the context of everyday life and the eyes of the public.

- Ale, BJM (2023). *Third Party Risk Policies in the Netherlands*, Cambridge Scholars

4.4 The "not the last word"

Decision-makers and politicians will learn that persuasion can only go so far.

Politicians and decision-makers will have to continue their balancing act between the various actors and proponents of various approaches and find ways to manage third-party risk from all sorts of origins.

In this vein, the policies will inevitably have to keep evolving and no word is the last one.

Ale, BJM (2023). *Third Party Risk Policies in the Netherlands*, Cambridge Scholars

See also Susskind, L and Field, P (1996). *Dealing with an Angry Public – The Mutual Gains Approach to Resolving Disputes.* The Free Press

4.4 Risk Analysis No 43:2, Feb. 2023.

ORIGINAL ARTICLE

The ethical dilemmas of risky decisions

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Abstract
Even in a pandemic there seem to be inherent conflicts of interest between the individual and societal consequences of remedial actions and strategies. Actions taken in the sole interests of patients, as required by the Hippocratic oath, can have broadly inconvenient economic implications for the State. ("Average" benefits for a population can impose individual inconveniences for the vulnerable.). Understandably these decisions are not normally made explicitly and transparently by governments. This leads to seemingly illogical and inhumane strategies which are not understood and hence mistrusted and often ignored by the public. Vaccination sentiments on social media are often an unwanted symptom of this dilemma. This article outlines and discusses a number of examples of such situations with a focus on ethical aspects. It concludes that each case must be considered individually as to the issues that need to be weighed in these difficult decisions; and that there are no clear and universally acceptable ethical solutions. What can be learned from the COVID-19 crisis is that short term utilitarianism has consequences that in the eyes of the population are unacceptable. This lesson seems equally valid for cost benefit evaluations regarding other risks, such as from hazardous industries, flood defenses, and air transport. Decisionmakers and politicians can learn that persuasion only goes so far. In the end the people appear to prioritize in terms of deontology.

KEYWORDS
Cost benefit analysis, COVID-19, deontology, risk, utilitarianism

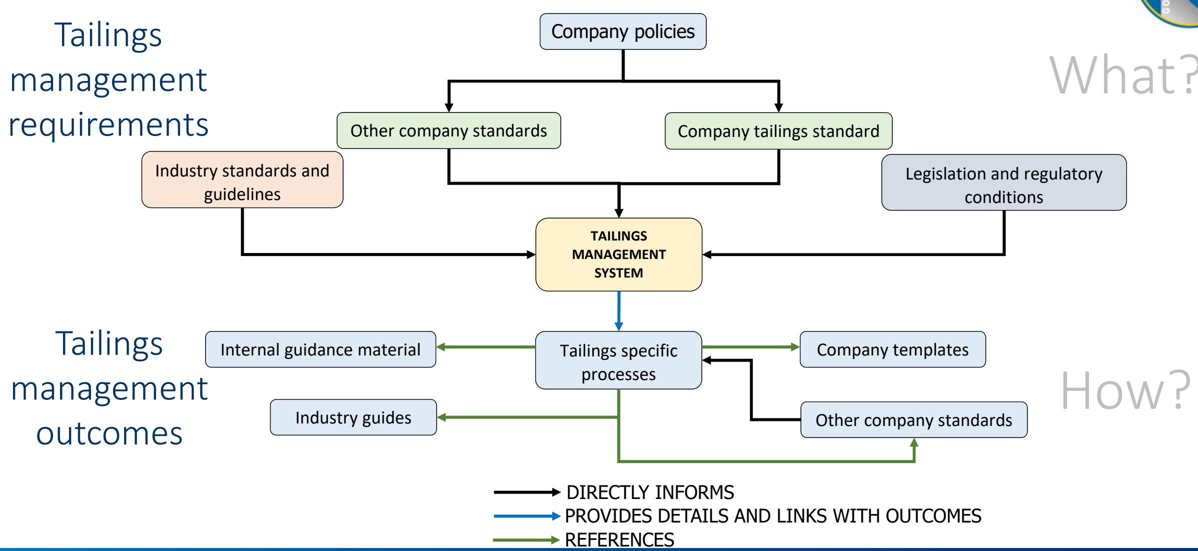
253

Part 4.5 Architecture of Dam Safety Management Systems

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

254

Part 4.5 Architecture of Dam Safety Management Systems



255

Part 5 Panel Discussion

Risk Assessment Short Course - Session 4.5

256

Short course feedback

Risk Assessment Shortcourse - Feedback

ICOLD 2023 – 91st Annual Meeting – Short Course 3: Risk assessment – Current state of practice for tailing dams

257

258

Appendix B. Panel discussion transcripts

The panel discussions were audio recorded and minor edits of the transcripts were made for clarity.

Panel Discussion No. 1

On ALARP

Paul Ridlen

The term ALARP is found throughout the Global Industry Standard for Tailings Management and has become the subject of much discussion in the mining industry. How well do you think ALARP is understood among the tailings practice, do you think it is an appropriate standard, and what do you think should be done to fill any current gaps in knowledge and regulation?

Des Hartford

Now there's one of my slides, which shows the difference between the ends of spectrum of what constitutes ALARP. In your notes you'll see a page that shows the spectrum of ALARP applications from at one end of the spectrum, which is general industry, health and safety at work, reducing risk, protecting people, which is the most commonly used version of tolerability risk and ALARP in the dams industry. Today, it has been in place for 20 odd years. According to John Remington who wrote the whole thing in the first place and formulated ALARP, it's not invalid for dams, but it's not directly applicable. One of the unwritten statements around ALARP, is that there is an underlying assumption that industry is malleable. What you mean by malleable is that you can continue to improve it over life, as technology advances. You know, science improves the new methods that arrived. This works for industrial plants doesn't work for dams because they're heavy civil infrastructure, because they are not malleable. So, the whole thing about ALARP is that rather than being a state, which is what's actually commonly used in the industry, that you've read a lot about, ALARP is a lever, mechanism used by government in these malleable industries to continually keep pressure on the owner, the creator of the risk to drive risk down. So, John Remington's advice in relation to the application of tolerability, risk and ALARP is that when you're building your dam, it doesn't matter whether it's a tailing dams or water dam and because they're not readily improved over time, once they are built, that you make them as safe as you can when you get the chance and you prevent a deterioration in the risk position. BC Hydro has taken John Remington's advice. We have worked with him for 20 years. Taking this advice and applied it to dams problem will be explained together with how we make decisions in the tolerability risk and on our framework on Tuesday afternoon 16:05. I'm not going to talk about it now, but the idea of ALARP as a downward thrust on the risk is central to how certainly John Remington explained to me. So, he says there's a spectrum. General industry reducing risk protecting people. The other end of the spectrum, you've got dams, rigid fixed infrastructures, not readily improved. And in the intermediate position you've got nuclear power stations, some which are fixed and some parts of which can be made safer and safer over time as technology advances. So, it's a completely different interpretation of a lot as applied to them.

Paul Ridlen

So maybe if I could rephrase the question, it was a three-part question. And I'm going to skip the one about whether it's understood or appreciated in the mining industry. The second one would be maybe more applicable is,

“Is that an appropriate standard?”

And again, I use it in a different term perhaps than what we conventionally think of, but is ALARP appropriate to be applied to tailings dams?

Des Hartford

It depends on how you're applying it, how you're interpreting it. If you're interpreting tailing dam as if it's a …Now, during construction you can continue and modify it. Once you've built it, it's done and by the way, it's there forever. So, what's this end state going to be is where your real target is. Sure, you don't want it to fail along the way, but at the end state, you want to close it out and walk away. Which means that you know the idea of reinvesting or decommissioning the tailing storage facility is really not on the table. And the whole question about decommissioning, you know, the large water dams is basically not on the table either. Very difficult to do in many cases. Sometimes it's impossible. So, you're still faced with these forever infrastructures. When you get the chance, make them as safe as you can because it's a one-shot deal.

Paul Ridlen

David, it looks like he wants to go next.

David Bowles

I'm not sure I've got anything really profound to add. However, it struck me as a little bit odd when I first went through the GISTM and saw ALARP, because I'm used to seeing it in the common law (originating in the in the UK) context; and to see it in a global standard I thought, well, that's interesting. I wonder how it got there and maybe some of you can answer that question. But it seems to me as long as it's there, and as long as there is a willingness by the industry to work towards that, there really is a need to better define what ALARP means for tailings dams, right? The things that I can offer, and that I think Des can offer are from our experience, which goes back to the roots that Des has described. But you're looking for something that applies across the globe. It seems to me that actually is in part a legal matter with a lot of different legal contexts around the world. I would think it's got to somehow mesh or connect to the legal context in different parts of the world. The mining industry needs to better define ALARP, so the industry can apply it. But that's not a simple thing to do and it's going to take some consultation with legal minds around the world, I would think.

Jiri Herza

I fully agree with David, and I don't think it is possible to define what ALARP means for all jurisdictions around the world in a single document. ALARP, in the Commonwealth world, refers to reasonably practicable controls rather than risk position. If you have a capital FN plot, you might not say what area is ALARP, or you might say it, but it would be wrong. ALARP is a temporal state at which you can objectively demonstrate that all reasonably practicable risk controls are in place, and they are managed using reasonable processes, that include verifications of the controls being effective. This may be a very basic definition of ALARP applicable in certain jurisdictions and if you want to apply it somewhere else, be aware that it (ALARP) is a temporal and circumstantial state applicable to a specific environment, in which the dams are operated. It's a very difficult quest to define what ALARP is for all dams in the world and I don't think it is going to work.

Attendee

But just sorry, I think it's like a continuous process. So basically, probably that's the reason it is not very clear and identified across the world what ALARP means. Because it should be continuous process at the end of the day.

Jiri Herza

The risk assessment and the verification, as David put in one of the slides (Slide 56) is the external loop and if something happens then you go into an internal loop before you return outside again. So, it (ALARP) is an ongoing process of improvements and reduction of risk. But being able to define ALARP is A, B, C, D, E and F? I don't think it (a globally applicable definition) is possible for the whole world.

Malcolm Barker

I guess I'm going to ask Des, is that the fact that you do improve the dam's facilities as you see a problem mean that they are malleable. In that sense, they are fixing them, they are improving them as they go along. And is that not part of the ALARP process?

Des Hartford

Well, you could construe it to be that if you wanted to, but it's no different to any construction project, like when we're building anything, you know you're applying the observational method. You're always modifying things as you go. So, there is the whole idea of the dynamic situation during construction as opposed to once you get to closure. It's when you get to closure that you've really got to be clear about what you're doing now. But the whole question about ALARP take out the R and think about it ALAP. So, in other words, have all the practicable things being done? Take a list of all practicable things and then justify why you haven't done some of them, if you haven't done them all. So, there's a reverse way into it: everything is practicable, and then justify why you haven't done everything practicable…and there will be justifications.

Paul Ridlen

So, what you're saying is, I think, is don't throw the baby out with the bathwater. It may be that there's an adapted approach that's needed for the industry that is distinct from other industries that have applied to ALARP.

Des Hartford

I would think so. And there's also the issue that never gets discussed and that is living with legacy risk. You're stuck with what you've got. And it's more dangerous to do anything than not do anything. So, there you're basically between a rock and a hard place. That's reality.

David Bowles

Des, the process that you described there of coming up with every practicable option is one that we recently went through on a portfolio of about 40 dams in Australia though they were water dams; but nevertheless that that's the process we went through. And then, the next step was to make the argument about why you wouldn't do everything on that list.

Paul Ridlen

Any anyone else, any comment for you?

Joel Mårtensson

Well, just two notes. One of course, having something that can be applied to all jurisdictions sounds like pretty much impossible. But this process of not going after what's reasonable first, but instead first defining what is possible to do, i.e., what it's practicable, and then saying whether or not it's reasonable, this pretty well resonates with the Swedish environmental code. There you start by looking at what technologies are the best possible, and also available, and then try which technology is reasonable to use. That is, I will say, a good way of thinking about it.

Paul Ridlen

Anything to add Dom?

Dom Galic

Our situation is different. I can talk about it but I'm not sure how relevant it is to anyone in this room though. As far as I know, there's no expectation of ALARP in the US legal system. Most liability for a dam owner is going to be based on negligence, I believe, at least private dam owners. If somebody is being taken to court over a failure that's (ALARP) probably not even going to come up. Rather, they're going to focus on how they were negligent. All the different parties that could have a part of that negligence and so on. Reclamation has adopted the practice voluntarily. Voluntarily, again because there's nobody above us that's saying you have to do this or demonstrate this. The way that we use it now is a little bit different than others use it because we have the flexibility to see what is appearing to be working and to adapt the process. It's just another example of how it's (ALARP) really different for everybody.

David Bowles

There's at least one case of ALARP in the US, that Des may know some details about as well. It was a class action suit against the Ford Motor Company a few decades ago because the Ford Pinto was having a problem. The gasoline tank (petrol tank) was in the back of the car and when it got hit from behind it would explode and people lost their lives or they got seriously injured from the resulting fire. It turned out that when they (Ford) did the design of the Ford Pinto, they identified this issue before it went to market. And they did calculations - they did them on a chalkboard. And the discount calculations where they said OK, this is what it would cost to provide extra protection that would significantly reduce the risk of that (the explosion) happening. And I think it was less than $40 a car at that time. But it would have taken that vehicle over the $2,000 mark, which was kind of a niche in the market that they were aiming for. That was one thing that made them hesitate. The other thing was they did some calculations where they looked at statistics of this kind of an accident, and they made some calculations about what their liability would be on a case-by-case basis. They did the sums, and they essentially got to a balancing point where the additional revenue they expected to get by going to market at under $2,000, they thought was justification in their minds for being prepared to compensate people who were harmed. It turned out that somebody wrote that information down from the chalkboard and it went into the file and it was discovered during the class action lawsuit. And they (Ford) lost that lawsuit and I'm not giving you the right legal details here, but the gist of it was because they were at that …, essentially at a balance point, they weren't prepared to invest in a disproportionate way to save lives even if it meant hurting their market share. So, you know there's an example where ALARP principle seem to be applied in the US.

Dom Galic

But that was also probably more of an emotional appeal. I don't know if it was a jury trial or not, but again, I don't think that's set up legal precedent for ALARP in the United States. It's an example of how it can be used in a trial, but if you can convince the jury that they should be outraged, doesn't really matter what the reason for that is. That’s going to determine liability.

David Bowles

So, another interesting thing is that Kip Viscusi[1] looked at product liability cases in the US and he also got some information on what U.S. companies were prepared to invest to avoid a product liability lawsuit - in terms of making things safer than maybe they needed to do. So, he came out with, an on average, about a 10:1 disproportionality, which again isn't a legal thing, but it's an interesting example of what people are prepared to do, or a company is prepared to do to avoid getting into that (liability) situation.

[1] Viscusi, W.K. 1998. Rational Risk Policy: The 1996 Arne Ryde Memorial Lectures. Oxford University Press, Inc. May.

Paul Ridlen

I'm a moderator but I would like to comment. Even though there is not a strict expectation of ALARP in U.S. law, we are held to a standard of care, which is typically a reasonable main type of principle, so the principle would still apply, even though it's not strictly stated, as ALARP, I think that's what you're saying.

Dom Galic

One thing that could be interesting is, again, FERC requires its licensees to demonstrate if they are ALARP. I don't know if they really understand what that means, but it's in there, it's in their guidance. So if a FERC regulated dam under the new guidance fails and it goes to trial, it's quite possible that that concept will come up, unless it's simply easier for the parties to, again, focus on the emotional arguments and skip all that.

David Bowles

I suspect, just as you pointed out that after the fact that (ALARP) probably won't really matter; but FERC has resisted providing any guidance on disproportionality and they basically say that's a matter for the owner.

Dom Galic

It makes it hard to demonstrate ALARP as an owner. If nobody's telling you what to do or use.

David Bowles

They (FERC) have laid out some ALARP guidance, but they've just said they haven't provided guidance on disproportionality.

On static liquefaction

Paul Ridlen

If you have a static liquefaction failure mode, should you not do a risk assessment without considering the mitigation measure in place? Or without considering the mitigation measure?

Malcolm Barker

So, should you do one considering the mitigation? Is there a double negative?

Paul Ridlen

If you have a static liquefaction failure mode, should you do a risk assessment without considering the mitigation measure?

David Bowles

The challenge there is how you're going to characterise a full range of triggers, right? That's the challenge and I don't know that there's a way to do that. So, to me, if it's really a viable failure mechanism, a viable process, then you need to prevent it to the degree that you can. That's the highest point on the hierarchy of controls, right?

Jiri Herza

We attempted to address that question (of static liquefaction) in Appendix A and B of the ICOLD Bulletin 194 and I think we provided some answers in there. After many months of negotiations, we hope we developed something practical for people to follow and it was reviewed by David Reid, who led the short course on static liquefaction yesterday. The conclusion we came to is basically that we don't have the knowledge to be able to predict when static liquefaction happens. We don't even have names for all the triggering mechanisms, and we would be kidding ourselves if we put numbers to them. So, our rule no. 1 is: don't allow conditions at a tailings dam to result in a situation where liquefaction can occur. If that situation exists, don't look for the trigger, because the trigger may not be visible to you, and we believe you should take action.

Attendee

The reason I would maybe take issue with that approach is, you know, we have to show compliance to GISTM and how can we define whether or not static liquefaction or dynamic liquefaction, you know is credible. I mean we have to make a judgement on what is credible. And I know I'm getting into all the definitions, but that's required of us by the GISTM. And so, at some point you have to make a judgement call. Now, I agree with everything that you've said on that. If you have these issues, then you need to mitigate those issues. But if you don't have those issues and you've documented that. You know how are you able to meet their criteria for the GISTM that we have to complete risk assessment? And because I guess sorry the going back to the original concept for me is I would not go in front of an independent technical review board with a risk assessment without having considered static liquefaction. So, that's the first thing that I wouldn't do and my company wouldn't allow that. And so, we have to, you know, put static liquefaction into our risk assessment. And somehow, we have to make a judgement call now in, in our case, we do a lot of SQRA. And so you know, we make qualitative estimates on some of these things. But, anyway, it would be impossible for us not to include something about static liquefaction.

Jiri Herza

I agree with you and we are not suggesting that you should say "I do not look into static liquefaction, or any other failure". Static liquefaction is one failure mode that might or might not occur. You might recall about two hours ago we opened the piping toolbox. The screening tool which was there provided conditions at which the mechanism (piping) could not take place. Take static liquefaction, if you have a dry stack with no phreatic line and no saturation whatsoever, you may say I'm excluding this failure mode from happening because I don't have the conditions which are required for static liquefaction to occur. Or I might have, for example, materials compacted to a level that I can't get static liquefaction for any foreseeable loading conditions because I'm so outside of the zone (referring to a state at which contraction is possible). So, you might have conditions at your dam you can provide documented evidence of, that will not allow static liquefaction to occur because we know what susceptibility to static liquefaction is. We can't predict when it happens, but we know the circumstances at which it might happen. So, if you can demonstrate that you don't have those conditions at your site then you don't have to even go into probability to estimate.

Attendee

Then maybe, perhaps change the statement that was said that that a quantitative estimate of the likelihood of static liquefaction is difficult, possible beyond our certain capabilities. Is that a more fair statement to say?

David Bowles

That's my understanding and if I was in your situation then I think the option is to say, when you present your risk assessment, "This is credible, but it's indeterminate." We just can't put a number on it, but we've got to address it. And then it becomes the baseline for looking at the additional or residual risk beyond that and making your ALARP arguments beyond that, because you've already dealt with that particular credible failure mode.

Paul Ridlen

And that's what we're saying, what Jiri is saying and what is in the ICOLD bulletin. If static liquefaction is possible, if it's technically justified, then you just consider that it will occur rather than trying to assign a probability of occurrence, you assume a probability of 100%, of 1, which is pretty much what Morgenstern said in his 2018 paper. Now he did limit in his statement to preliminary design. But what he said is in his practice for preliminary design, if liquefaction can occur, I assume that it will and design for it. I think that's really where the current kind of standard of care is that you can actually have a static liquefaction to occur. And again, Jiri had described two ways that you can eliminate it, if the structural zone is compacted sufficiently so that it cannot occur under all reasonably anticipated loading conditions, or if it's unsaturated or saturated to such a low degree under all loading scenarios that that it can't be triggered as well, those would be the two kinds of primary exclusions that you could justify eliminating static liquefaction as a possibility.

Attendee

Or you have very plastic soil? You have a very plastic soil, so maybe, you're working in the very plastic domain and you're not having cohesionless soil. But you may have undrained conditions.

Paul Ridlen

Potentially, yes, potentially that there's enough plasticity or some other behaviour or you have, actual cement, right? So maybe, you add cement and you have a concrete dam in essence, so concrete dams typically are not considered to be liquefiable.

Attendee

Thank you for clarification.

Jiri Herza

Thank you all very much.

Panel Discussion No. 2

On duration of comprehensive risk analysis

Paul Ridlen

This one is for Dom. How long would it take to complete that (risk) review process on the example project that you presented?

Dom Galic

It depends on when you start the clock, but there is a formal milestone involving the physical exam of the dam, and then there's three months between then and when the results are presented. However, the review, the tabletop review can begin before the physical exam, so from the first time the team meets to when the work is completed could be on the order of 6 months. They usually end up being 500, 600 page documents, so they're pretty comprehensive.

On GISTM

Paul Ridlen

How do you, to the panel, correlate the ALARP requirement versus the GISTM's goal of zero harm to people and the environment, risks identified in the broadly acceptable zone versus acceptable loss of life. This is a risk, as it could wrongly suggest, that any additional preventative measures shall be implemented? ALARP does not mean necessarily safe TSF operation or safe closure. Does that make sense, or do I need to repeat?

Malcolm Barker

I think, Des once said, there's no such thing as a safe dam. There is always a probability that a dam could fail. ALARP is just trying to address what you can do to bring it down as far as the risk is concerned. It's not saying, “It's going to be safe.” It's just you're trying to bring down your safety margin.

Paul Ridlen

So, in other words, it isn't totally consistent with having a zero-harm goal but requiring ALARP to be met.

Jiri Herza

I believe that zero harm is an aspiration rather than objective. The only way you achieve zero harm associated with any asset is not to have that asset. But then it brings the burden to society of not having any benefits from the asset. You have one thing being an aspiration and another (thing) being a goal that you can actually achieve. I don't see that there is any disagreement and I see zero harm as the aspiration and we manage the dam towards this aspiration although it is not something that we may physically achieve.

Des Hartford

Can I make an observation? I was very surprised when the GISTM came out the way it did. Not only the way it did, but it didn't come out in interim form. Because if it came out in interim form it would be possible to test drive and work out all the bugs, over the five or a 10-year period and then revise it. So, is there a mechanism to go and get the GISTM into some type of, revision, evolving, updating basis? Because if it is not going to evolve, it will not be relevant in what is an evolving policy world anyway. So, in my view, there's a need to essentially take the step of getting to an updatable document where a lot of these wrinkles can be ironed out. The simplified matter is that we take these risks in the interests of societal progress. That's reality. We cannot come up with zero risk. It's impossible. And the rest is this is a balancing act. In my view, there's too much of government running away from it, dealing with its position as to what should be in relation to the public interest. If they were a little bit clearer there, then policy scientists would be able to work with it. COVID did expose, in governments all over the place, total inadequacy to deal with these types of tough issues. 40 years ago in the UK, Health and Safety Executive is only a shadow of its former self. They had a huge amount of capability in those days. They've lost a huge amount of it for political reasons. So, the whole question about the role of government, the role of regulations, the interpretation and where the owners sit relative to that, is something that is going to evolve. Who actually is the authority that produced GISTM?

Paul Ridlen

It was a temporary committee convened by three groups.

Des Hartford

Well, and now, look at what people have to deal with on the ground. Something that doesn't fit together.

Jiri Herza

Unfortunately, there is no one to complain because the offices are closed, and there is no one to receive feedback.

Des Hartford

Well, the offices might be closed, but the initiators, like one of them was in Sweden there was the Church of England, so the initiators are still around. It doesn't mean to say," It's closed." You can find these groups and then, once use of this approach and we have the experience, then we can go back to the same groups as the pension funds aren't going to disappear.

On failure modes

Paul Ridlen

OK, I'm going to try to get through these (questions) so we get as much as we can. The next one I think is pretty practical. Is there any list or generic list of failure modes and associated controls that are being developed for companies to use as a checklist or a starting point for identifying failure modes on TSF? Anybody aware of any? Papers or documents in progress.

Jiri Herza

There is one you might be aware of it. It's ANCOLD guideline on geotechnical investigation for dams that lists typical failure mechanisms and controls. It's not exhaustive and it just refers to failure mechanism associated with foundations including tailings dams. I'm not aware of any exhaustive list of potential failure modes and what you should do (referring to controls).

Paul Ridlen

There is a list of failure modes in the ICOLD Bulletin 194. It's not comprehensive and its very high level, but that is a place to start.

Des Hartford

Could I make an observation on this line because the question about failure modes is a difficult one. And again, all dams are unique. But every component in the dam has a functional mode. And you can invert the functional mode to get the failure mode directly. Loss of function gives you a failure mode, so if you know the functional mode, if you know how your dam your tailings dam works (you also know the failure mode). Now you've got these long structures, so you're going to have differences in foundation condition. You'll have to discretise your structure to be able to say everything in this section is pretty well the same. All the components work the same way. They're all under the same state of stress or whatever. But if you understand the functional modes, you can then invert them to get your failure modes unique to your structure and the way it works.

Jiri Herza

And vice versa, if you are able to express the narrative of failure, you are able to express the narrative of controls.

Malcolm Barker

I think just going out with that, every failure mode you define when you start to work through your process of the failure mechanism. To have a generic thing is sometimes dangerous. But you've got to think about your own dam and say well, what are the failure mechanisms, what other failures, what other components, what other functions, etc. To force you to think carefully about your dam, your tailings dam.

Paul Ridlen

I'm the moderator, but if I could just say that was the purpose of the exercise with the tool for piping. It was really more to walk through the process of thinking through and it's a well-documented process which has its value not to determine the actual calculation precisely. What the risk is, but of really informing the process so you follow the same process for other types of modes. They're identified through your understanding of how it functions.

Malcolm Barker

I know that the risk assessment guidelines at ANCOLD have a very small bit on tailings dams and basically say, you've got to look into tailings dams where the process is similar, but the failure modes are different, and you need to look carefully at the failure modes. They don't go through a list of exhaustively …, there's nothing of that.

On evolving nature of tailings dams

Paul Ridlen

This one should be quick. TSFs are structures that are continuously evolving over time. So what should you consider in the analysis? In the risk analysis? Do you evaluate the current condition or do you evaluate ultimate or final conditions?

David Bowles

I think there's some stages in between as well and you look at essentially critical stages all the way.

Malcolm Barker

I think you got to be very, very careful in saying this is what it's going to look like in 10 years time. You have no idea as it might change. You look at it right now, this is what it is now. And if you think it's going to change, you can try and do that. We've been asked to do all the time. What about in 10 years' time you say? Well, hang on, the population's going to change. They are going to put something over there, forget about the dam itself, the whole. downstream consequences will change. You don't know, so I think it's dangerous to try and say, yeah, I can evaluate it for 20 years time. Forget it. But closure is a different beast. If you said I'm going to have to close this, I have to reduce, I have to eliminate this, as Des says you walk away. I don't think any dam owner walks away. Actually mines, all the mining guys I know of, they still have to go there and do their operation and maintenance on a closed dam because they realise I cannot walk away from this beast, it has things that are happening.

Des Hartford

If the company still exists.

Malcolm Barker

Some don't exist and the government had to take over, right? And it's a nightmare for them.

Jiri Herza

I believe that, especially for tailings dams and especially for those that are raised upstream, you have to understand the future conditions. We discussed risk informed decision making during the design earlier, when, as Des explained, the situation is malleable, and we can modify design and reduce the risk. If you build upstream, what you are doing now will one day form a structural zone underneath the dam shoulder. You must therefore consider the future conditions and make risk informed decisions. For example, you have to compact say a 150 m long strip (of tailings) along the perimeter embankment in preparation for future raises and you have only one opportunity to do so, as now. In the future, you can't go back, remove the upstream raises and recompact (the tailings). You're right Malcolm, you never know what you're going to have, but you have to have in mind the foreseeable loading conditions.

Paul Ridlen

I guess my thought would be you, you have to evaluate the future conditions based on your current state of knowledge. So you don't know everything about the future, but you have a current state of knowledge and you use that to evaluate future conditions to the best of your knowledge. But I don't think you could stop just now because of the way that loading changes over time.

Ryan Singh

When you talk about risk assessment also depends the form, the tools you use. So something like the piping toolbox requires an understanding of your current performance, which you can't have for future facilities. It doesn't exist so you can't measure the performance, but you can use a risk informed design. The future actions, so it depends on what you mean by risk assessment as well.

Jiri Herza

The risk profile of water dams is changing as well. In Western Australia, we have a growing population and in Denver you have a growing population too Dom, right? So, you might have a dam, which had zero consequences of failure in terms of potential fatalities (when it was built) but as the population (downstream) has since grown and the consequences and risks have increased.

Malcolm Barker

To finalise that, as far as I'm concerned, when you're designing your facility you have to plan for the closure. That's part of your original plan, right? How many times have you had a closure plan that's changed? I guarantee your closure plan changes. Every single dam I've worked on has changed from the original. So you're struggling to actually say I'm going to be there in 10 - 20 years time. You really struggle. You can only do your best. And as things change, exactly like the population downstream, you got to fiddle around and that's where I'm coming from. You got to be very careful in saying, I can predict the future, you can't predict.

On risk informed design process

Paul Ridlen

I think there is one more important question and I think we've covered most of it, Dr. Morgenstern and others has advocated for the application of risk in the design process. The performance based, safe or performance based risk informed safe design? Do you think these concepts of risk assessment are applicable to design and is there adequate guidance in the literature to actually implement that? Ask Dom to start.

Dom Galic

Obviously, we've talked about this, but we are a little bit sceptical of risk for design at Reclamation simply because we don't want to be put in a corner. We don't want somebody to say to us, hey, look, if we do this, you're below guidelines, therefore it's OK. The guidelines are not a design tool. Designers should be making design decisions based on good practices and I can elaborate on that, but I won't. What I will say is there are some situations where there's really no existing design guidance. One example would be Teton Dam, like I mentioned earlier, Reclamation's only catastrophic failure to date. The reason the dam failed was because they decided, during the design process, that they could save money by creating these trenches in the fractured rock at either abutment. Once they did that, they could backfill those trenches with soil and basically be grouting from a lower elevation to save on grouting costs. There was no existing design standard at the time saying not to do that. And really the threats associated with that kind of design decision I don't think could have been appreciated at the time without really looking at it from a PFM perspective. I think if we had encountered that scenario today, we would be able to convince ourselves that it probably wasn't a good idea regardless of what the design standard said. So I think there's a place for it but we also have to be cautious about how it's going to potentially be used against you to put you in a place where you don't want to be, which is not what we should be doing.

David Bowles

I think the process of, as you go through your design, identifying failure modes, identifying controls and then making choices on what are reasonable controls to implement, that's a very good discipline to go through in the design.

Jiri Herza

And as engineers we do it although not explicitly expressed as a risk informed design process.

David Bowles

Yes, it's the thought process.

Malcolm Barker

We have to do safety in design. It's a requirement to do a safety in design evaluation, which is a living document that starts from when you can go from conceptual right through to the final construction. That's a risk basis in the sense of you're looking at safety. How you can do all your construction safely? Are you posing a risk by doing A, B or C or whatever else you can take it right down to component level or building a concrete beam that has to go across in a tunnel. Is it safe? Well, how do you put it in there? And what are the risks associated with this thing collapsing on somebody, et cetera. So I think it's quite appropriate to use risk informed design in that sense.

Des Hartford

Having tried on numerous occasions to understand precisely what Professor Morgenstern was saying, I failed on every occasion, but there is not sufficient guidance as to what is meant and how it might be applied, and across a broad spectrum of situations. What might be used in relation to risk informed design? Good practise risk assessment to plug the holes in good practise. Can't do much better than that, but basically you're meeting your deterministic criteria and your probabilistic criteria. Because the whole thing about these big structures that are there forever, as I mentioned earlier, they are a one-shot deal and you can't do cost benefit analysis on future generations. Just doesn't make sense.

Paul Ridlen

So it seems like the consensus is, again for the sake of closing things out, is that there is an application of these risk principles in design, but there's inadequate guidance currently on how to actually do that. I think we agree on that.

Dom Galic

And we could probably also agree that plotting below guidelines, whatever that means, does not mean the dam won't fail. It's an arbitrary bar. We said that we want to be below, but it doesn't mean anything in that sense.

Malcolm Barker

I think Des made the very good point that when a dam fails they're going to check you out. They're going to say "did you identify that failure mode and all of the things you did?" and if you say, "oh I didn't see that" you're in trouble. At the same time, when you're doing your design, what else you've got to find, you have to dig into. My ex-boss in Zimbabwe, he said there's a whole lot of work they're doing on Kariba Dam that is a complete waste of time on the plunge pool. I don't know if you know all about that now, doing this huge excavation, millions of dollars going into this. He disagreed with that whole failure mechanism in there and considered that rubbish. But it's been postulated, therefore, they've done something about it. If it failed and they hadn't done something about it, they'd be in serious trouble. Even though you might think it's a waste of time, it's not. It is a plausible failure mechanism, it can happen and you need to address it in some way, if it is really going to be serious.

On responsibility

Attendee

What's the responsibility? I mean, how does it work for a closed facility with very small consequences because there was nobody living downstream. Then, the government decides to build a town downstream and your consequences and your ALARP is out. So who's responsible and accountable for that?

Malcolm Barker and Jiri Herza

The government.

Des Hartford

Well, they (the government) should be responsible but they will do their best to pass it on.

Jiri Herza

The government should be (responsible), but in reality is not. They (the government) would grant the permit for those to build a house and it's up to you to make sure that they are not killed I'm afraid. That would be the case.

Paul Ridlen

I think it would depend on the location where you're at, so in theory it should be. The government is the one that imposed the risk because they're the one that imposed the consequence. But I think it depends on the location.

Des Hartford

But they (the government) also permitted the dam in the first place. So they've got it from all angles. It's just a difficult political decision for people who've got a short four-year mindset.

Dom Galic

You could also be a different government that granted the permit like in the United States, could be a local government, that permits the land use, whereas somebody else granted the permits for the dam.

Jiri Herza

And the circumstance may have changed. The pressure then was to build a dam for, let's say, agriculture. Now the pressure is to create more room for people to live in and it might be that the inundation zone below the dam break is the best zone for people to live in.

Dom Galic

Or the only area left to build it.

Des Hartford

I do agree, because I've had situations where chief executive would come to me and say, here's the one we're stuck on, come up with something and come up with basically a justification to take risk at a particular level. After doing everything that we could reasonably do to minimise the risk. I have got the dubious privilege of actually writing these things for them and it does actually force you to really think hard and going way beyond. You do an awful lot of things that are uneconomical to get yourself out of a political bind.

Jiri Herza

This is the last request for today. Can you all try to use this QR code and provide feedback for us to get better?

Appendix C. Material for group activities

Example dam – TSF1

Summary of facility statistics

Operational details

Type of information	Data
Name of facility	TSF1
Country	Australia
Region	Pilbara
Site/Operation	Undisclosed
Mineral	Iron Ore
Climate	Arid with hot dry summers and mild winters
Ore process	Crushing and screening

Facility details – Current arrangement

Component	Type of information	Data
Facility details	Facility-type	Single cell storage with one cross-valley embankment (Main Embankment) and two saddle embankments.
	Status of facility	Active
	Years active	30
Storage areas	Facility impoundment area (present) (m^2)	800,000
	Facility catchment area (m^2)	900 ,000
	Storage capacity (Mm^3)	18
	External catchment description	Catchment area sparsely covered with shrub and spinifex grass.
	External runoff coefficient	Not specified
Freeboard	Beach freeboard allowance	< 0.5 m
	Operational freeboard allowance	> 1.5 m

Component	Type of information	Data
	Wet season allowance	None
Flood handling	Flood handling capacity	PMF, estimated to be 1:1,000,000 AEP
	Flood management	Flood managed through flood freeboard and spillway.
Seismic design	Operating Basis Earthquake (ANCOLD)	1 in 475 AEP, PGA 0.0359g to 1 in 1000 AEP, PGA 0.0580g
Spillway	Location	Excavated into natural ground (rock). Located approx. 500 m away from the confining embankment. Arranged such that flows are directed away from the confining embankment.
	Type of spillway crest	Broad crested
	Type of spillway chute	Over natural ground (rock)
	Type of energy dissipating structure	N/A
	Sill level (RL m)	765
	Depth (m)	1.0
	Width (m)	35
	Capacity (m^3/s)	48

Facility details – Current arrangement (cont.)

Component	Type of information	Data
Tailings deposition system	Stored material delivery method	Delivery pipeline
	Deposition arrangement	Perimeter discharge, multiple spigots
	Sub-aerial / sub-aqueous?	Sub aerial
	Pipeline details (process plant to TSF)	DN 300 PE lined steel pipeline
	Pipeline details (at TSF)	DN355 HDPE PE100 PN10
	Spigot details	DN225 HDPE PN10 slotted pipe

Component	Type of information	Data
	Spigot spacing (m)	50
Return water system	Decant arrangement	Skid mounted diesel pump with floating suction line and screen
	Pump details	No details
	Pipeline details	DN250 PN10 HDPE
	Suction line details	DN315 HDPE PN10 open end pipe
	Decant return rate (m^3/hr)	200
Decant causeway	Details	Earth fill access ramp with a series of pads for the decant ramp to be located. Access ramp is located approx. 500 m upstream of the embankment, along the storage rim.
	Crest level (RL m)	Ramp down from RL 766 m to RL 759 m
	Raise details	N/A

TSF1 Main Embankment details – Summary

Component	Type of information	Data
General	Function	Confining embankment of TSF1
	Crest level (RL m)	766
	Max. dam height above ground level (m)	24
	Facility crest length (present) (m)	300
	Dam crest width (m)	6
	Average upstream slope (1v to ??H)	2
	Average downstream slope (1v to ??H)	2.75
	Depth of foundation cut-off (m)	2

Component	Type of information	Data
	Chimney filter present?	Yes
	Blanket filter present?	Yes
	Liner details	None
	Number of raises	1
Foundation	Foundation type	Soil foundation
	Foundation geology	Alluvial (soil)
PAR / PLL	Population at Risk (Flood Failure (FF))	10
	Population at Risk (Sunny Day Failure (SDF))	5
	Incremental Potential Loss of Life (FF)	5
	Incremental Potential Loss of Life (SDF)	0
ANCOLD consequence category	ANCOLD Flood Consequence Category (CC)	High B
	ANCOLD SDF CC	High C
	ANCOLD Environmental Spill CC	Low
Underdrainage	Type	None
	Drainage details	N/A
	Outlet details	N/A

Component	Type of information	Data
Starter embankment	Type	Cross valley embankment
	Crest level (RL m)	762
	Construction date	1989
	Construction material	Zoned earth fill: Compacted clay core with compacted earth fill shoulders with filter blanket and chimney filter
Raise 1	Type	Modified centreline raise

Component	Type of information	Data
	Crest level (RL m)	766
	Height	4 m raise
	Construction date	2015
	Construction material	Homogenous earth fill

History of TSF1

The original TSF1 was designed by a reputable design consultant (Consultant A) with a demonstrated history in the design and construction of water and tailings. The construction for the original TSF was carried out between June to October 1989 and the facility was commissioned in 1990. The TSF1 storage area was formed by the construction of one Main Embankment built across a valley in a historical watercourse that featured seasonal flows prior to the facility being built.

The Main Embankment was constructed to a reference level of RL 762 m. The Main Embankment was originally 20 m high and designed as a water retaining structure. A steel decant tower was constructed upstream of the Main Embankment with buried decant outflow pipes leading to a lined return water sump located downstream of the Main Embankment. The original tailings deposition formed a decant pond against the embankment to allow for decant water to be transferred via the decant tower to the return water sump. From there the return water was pumped back to the process plant.

A Pre-Feasibility Study (PFS) completed by another design consultant (Consultant B) in 2008 recommended that the next stages for TSF1 include staged upstream raising to a final height of RL 790 m to provide storage for then planned Life of Mine. To facilitate this, a change in the deposition practice occurred in approximately 2009 to move the decant pond away from the Main Embankment to allow for potential upstream raises. The decant tower was decommissioned and an alternative decant location was developed upstream in the storage area with ground-mounted pumps.

The buried outlet conduit was sealed and decommissioned during this time, however, there are limited design and construction records for this project.

The required deposition change was not implemented in sufficient time to develop adequate tailings conditions to allow an upstream raise of the Main Embankment. As a result, the strategy to upstream raise TSF1 was abandoned.

Instead, a mined-out pit was used for tailings storage between 2010 and 2015.

Additional TSF1 storage was created in 2014 by raising the Main Embankment by 4 m raise to RL 766 m. The raise was designed by a third design consultant (Consultant C), and construction was completed in February 2014. The condition of the tailings beach upstream of the Main Embankment had improved during the inactive period and the raise was completed using the centreline method. The raise also included the construction of two homogeneous earthfill saddle embankments.

Main Embankment details

Length: 300 m

Height: 24 m.

Cross section from original design report by Consultant A details embankment with zoning and filters. Internal clay core and chimney filter constructed to 757 m with starter embankment to RL 762 m, however, during the centreline raising of the embankment to RL 766 m, the filter and clay core were not extended.

Downstream face of 1V:2.5H.

Nominal 2 m depth cut-off shown in the As-Constructed Drawings. The photos of the keyway in the Construction Report suggest the cut-off was slightly deeper at the south abutment.

Has been raised 1 time using centreline raise technique.

Foundation details:

Original geotechnical investigation report for the facility stated that the ground conditions was identified to comprise variable thicknesses of clay and gravel overlying variably weathered banded iron formation rock types. The selected location for TSF1 was located across a narrow steeply sided valley. The abutments and downstream section of the valley were identified to comprise slightly weathered, dipping and jointed hard ridges and near vertical cliffs. Additionally, relatively thin scree slopes of gravels and clays were present at the bases of these ridges.

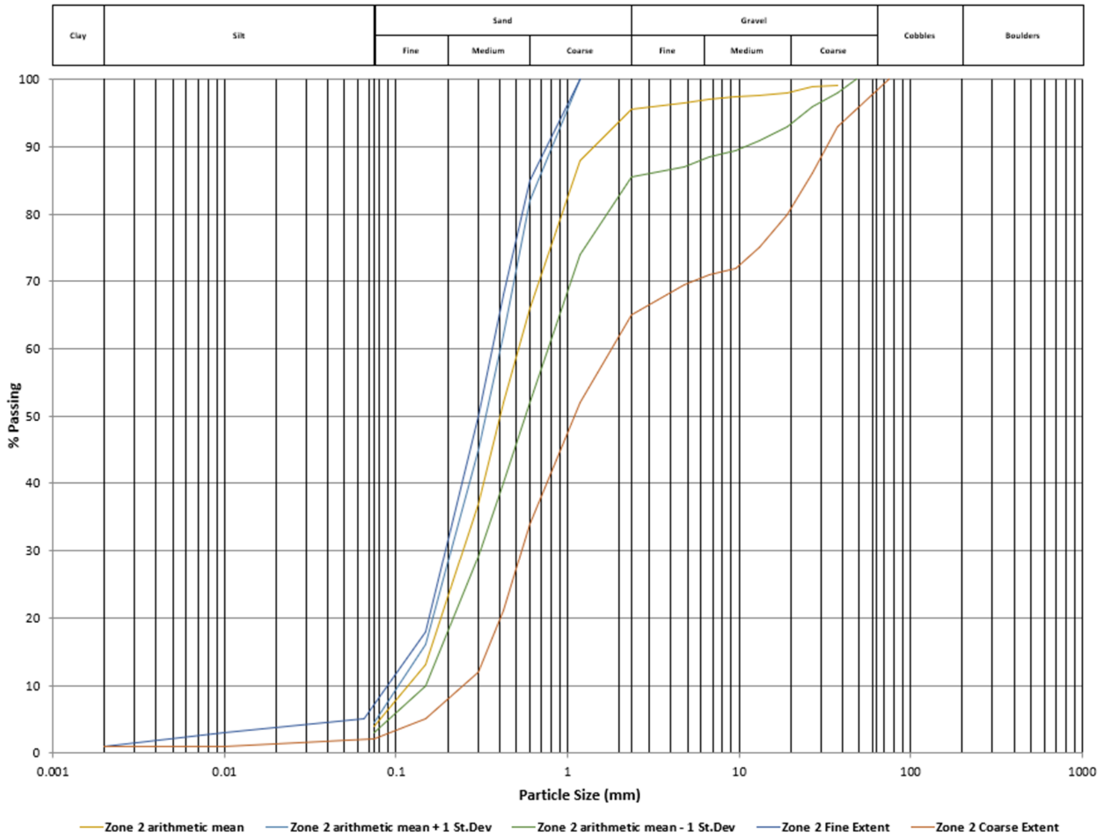
In the valley floor and towards the upstream section of the proposed embankment footprint, the ground conditions typically comprised clays and gravelly clays overlying variably weathered dipping and jointed shales and cherts. The report also documented that the abutment slopes were gentle to steep and covered by variable thickness of scree material. Identified rock outcrops generally coincided with the steeper sections of the slope near the contact with the banded iron rock.

A fourth consultant (Consultant D) completed a 2019 geotechnical investigation which included drilling of 3 boreholes in the Main Embankment crest, one in the middle, and one at either abutment, as well as a borehole at the downstream toe. The borehole logs indicate the foundations are soil, inferred to be alluvial.

Chimney and blanket filters:

The design of the filter zones in the Main Embankment was not clearly documented in the documentation made available for review. Additionally, there were no Quality Control or Quality Assurance certificates available, however, a Particle Size Distribution was found in available construction records which provide the bounds of the filter material.

These were later digitised as part of the raise design, in addition to the particle size distribution mean and standard deviations.



Tailings delivery arrangement:

HDPE delivery pipe running along crest of embankment and perimeter roads of the storage, with a series of spigots along the crest and perimeter roads. No structural assessment of the HDPE pipe is available, though it has been in operation for more than 6 years.

Supernatant pond details:

Decant pond has been located away from the Main Embankment for some time, with a stated minimum beach length of 200 m to be maintained. The beach length has typically been maintained at more than 400 m. These beach lengths correlate to a current pond elevations of RL 764.20 m and RL 763.20 m.

Extreme rainfall management:

The detailed design report for the raise to RL 766 m included flood routing which confirmed that the spillway at TSF1 will have sufficient capacity to convey the PMF flood, with the maximum water level as a result of the PMF being estimated to just be below the embankment crest level. Other rare and extreme flows were routed through the facility as part of the design, with the reported maximum water level, assuming a maximum operating pond for the facility at RL 764.5 m.

Event	Maximum water level (RL m)
PMF (1:1,000,000 AEP event)	765.94
1:10,000 AEP event	765.15 m
1:100 AEP, 72 hour event	764.6 m

Operational details and practices:

Based on available documentation, TSF1 has been operated as intended and has performed within expected limits.

Key inspection and performance note

Cracking – Transverse cracking on the crest of the Main Embankment has been noted periodically throughout the life of the facility. Typically, these cracks have formed all along the crest and does not appear to be located preferentially at any point on the crest. The majority of reported cracks have been in the order of 3 mm wide, however, there have been four reported instances of cracks being up to 20 mm wide at the crest. For these four instances, the crest was locally excavated up to 0.5 m deep, and material was replaced. An effort was made to see whether the cracks extended beyond the excavations, however, the earthworks resulted in the embankment conditions being obscured.

Seepage – There have been no reported instances of seepage from the Main Embankment, including during Stage 1 of the facility, when water was stored against the Main Embankment.

Stability assessments

A single section on the Main Embankment was analysed for stability in the raise to RL 766 m as presented in the design report. No discussion is provided in the report regarding the process of selecting and locating the sections.

A subsequent review in 2022 identified that the stability analyses presented in the design report for raise to RL 766 m does not meet current state of practice standards. This was due to the reviewer identifying that not all applicable scenarios or loading conditions were assessed. Additionally, pseudo-static analyses was carried out and at the time of the review it was deemed as an inappropriate technique for seismic stability assessments of TSFs.

Assessed Factors of Safety in the design raise report were:

- Drained – 1.6
- Undrained – 1.6
- Post-Seismic – 1.6

The outputs from the stability assessments completed in the raise design report are presented on the following pages.

Available documentation

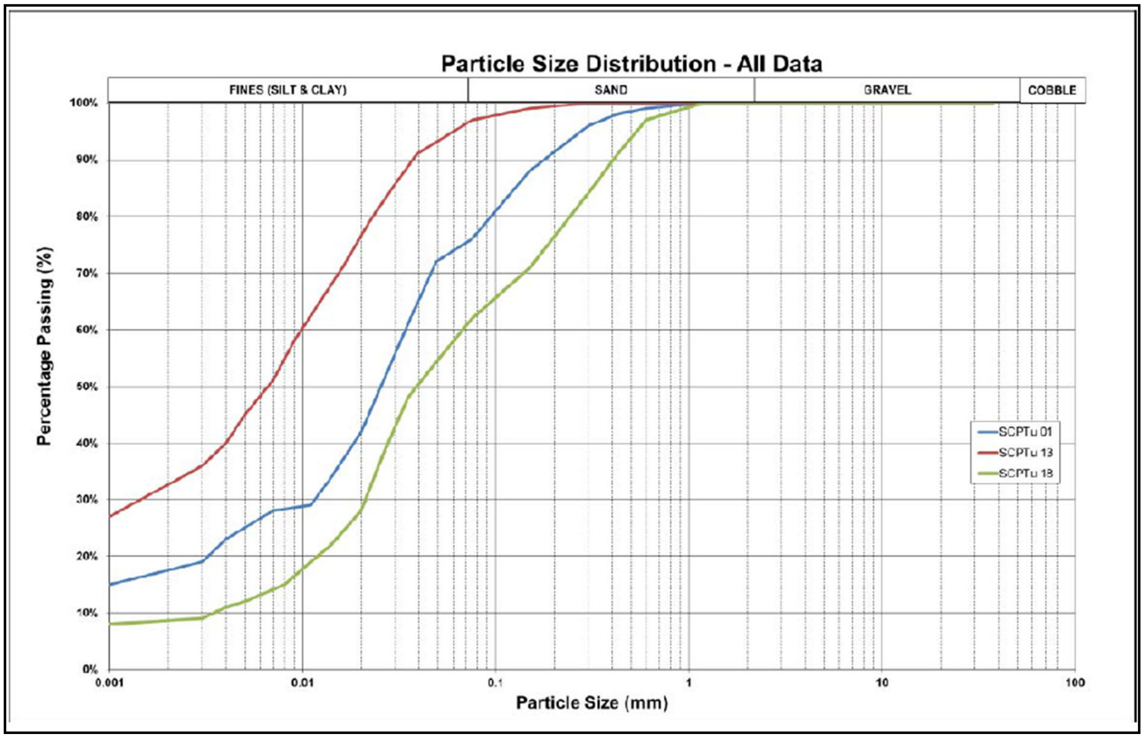
Geotechnical investigation reports and data

A significant number of native files related for the factual and interpretive geotechnical information from the original and raise projects was not available for this assessment.

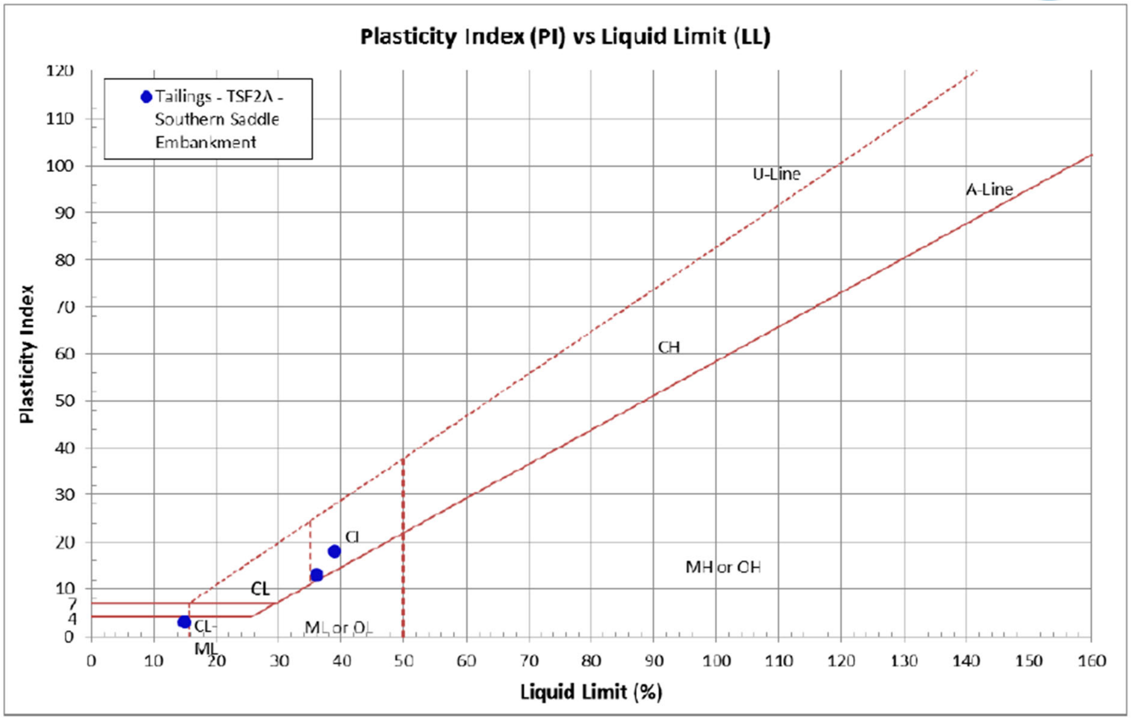
Select information, with notes, is presented below.

Tailings geotechnical data and interpretation

PSDs (locations of testing unknown, though understood to be from within 20 m of starter embankment)



Atterberg Limits – Tailings (locations of testing unknown, though understood to be from within 20 m of starter embankment)



Tailings particle density (locations of testing unknown)

Particle density tests completed for tailings sampled within 20 m of the starter embankment estimated a range of specific gravity between 3.42 and 4.20.

Tailings in situ moisture content

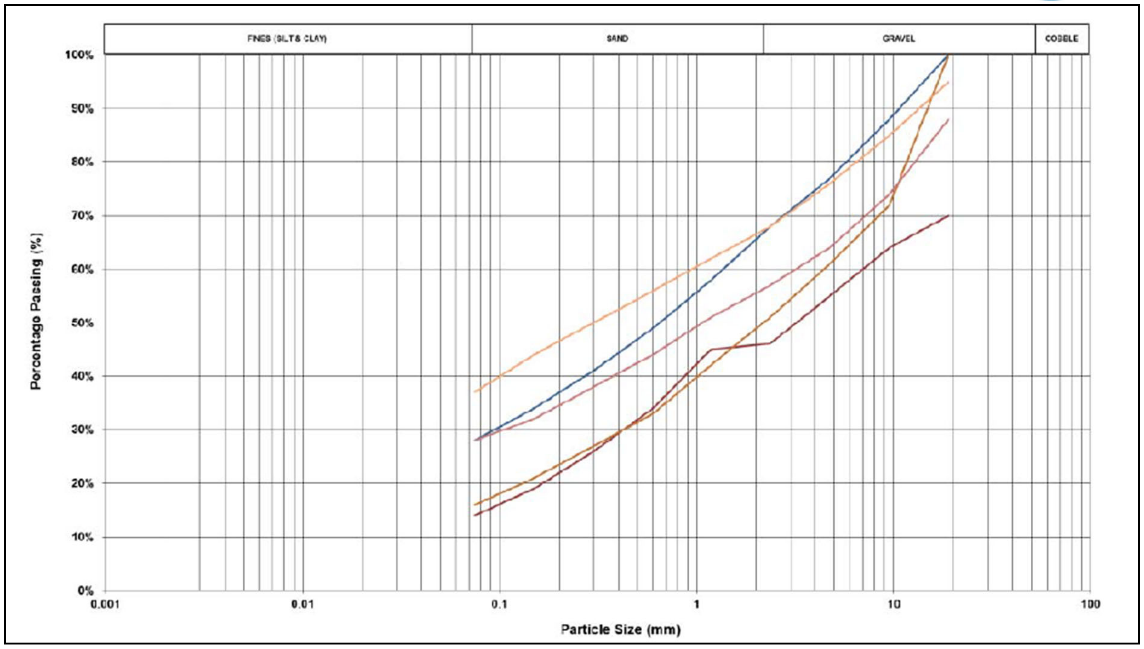
The moisture content of several tailings samples obtained from the tailings beach surface was measured by oven drying and the results ranged from 2.2% to 40.0 %

Tailings in situ density

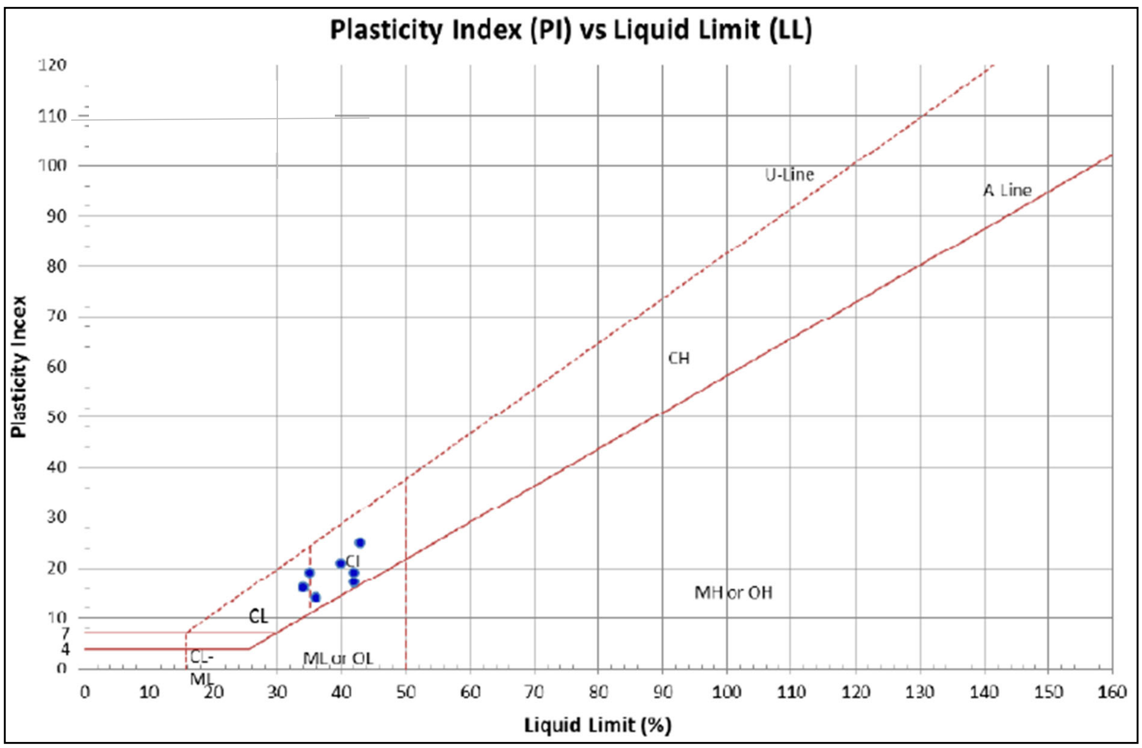
The in situ unit weight of the tailings was estimated from CPTs along the tailings beach of the starter embankment during the TSF1 raise project. The bulk unit weights shown in the table below were adopted for the embankment design stability analyses.

Embankment geotechnical data and interpretation

PSDs - Embankment core material (depths and locations unknown)



Atterberg Limits – Embankment core material (depths and locations unknown)



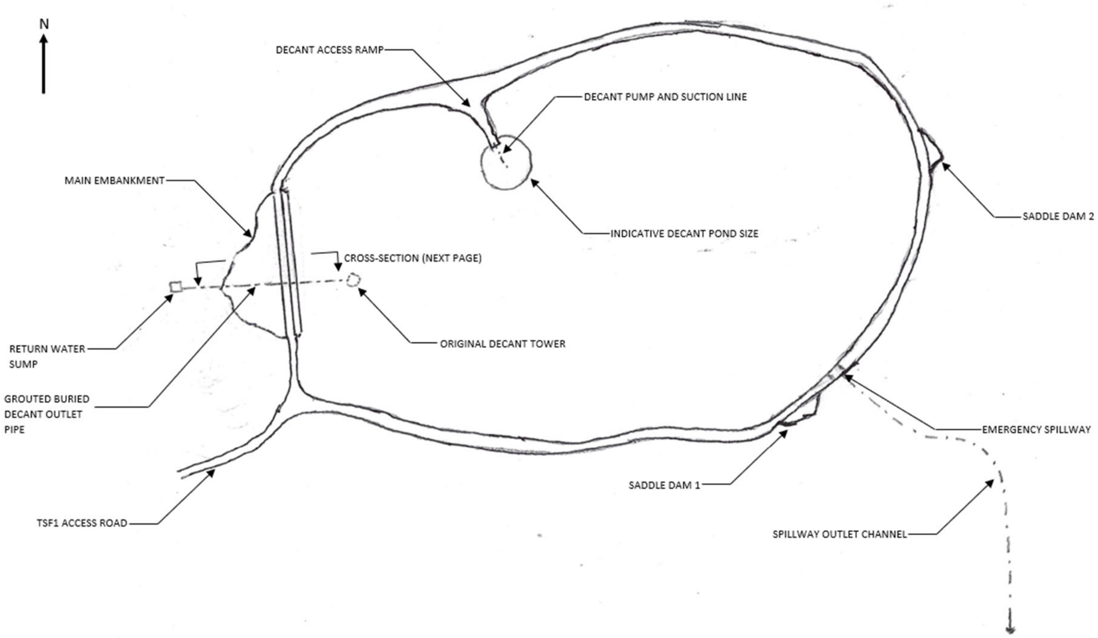
Embankment material moisture content and in situ density

For the TSF1 raise design, the dry density and moisture content of the embankment fill was estimated using lab certificates reporting the dry density of samples obtained from geotechnical investigations completed in 2010.

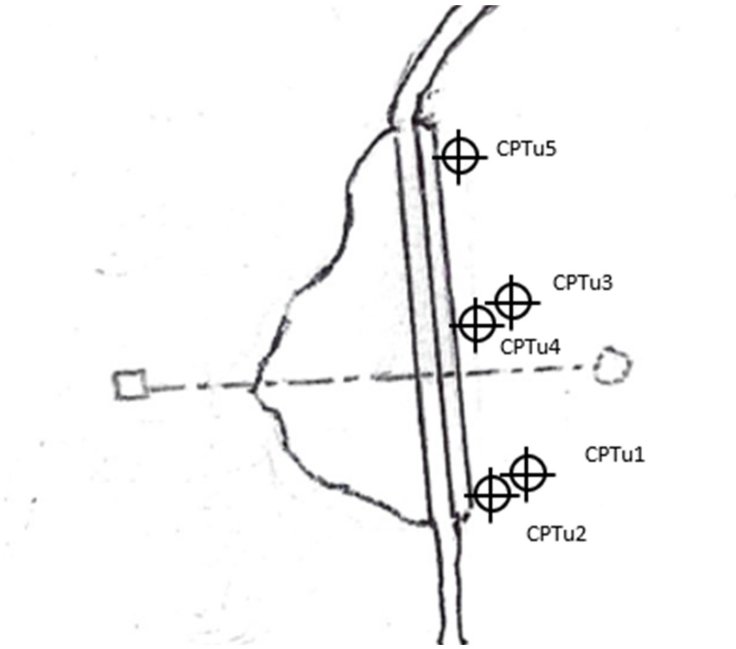
The results showed that the material moisture content was generally between 10% and 20% with a dry density of 1.75 t/m^3 to 2.15 t/m^3. This corresponded to a bulk density of 2.06 t/m^3 to 2.43 t/m^3. The average of these values corresponds well with the bulk density stated to be adopted in the design for the starter embankment. The raise design adopted a bulk density for the Zone A and Zone B embankment fill material for the Main Embankment of 21.5 kN/m^3 and 22.0 kN/m^3 respectively.

Additional figures

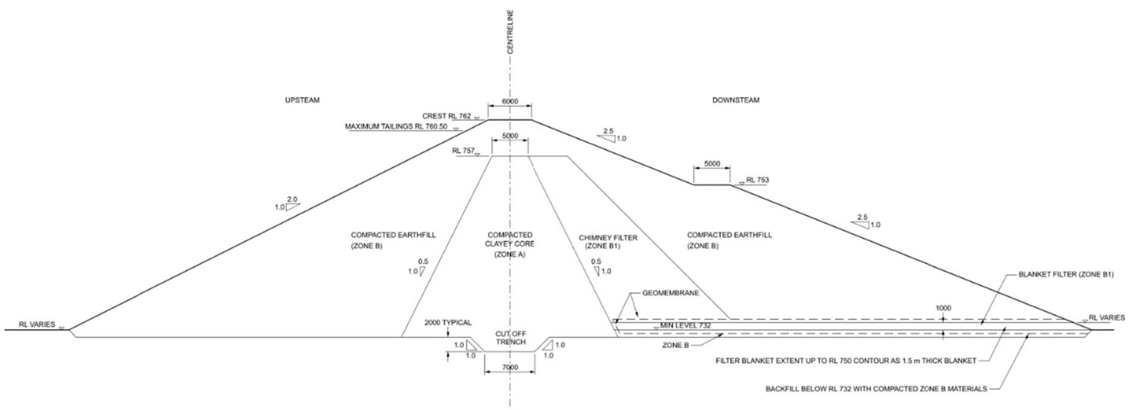
Hand-drawn plan of TSF1, indicating layout of key infrastructure (not to scale)

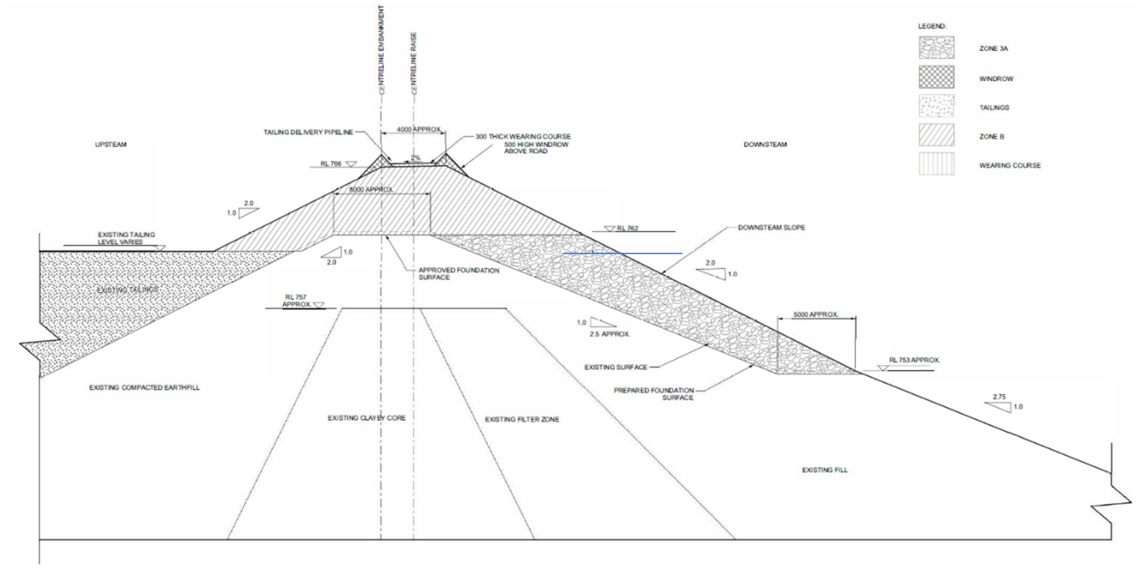


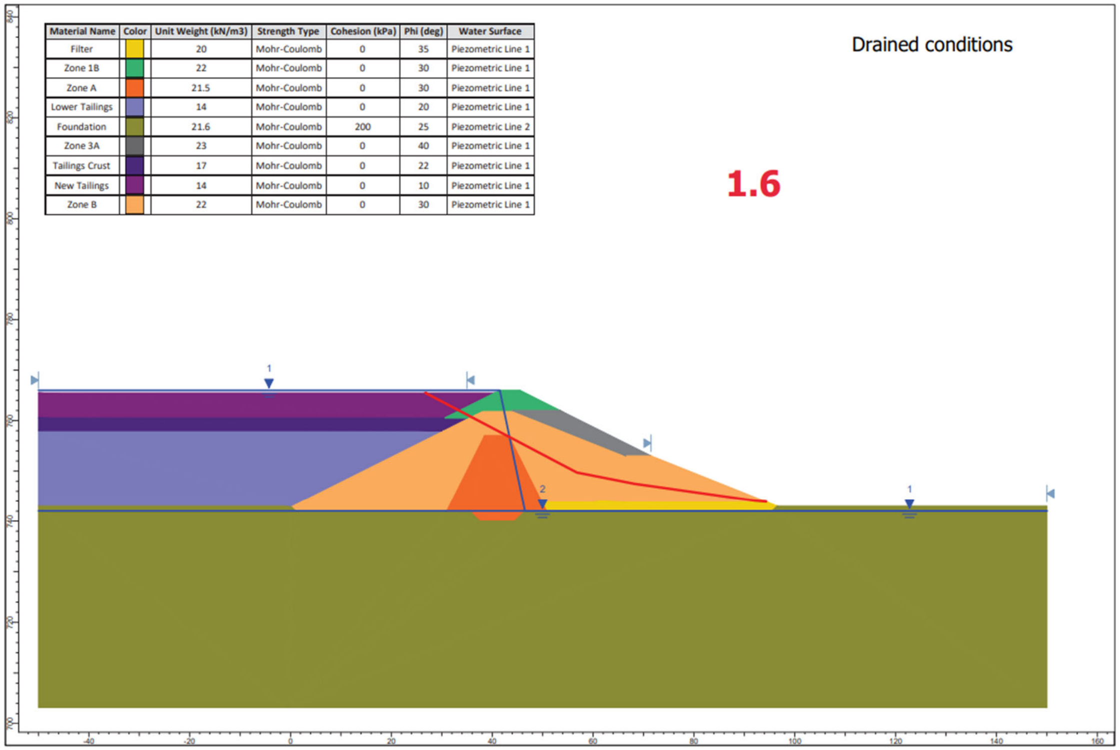
Hand-drawn plan of Main Embankment, indicating nominal locations of CPTu tailings investigation



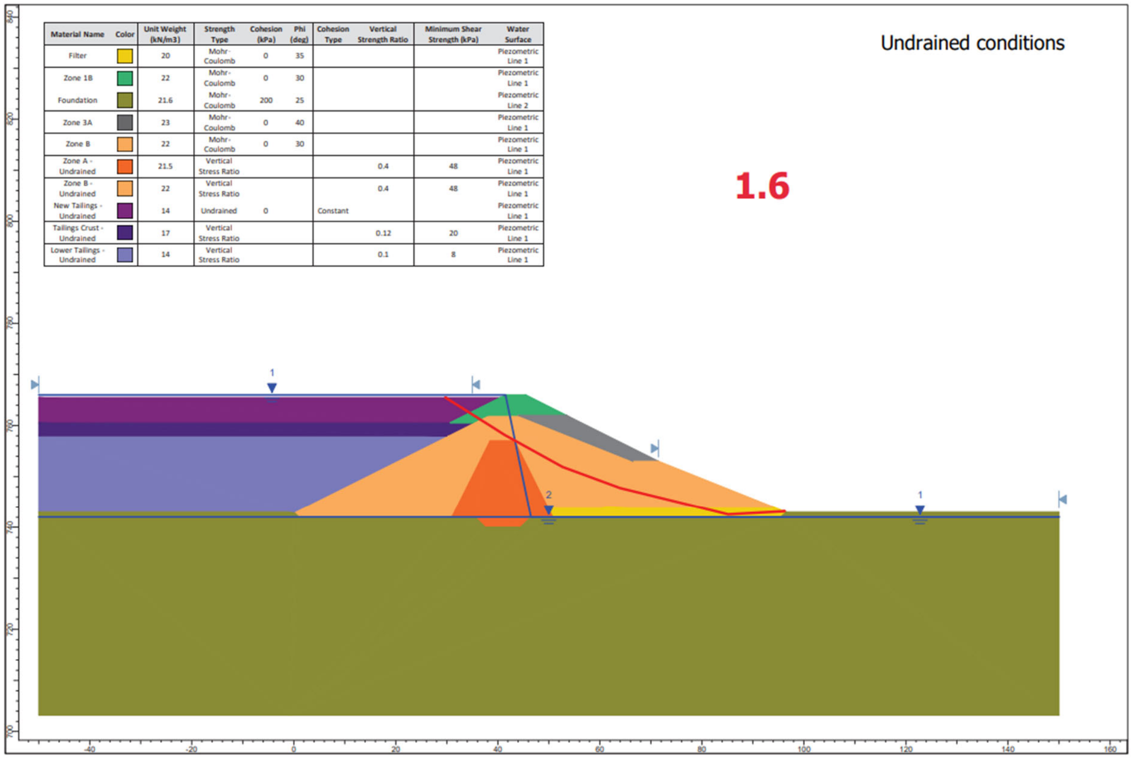
Typical section of Main Embankment – Starter Embankment



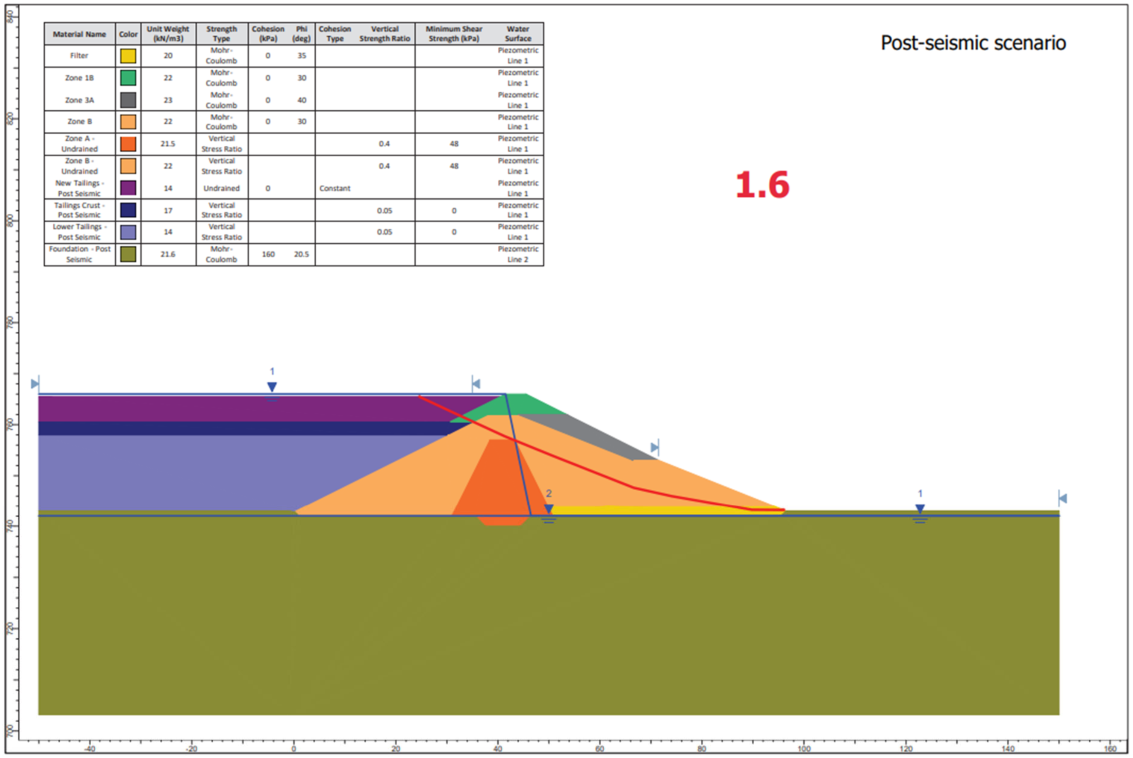

CENTRELINE EMBANKMENT
CENTRELINE RAISE
LEGEND:
ZONE 3A
WINDROW
TAILINGS
ZONE B
WEARING COURSE
UPSTEAM
DOWNSTEAM
TAILING DELIVERY PIPELINE
4000 APPROX.
300 THICK WEARING COURSE
500 HIGH WINDROW ABOVE ROAD
2%
RL 766
6000 APPROX.
2.0
1.0
EXISTING TAILING LEVEL VARIES
EXISTING TAILINGS
1.0
2.0
APPROVED FOUNDATION SURFACE
RL 757 APPROX.
RL 762
DOWNSTEAM SLOPE
2.0
1.0
1.0
2.5 APPROX.
5000 APPROX.
EXISTING SURFACE
PREPARED FOUNDATION SURFACE
RL 753 APPROX.
2.75
1.0
EXISTING COMPACTED EARTHFILL
EXISTING CLAYEY CORE
EXISTING FILTER ZONE
EXISTING FILL



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
Filter		20	Mohr-Coulomb	0	35	Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30	Piezometric Line 1
Zone A		21.5	Mohr-Coulomb	0	30	Piezometric Line 1
Lower Tailings		14	Mohr-Coulomb	0	20	Piezometric Line 1
Foundation		21.6	Mohr-Coulomb	200	25	Piezometric Line 2
Zone 3A		23	Mohr-Coulomb	0	40	Piezometric Line 1
Tailings Crust		17	Mohr-Coulomb	0	22	Piezometric Line 1
New Tailings		14	Mohr-Coulomb	0	10	Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30	Piezometric Line 1



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Cohesion Type	Vertical Strength Ratio	Minimum Shear Strength (kPa)	Water Surface
Filter		20	Mohr-Coulomb	0	35				Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Foundation		21.6	Mohr-Coulomb	200	25				Piezometric Line 2
Zone 3A		23	Mohr-Coulomb	0	40				Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone A - Undrained		21.5	Vertical Stress Ratio				0.4	48	Piezometric Line 1
Zone B - Undrained		22	Vertical Stress Ratio				0.4	48	Piezometric Line 1
New Tailings - Undrained		14	Undrained	0		Constant			Piezometric Line 1
Tailings Crust - Undrained		17	Vertical Stress Ratio				0.12	20	Piezometric Line 1
Lower Tailings - Undrained		14	Vertical Stress Ratio				0.1	8	Piezometric Line 1



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Cohesion Type	Vertical Strength Ratio	Minimum Shear Strength (kPa)	Water Surface
Filter		20	Mohr-Coulomb	0	35				Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone 3A		23	Mohr-Coulomb	0	40				Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone A - Undrained		21.5	Vertical Stress Ratio				0.4	48	Piezometric Line 1
Zone B - Undrained		22	Vertical Stress Ratio				0.4	48	Piezometric Line 1
New Tailings - Post Seismic		14	Undrained	0		Constant			Piezometric Line 1
Tailings Crust - Post Seismic		17	Vertical Stress Ratio				0.05	0	Piezometric Line 1
Lower Tailings - Post Seismic		14	Vertical Stress Ratio				0.05	0	Piezometric Line 1
Foundation - Post Seismic		21.6	Mohr-Coulomb	160	20.5				Piezometric Line 2

Group Activity 1

Potential Failure Mode Analysis for piping failure mode

Produce a Potential Failure Mode Analysis using suitable tools, such as event trees, fault trees or bow-ties for an embankment piping failure mode.

The Potential Failure Mode Analysis should include the cause and steps to the development of uncontrolled release of stored material.

Note: It may help to first define the system and sub-system of the TSF relevant to this failure mode.

Group Activity 2

Quantification of probability of embankment piping

Estimate the probability of piping through the embankment due to a poorly compacted layer in the embankment clay core.

Please refer to the calculation spreadsheet which will be provided on the day.