Potential Failure Modes and Semi-Quantitative Risk Analysis

Best Practices in Dam and Levee Safety Risk Analysis

Part A – Risk Analysis Basics

Chapters A-3 and A-4

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US Army Corps of Engineers®

U.S. Department of the Interior Bureau of Reclamation

Department of Energy Federal Energy Regulatory Commission

TVA

Objectives and Key Concepts: Potential Failure Modes (A-3)

Objectives

- Identify and describe failure modes.
- Understand what information is needed to develop failure modes.
- Understand how a potential failure mode analysis (PFMA) is accomplished.
- Understand how to screen failure modes and prepare for risk analysis.
- Learn the most common failure mechanisms.
- Learn how to identify and describe more and less likely factors.

Key Concepts

- PFMA is the foundation for risk analysis.
- Diverse team is important.
- Thorough review of information is critical.
- Examining how structures fail versus how structures are designed is important.

Objectives and Key Concepts: Semi-Quantitative Risk Analysis (A-4)

Objectives

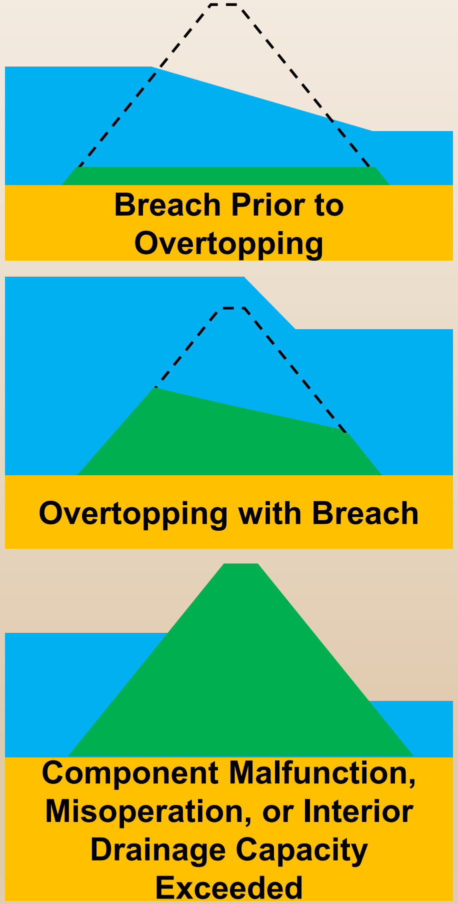
- Understand how to complete a semi-quantitative risk analysis (SQRA).
- Understand why one would do an SQRA.

Key Concepts

- Reasonable selection of likelihood and consequence categories.
- Understand how to combine loading and response probabilities to guide category selection.
- Understand the importance of uncertainty and category selection.
- Understand limitations of SQRA.
- Understand what SQRA results can be used for.

Potential Failure Mode

- A unique set of conditions and/or sequence of events that could result in failure or breach.
- Failure or breach characterized by the “sudden, rapid, and uncontrolled release of impounded water” (FEMA 148).
  - Loss of damming surface.
- Other “failures”
  - Loss of service issue with economic risk only (e.g., closure of navigation lock)
  - Inability of the damming surface to function properly leading to upstream consequences.

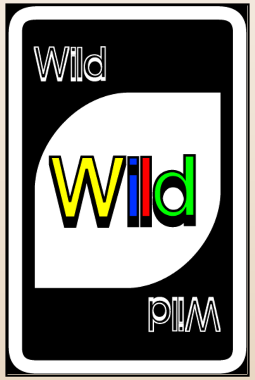


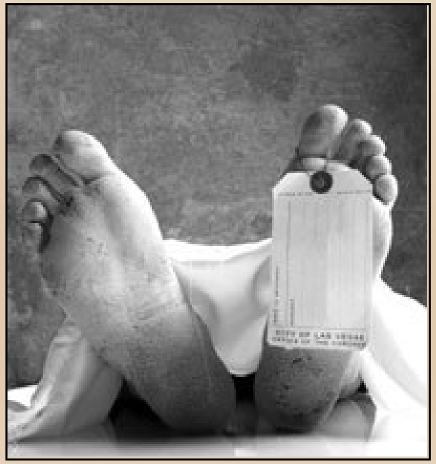
Potential Failure Mode Analysis (PFMA)

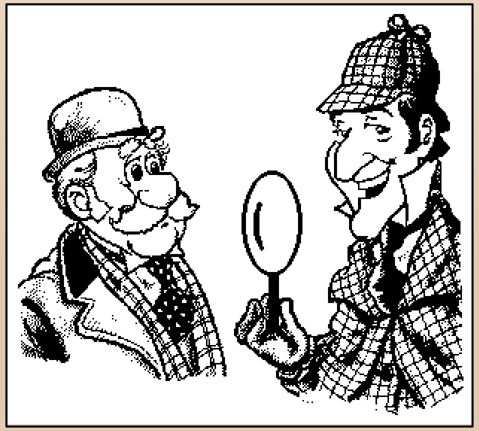
- Facilitated process of identifying and fully describing potential failure modes.
- Based on a diverse team's understanding of the project's vulnerabilities from a review of existing data and conditions.
- First step in any risk analysis after collecting and reviewing all pertinent background data.

Key Concepts of PFMA

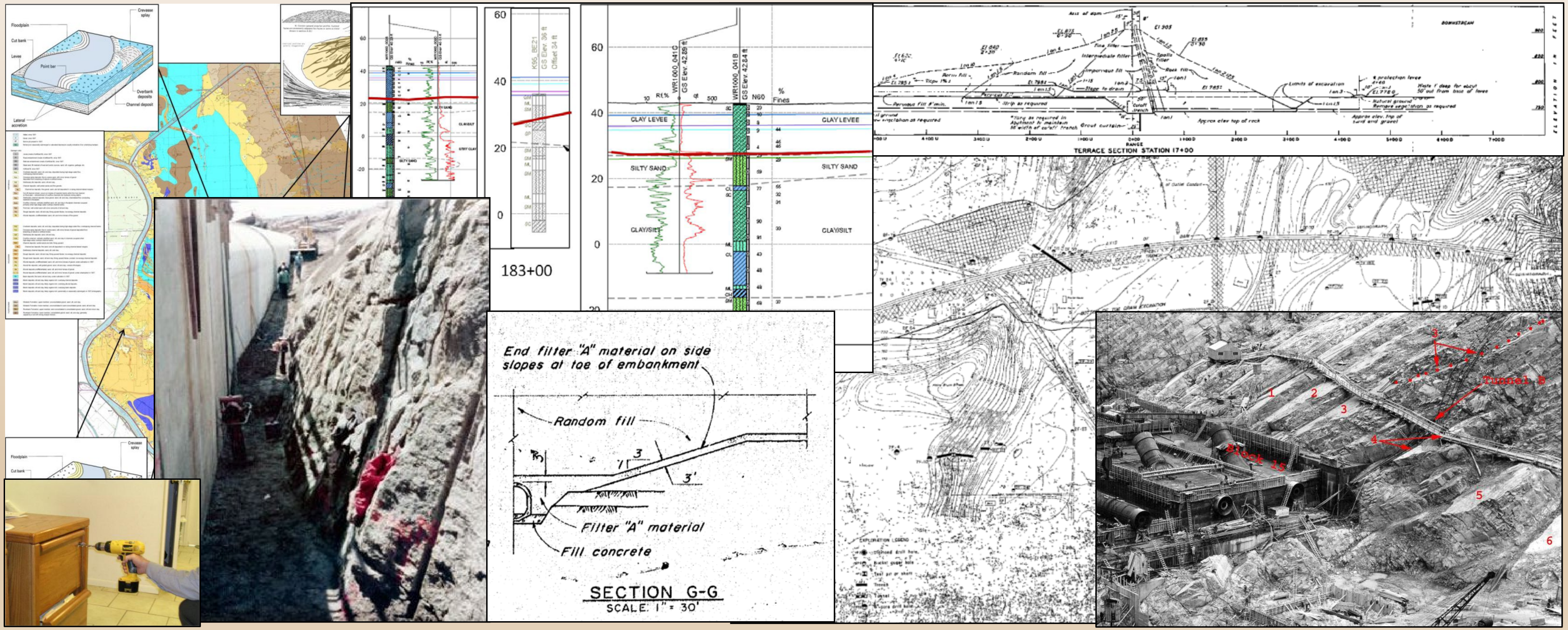
- Think beyond traditional standards-based analyses.
- “Beware the oddball” (creative thinking).
  - Consider malfunction and misoperation.
- Think like detectives or coroners (forensic work).
  - Look for susceptibilities and vulnerabilities.
- PFMs can cross disciplines (use multi-disciplined teams).
  - Seismic deformation of a concrete structure leads to initiation of internal erosion in the embankment.



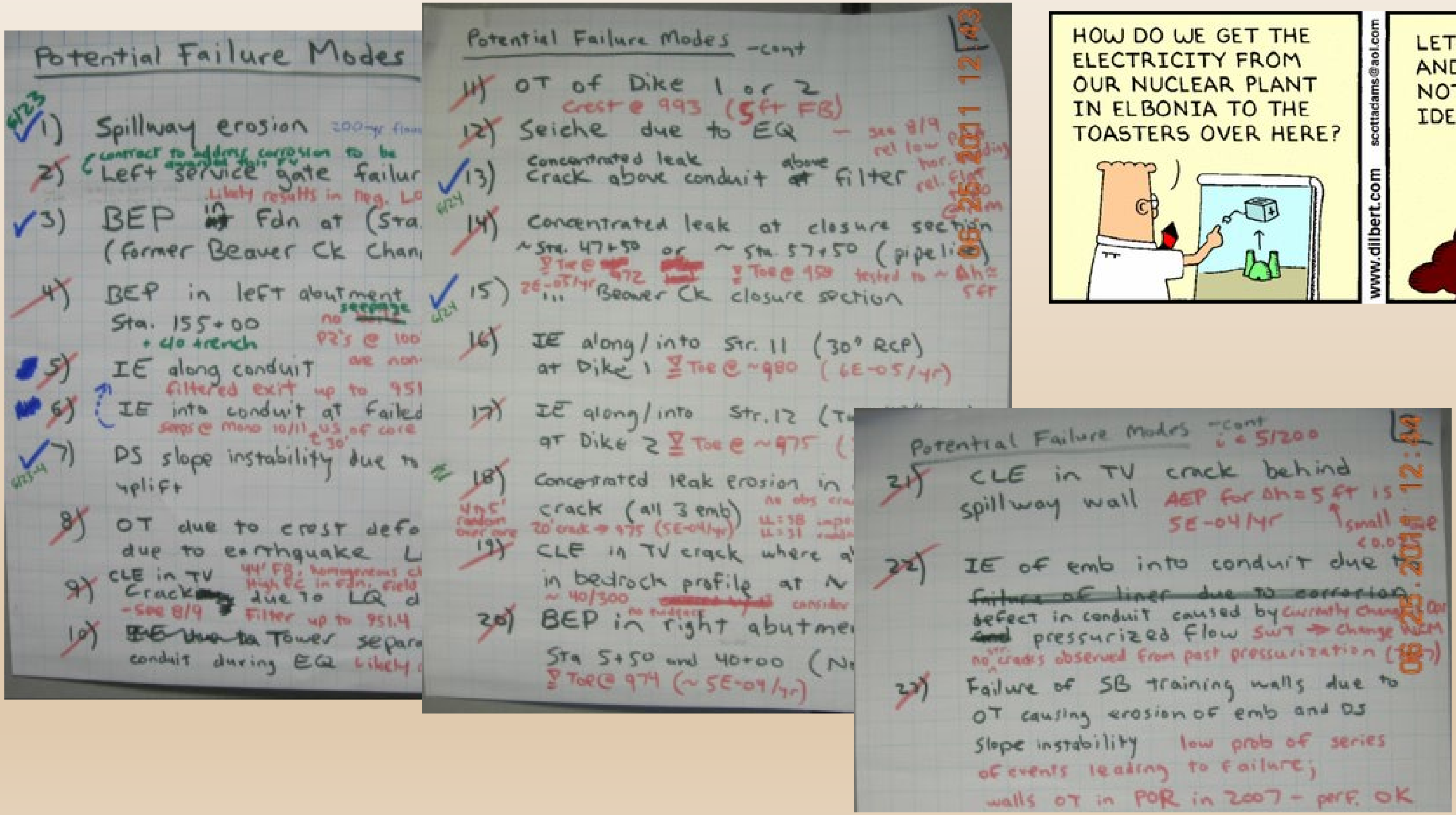


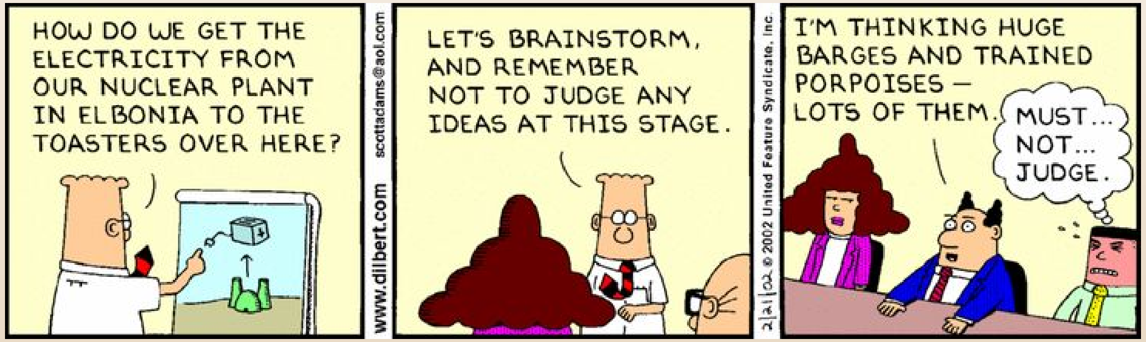


Background and Performance Data



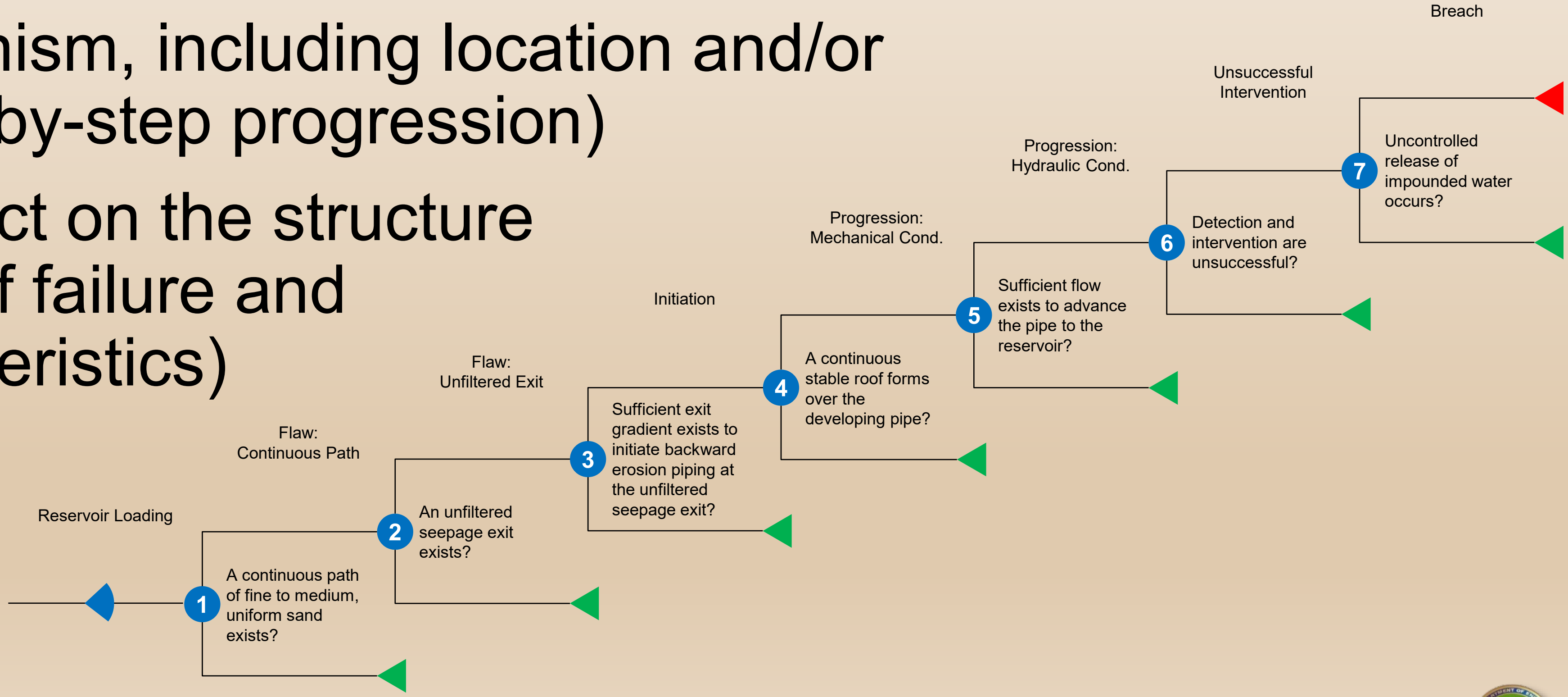
Brainstorming Potential Failure Modes



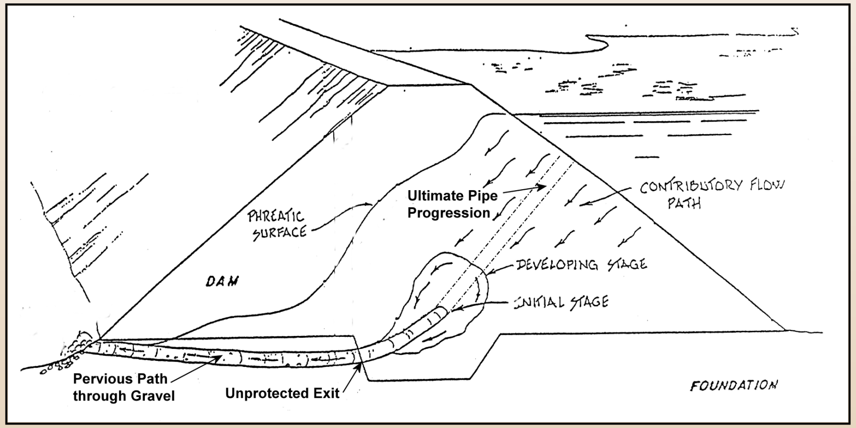


Elements of Failure Mode Description

- Initiator (e.g., impounded water load, earthquake, misoperation/malfunction, degradation or deterioration)
- Failure mechanism, including location and/or pathway (step-by-step progression)
- Resulting impact on the structure (e.g., rapidity of failure and breach characteristics)



Example of Failure Mode Description



- Unedited (insufficient detail):
  Piping from embankment into foundation
- Edited: During a period of reservoir levels exceeding EL 950 ft-NGVD (1/300 ACE), piping of the embankment core initiates at the gravel foundation interface in a shallow cutoff trench near Sta. 2+35 (where problems with the sheet pile and sinkhole occurred). Detection and intervention are unsuccessful. Backward erosion occurs until a “pipe” forms through the core exiting upstream below the reservoir level. Rapid erosion enlargement of the pipe occurs until the crest of the dam collapses into the void, and the dam erodes down to the rock foundation.

Adverse "More Likely" Factors

- **The gravel alluvium** ***in contact with the embankment core on the downstream side of the cutoff trench is*** **similar to the transition zones which do not meet** ***modern "no erosion"*** **filter criteria** ***relative to the core base soil*****.**
- The gravel alluvium is likely internally unstable, *leading to erosion of the finer fraction through the coarser fraction and even worse filter compatibility with the core*.
- The reservoir has never filled to the top of joint use; *it has only been within 9 feet of this level; most dam failures occur at high reservoir levels; the reservoir would fill here for a 50 to 100-year snow pack (based on reservoir exceedance probability curves from historical operation)*.
- The core can sustain a roof or pipe; *the material was well compacted (to 100 percent of laboratory maximum), and contains some plasticity (average Plasticity Index ~ 11)*.
- **There is likely a** ***significant seepage*** **gradient** ***from the core*** **into the** ***downstream*** **gravel foundation,** ***as evidenced by the hydraulic piezometers installed during original construction (and since abandoned)*****.**
- *It is likely that* all flow through the foundation cannot be observed *due to the thickness and pervious nature (transmissivity) of the alluvium*.

Favorable or “Less Likely” Factors

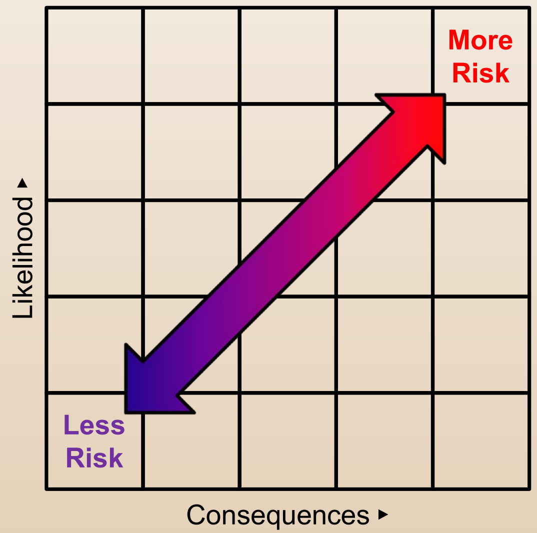
- Very little seepage is seen downstream; *the weir at the downstream toe, which records about 10 gal/min at high reservoir when there is no preceding precipitation, indicating the core is relatively impermeable; these flow rates may be too small to initiate erosion*.
- The core material is well compacted *(to 100 percent of laboratory maximum)* and has some plasticity *(average Plasticity Index ~ 11), both of which reduce its susceptibility to erosion*.
- No benches *were left in the excavation profile that could cause cracking* and *the abutments were excavated to* smooth slopes less than 2H:1V.
- *If erosion of the core initiates,* the gravel alluvium may plug off before complete breach occurs, *per criteria for “some erosion” or “excessive erosion” (Foster and Fell 2001)*.

Review Consequences of Failure

- If the dam were to breach, a highway, railroad, two bridges, farmhouses, gas station, aggregate plant, barley mill, transmission line, and the town of Tannerville (30 river miles downstream) would be at risk. There is little recreation activity downstream of the dam.
- The flood wave would spread out into the wider valley by the time it reaches the population centers, 6 hours after breach, and there are numerous evacuation routes to clear the inundation zone. The total population at risk is estimated at about 1,400.
- The embankment is constructed of well compacted, moderately plastic material, and the foundation alluvium is mostly cohesionless sand. A moderately fast erosion breach would likely occur down to bedrock.

Why Semi-Quantitative Risk Analysis?

- Situations where it is desired to apply risk analysis principles to decision making without the time, cost, and data/analysis requirements associated with a full quantitative risk analysis.
- Portfolio assessments where it is desired to get a quick evaluation of risk so that risk-reduction studies and actions can be prioritized.
- As a high-level screening to determine which PFMs should be carried forward for quantitative analysis or require additional studies to reduce uncertainty.



Failure Likelihood in SQRA

Quantitative Risk Analysis

Average Annual Life Loss (AALL)

Annual Probability of Failure (APF)

Incremental Consequences

ACE

SRP

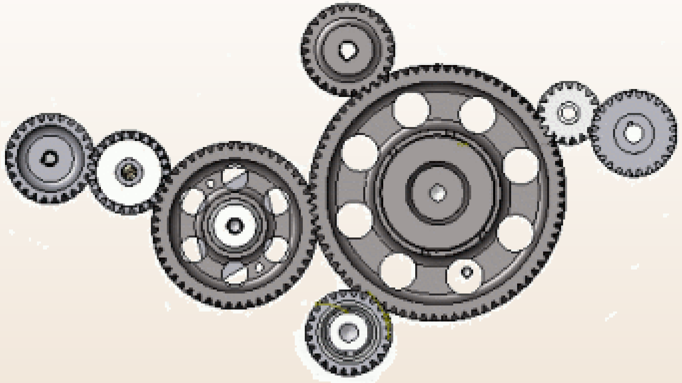
$$\text{Risk} = f\left[\left(\begin{matrix}\text{Probability}\\ \text{of the Loading}\end{matrix}\right), \left(\begin{matrix}\text{Probability of Failure}\\ \text{Given the Loading}\end{matrix}\right), \left(\begin{matrix}\text{Consequences}\\ \text{Given Failure}\end{matrix}\right)\right]$$

Semi-Quantitative Risk Analysis

Likelihood of Failure
f(Loading <u>and</u> System Response)

Consequence Level

Overview of SQRA Process



- Review all available background information diligently.
- Conduct a brief site visit focused on vulnerabilities.
- Review loading (Part B) and baseline consequences (Part C).
- Brainstorm potential failure modes.
- Categorize as risk drivers or non-risk drivers.
- Discuss, evaluate, and classify risk for risk drivers.
- Evaluate urgency of action (A-9), IRRM, and data/analyses needs.
- Document major findings and understandings.

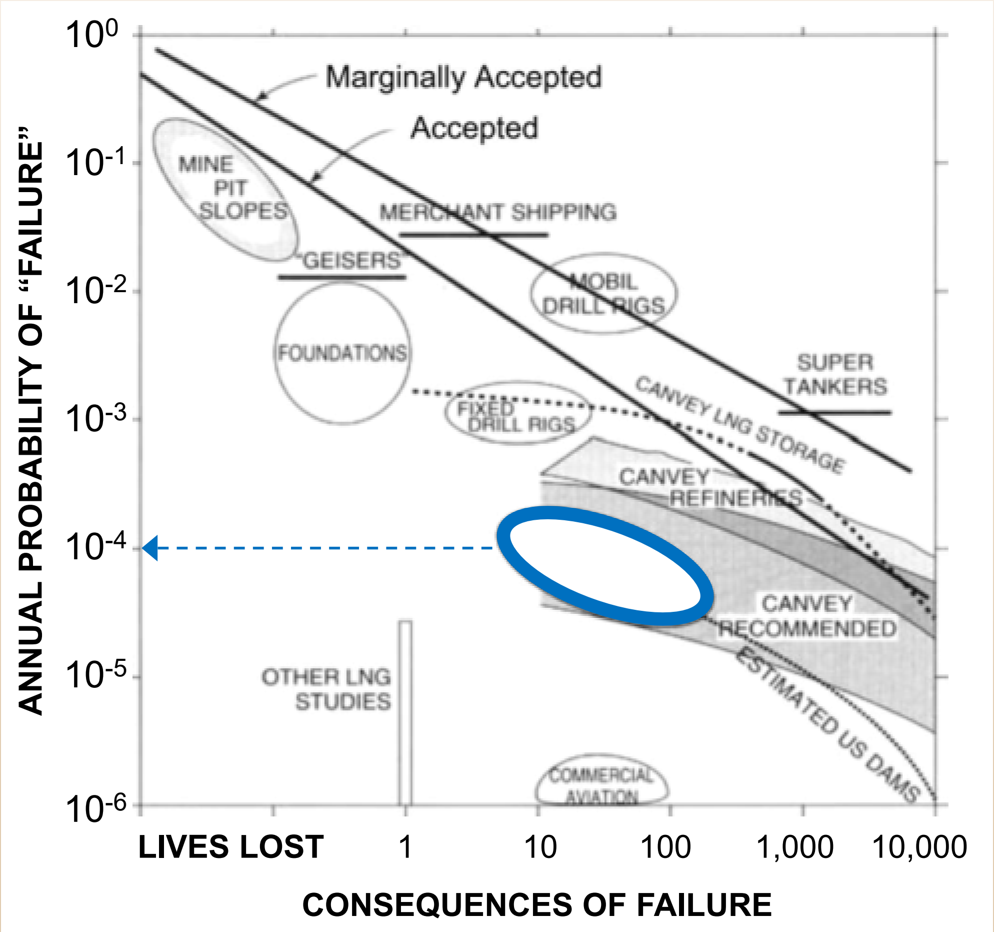
Categorization of Potential Failure Modes

- Risk drivers ► Fully described/evaluated using SQRA
  - Potentially contribute the most to the risk.
  - Evaluate at least one risk driver associated with the damming surface.
  - Consider the greatest vulnerability in each major project feature (e.g., embankment, foundation, spillway, concrete gravity section, etc.).
- Non-risk drivers ► Rationale documented
  - Physically implausible or non-credible.
  - Credible but not expected to contribute significantly to the risk.

Discussion of Risk Drivers

- Document pertinent background and performance data.
- Fully describe from initiation to failure or breach.
- Document “more likely” and “less likely” factors.
- Estimate likelihood of failure and provide rationale and confidence.
  - Loss of damming surface: order-of-magnitude range of APF.
  - Loss of service: likelihood of failure category.
  - Consider intervention and likelihood of success.
- Estimate incremental consequences (order-of-magnitude range) and provide rationale and confidence.
- Discuss possible recommendations for additional monitoring, risk reduction, data, or analysis.

Historical Failure Rate for Dams

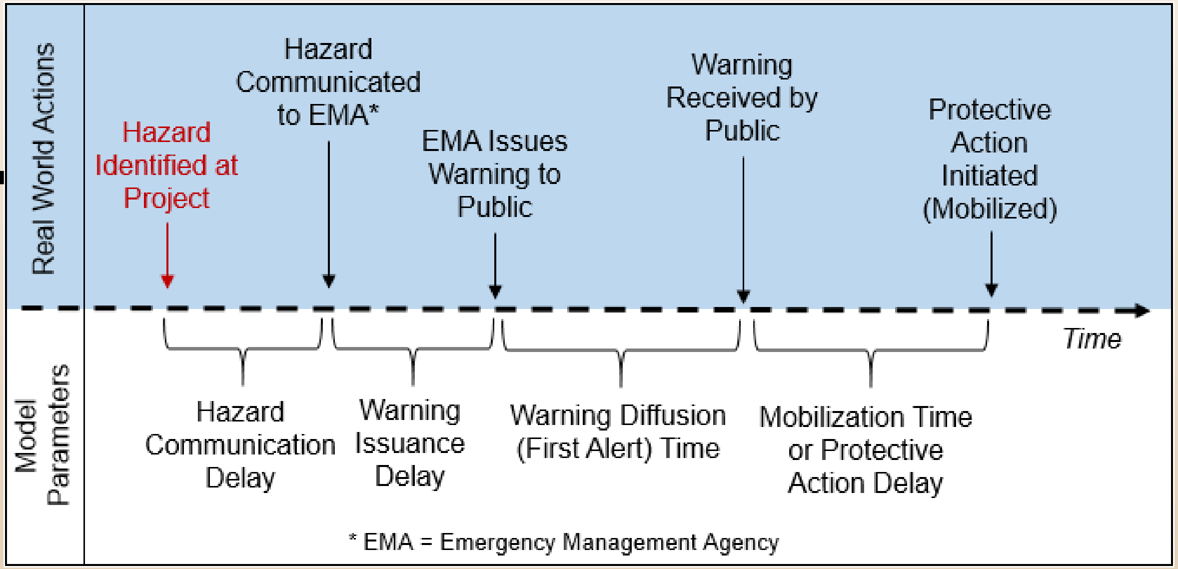


Source: Baecher (2003) *Reliability and Statistics in geotechnical Engineering*

- APF ≈ 1 in 10,000 failures/year
- Whitman and Baecher (1981)
- Von Thun (1985) 1.4E-04
- Hatem (1985) 2.6E-04
- M.K. Engineers (1988)
- Foster et al. (1998, 2000)
  - Built before 1950: 3.6E-04
  - Built after 1950: 1.6E-04
  - All Dams: 2.0E-04
- Douglas et al. (1998)

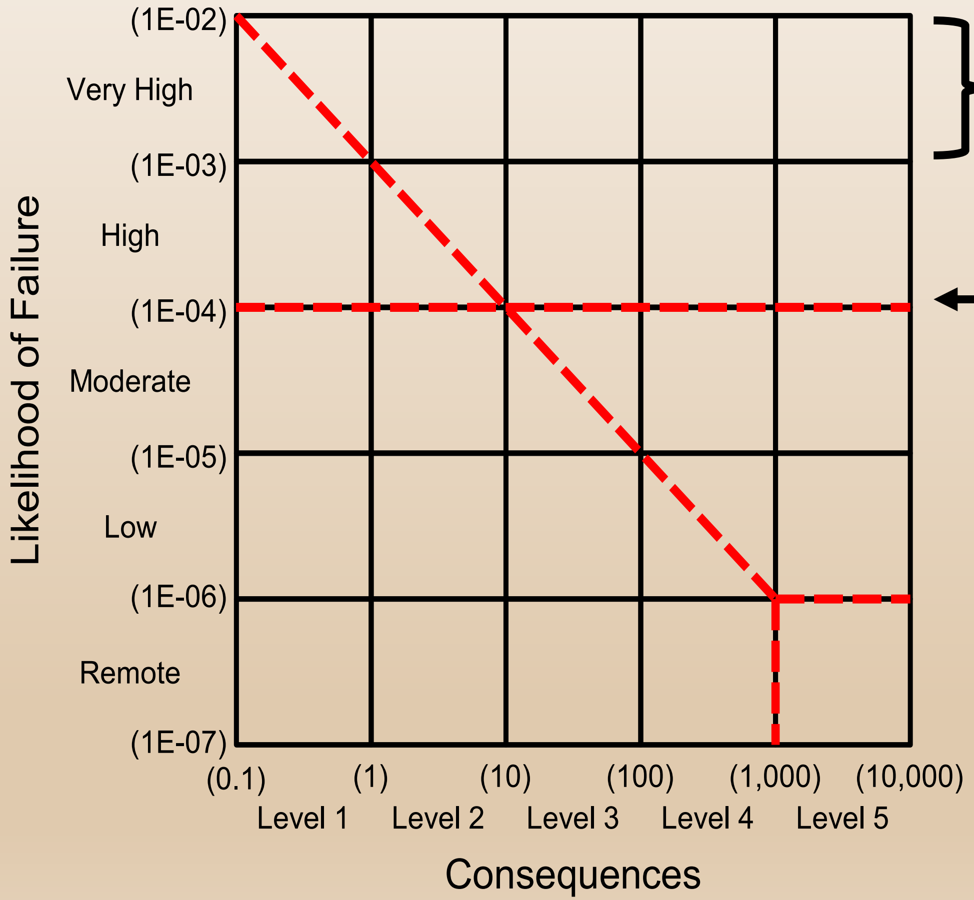
Consequences

- Initial distribution of people (PAR)
- Redistribution of people
  - Threat recognition / warning issuance
  - Warning diffusion
  - Protective action initiation
  - Evacuation potential



- Flood characteristics
  - Flood wave arrival time, depth, and velocity
- Shelter provided by final location
  - Potential for vertical evacuation and shelter in-place: number of stories
  - Survivability: structure damage, human stability, and vehicle stability

Risk Matrix



Likelihood of failure is more than 10 times higher than the average dam in the U.S., including all high, significant, and low hazard dams built by everyone.

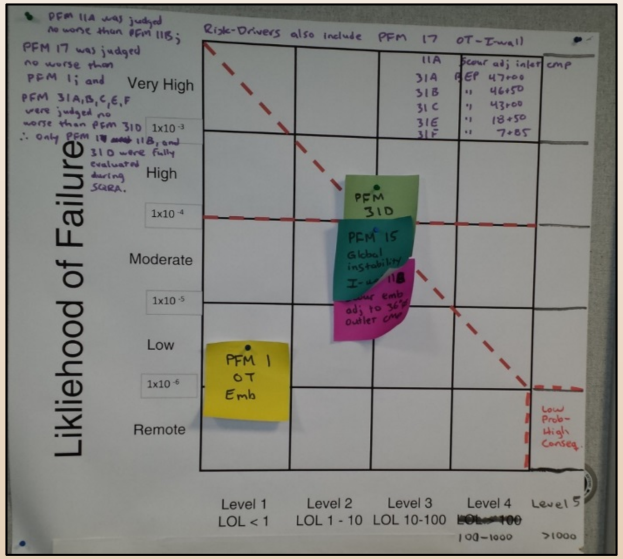
Historical failure rate for <u>all</u> dams worldwide.

General Elicitation Process

- Conduct first round of estimates anonymously.
  - Minimizes “bandwagon” effect and “anchoring” bias.
  - Must discuss extreme estimates or outliers.
- Share thoughts on initial responses.
  - Open discussion encourages group interaction.
  - Provides insight into different interpretations and improves overall understanding.
- Conduct second round of estimates, if necessary:
  - Final responses usually show less spread.
  - Goal is to reduce the range of responses and arrive at something closer to team consensus.

Failure Likelihood Assignment

- Discuss critical load level for PFM.
  - Consider tailwater (e.g., lower differential head).
  - Consider earthquake AEP and coincident water level.
- If ACE for critical load level is virtually certain to cause failure (SRP ≈ 1), then APF ≈ ACE.
- Start discussions with ACE of the loading.
  - Reduce that probability based on likelihood of each node in step-by-step progression leading to failure.
  - Evaluate failure likelihood of PFMs prior to overtopping with respect to the overtopping ACE.
- Consider likelihood of unsuccessful intervention.



Confidence and Uncertainty

Confidence	Description
High	The team is confident in the risk characterization, and it is unlikely that additional information would change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
Moderate	The team is relatively confident in the risk characterization, but key additional information might possibly change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
Low	The team is not confident in the risk characterization, and it is entirely possible that additional information would change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

Failure Likelihood and Consequence Rationale (Building the Case in A-10)

- Part of building the case for the failure likelihood is discussing the presence of features or susceptibilities that may lead to vulnerabilities and lack of defenses.
- Even if a consequences study exists, the results may not adequately reflect the PFMs being considered.
  - Critically review the consequences study
  - Make adjustments as appropriate.

Summary

- PFMA is the first and most important step in any risk analysis.
  - Review all background and performance data.
  - Use diverse team and include operations personnel.
  - Think beyond traditional analyses.
- PFMA, assigning likelihood and consequence categories, and using a risk matrix provide a relevant risk categorization system.
- A risk matrix approach to conduct SQRA is a useful and quick means to prioritize dam/levee safety program activities, especially to determine if higher level studies would be beneficial.

Questions, Comments, or Discussion

Thank you for your attention.