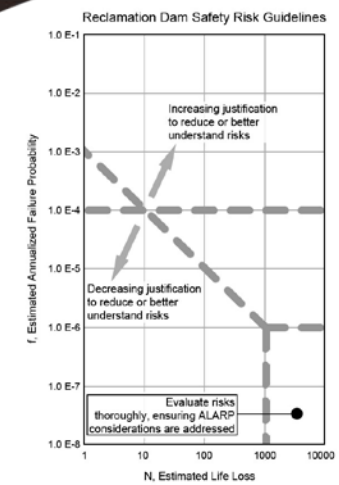
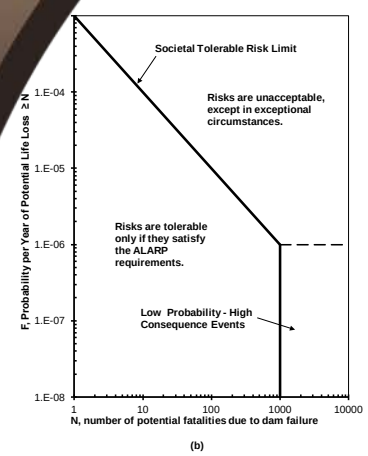
Best Practices in Dam and Levee Safety Risk Analysis

I-8. Combining and Portraying Risk

29 May 2015





RECLAMATION
Managing Water in the West

US Army Corps of Engineers
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Objectives

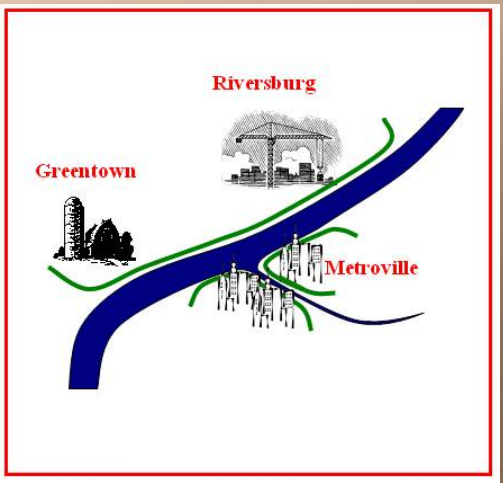
- Become familiar with some commonly used techniques for transforming individual PFM risk estimates into a total risk estimate for the facility
- Understand the nature and potential magnitude of the errors that can result from improperly combining risks
- Become familiar with some common methods of portraying total and individual risk estimates and risk estimate uncertainty

Outline

- Key concepts
- Common cause adjustment
- Special topics
  - Length effects
  - Cascading failures
  - Intervention
  - Incremental risk
  - Non breach risk
- Portraying risk and uncertainty

Key Concepts

- For risk analysis purposes, a dam or levee system includes all components of the project that are intended to retain the reservoir (dams) or exclude water from the leveed area (levees)
- The failure of any of these components can result in the inundation of the downstream area or floodplain
- The risk of failure for each of these components contributes to the total risk associated with the system. The individual risk estimates must therefore be combined to obtain a total risk est.

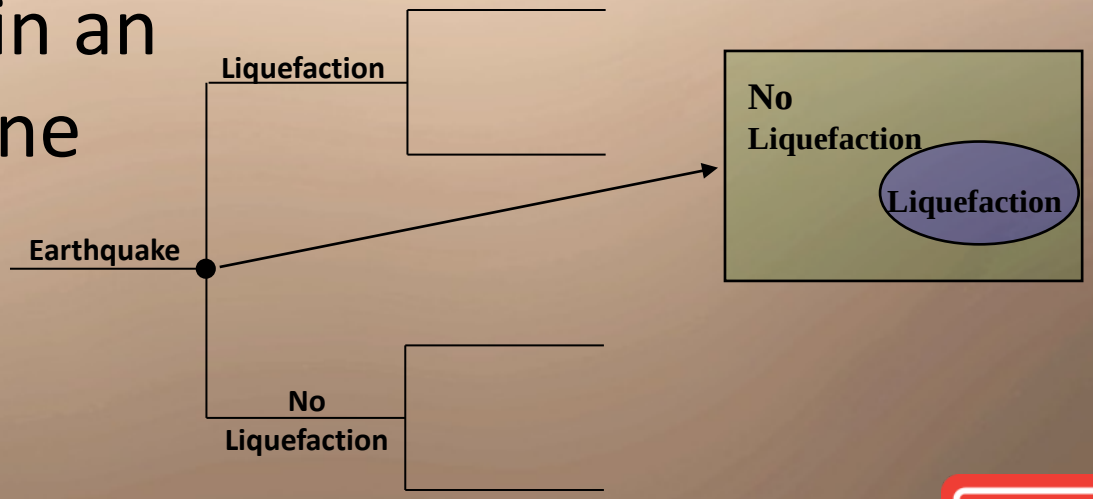


Key Concepts

- Risk estimates must be combined in a way that is technically correct so that the collective impact can be expressed in a credible manner
- Risk estimates must be portrayed in a way that can be readily understood by decision makers so they can take appropriate action

Recap: Mutually Exclusive Events

- If one event occurs, then the other does not
- Risk estimates conditioned on the occurrence of ME events can be directly summed, because there is no intersection event
- E.g., branches in an event tree define ME sub-PFMs



Statistically Independent Events

- The occurrence of an event does not affect the probability of the other event(s)
- Multiplication rule reduces to $P(AB) = P(A)P(B)$
- Risks for SI events can be summed if the intersection is small enough to be ignored
  - e.g., for $P(A) = 2E\text{-}4$, $P(B) = 1E\text{-}4$, $P(AB) = 2E\text{-}8$, and $P(A \cup B) = 2E\text{-}4 + 1E\text{-}4 - 2E\text{-}8 \approx 2E\text{-}4 + 1E\text{-}4$
- Ideally, a set of PFMs would be developed in a way that ensures the PFMs are mutually SI

Correlation

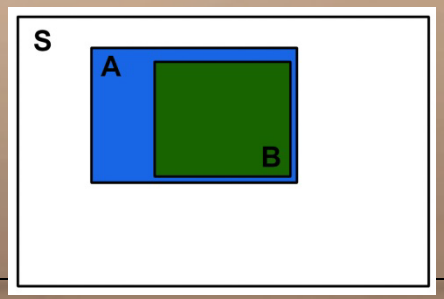
- A measure of the degree to which two random variables are linearly related
- Statistically independent random variables (and events) are uncorrelated ($\rho = 0$)
- Example of positive correlation: If one spillway gate fails to operate, it may be likely that multiple spillway gates will also fail to operate
- Positive correlation does not imply causation (not the same as high conditional probability)

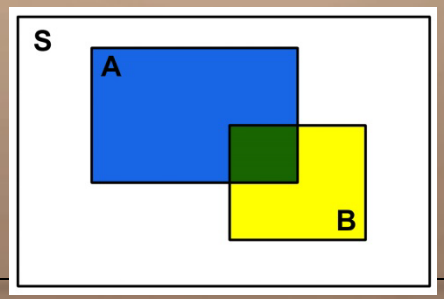
Total Probability

- For non-negatively correlated PFMs (the occurrence of one PFM either increases or does not affect the probability of the other PFMs occurring), the total probability of system failure lies between:
  - The highest probability for an individual PFM
  - The total probability that would be computed for SI PFMs

$$\max_{i} P(E_i) \leq P(E) \leq 1 - \prod_{i=1}^{n} [1 - P(E_i)]$$

← Increasing correlation





Decreasing correlation →

Total Probability

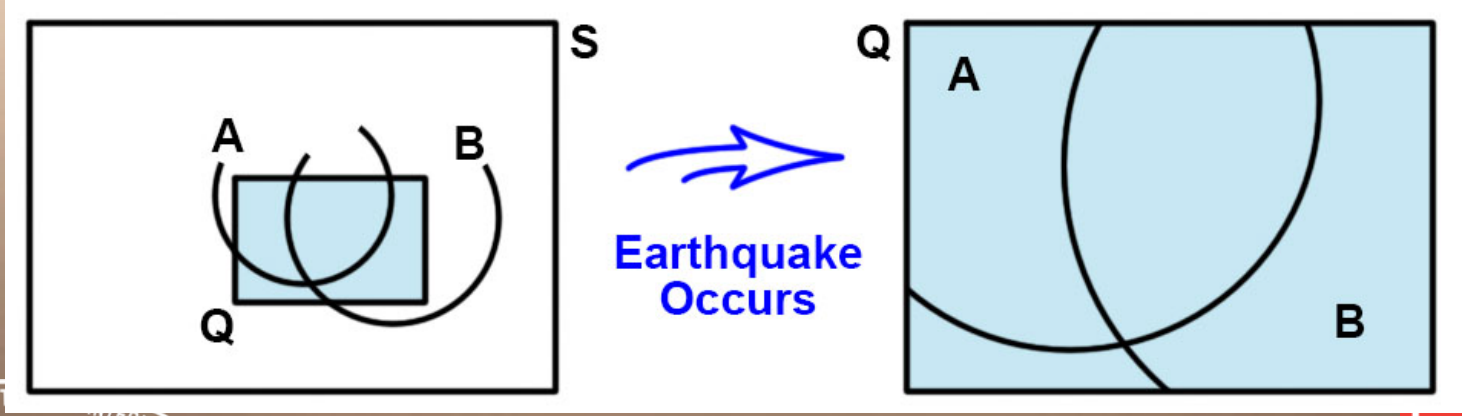
- If one PFM is dominant, then the upper and lower bounds will be approximately equal
- If PFM AFPs are "small", then for SI PFMs the total AFP can usually be approximated by summing the probabilities for individual failure modes
  - e.g., for P(A) = 2E-4, P(B) = 1E-4, P(A U B) ≈ 3E-4
  - Note that if B ⊂ A (→ strong positive correlation vs SI), P(A U B) = 2E-4. In this case, ignoring ∩ gives 33% error even though the AFPs are "small")

Common Cause Adjustment

- Ideally, PFMs are developed so as to keep them more or less statistically independent of other PFMs
- Intersection events are rarely evaluated unless they are important to the risk estimate or the decision
- Since the PFM AFPs are typically "small" (< 0.1), the total AFP can usually be calculated as a simple sum, even though the equation for probability of the Union includes adjusting for double-counting of the intersection
  - e.g., for SI PFMs A, B, C, total AFP ≈ P(A) + P(B) + P(B) versus P(A) + P(B) + P(B) – P(AB) – P(BC) – P(CA) + P(ABC)
- For AFPs > 0.1, the approximation error could be large
- Issue often arises in the context of flood or EQ PFMs

Common Cause Adjustment

- E.g. consider the following seismic PFMs
  - PFM A: Sliding failure of the gravity section under the 50K quake loading (Estimated AFP: 1E-5)
  - PFM B: Liquefaction failure of wing dam under the 50K quake loading (Estimated AFP: 2E-5)
- Given the occurrence of the 50K quake, the conditional failure probabilities are P(A|Q) = 0.5 and P(B|Q) = 0.9

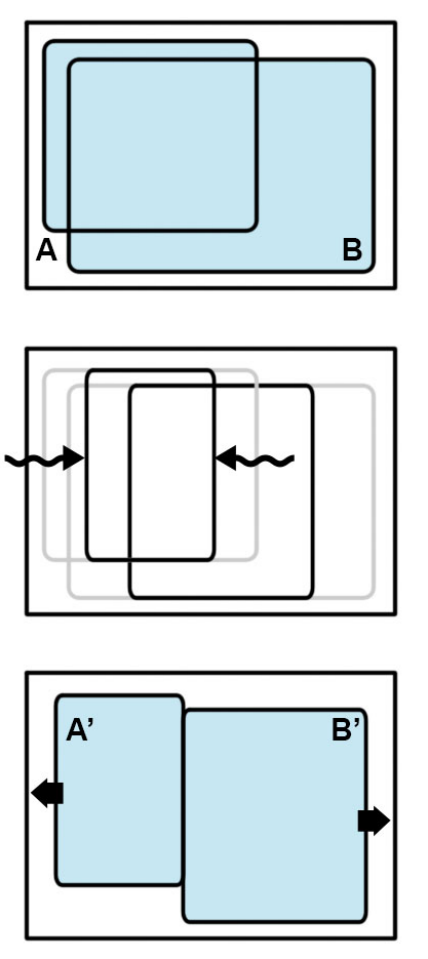


Common Cause Adjustment

- Note that PFMs A and B may not be SI, since they are both premised on the occurrence of the 50K quake
- Given the occurrence of the 50K quake, however, these PFMs are SI, since the properties of the embankment soil and those of the rock foundation are independent
- Given the occurrence of the 50K quake, directly summing the conditional failure probabilities would give 0.5 + 0.9 = 1.4, which would violate axioms
- The "problem" is double-counting of intersection area
- Solution: apply a Common Cause Adjustment (CCA)

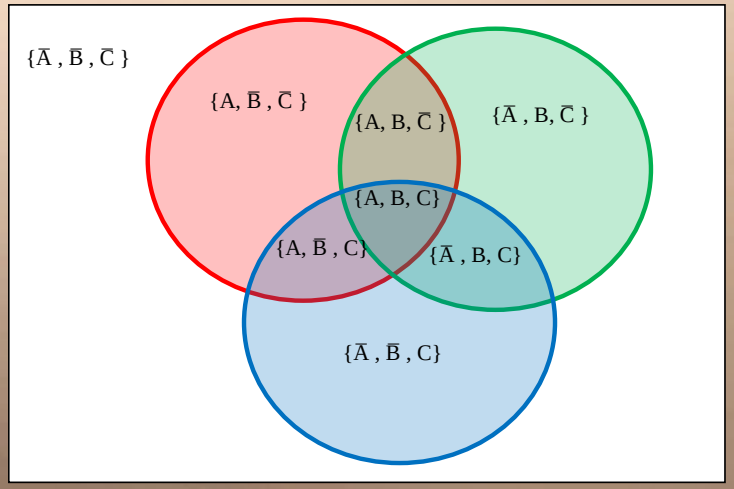
Common Cause Adjustment

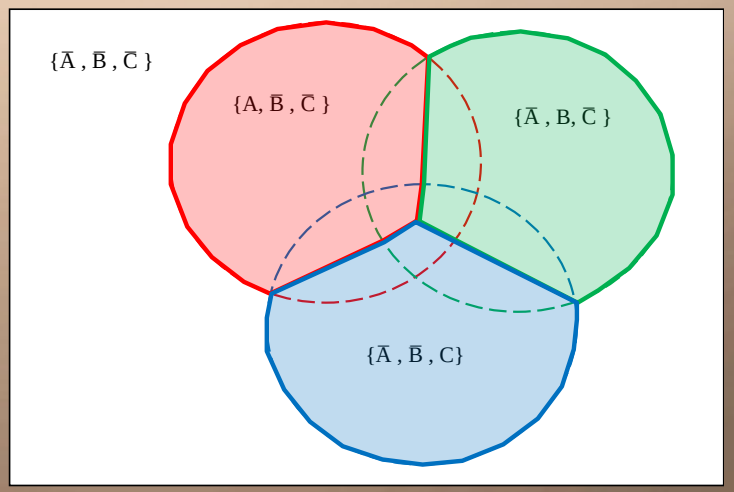
- The CCA can be applied to SI PFMs
- Purpose is to correct the total AFP
- In a practical sense, the CCA reallocates the intersection area to individual PFMs, allowing their AFPs to be summed directly
  - Essentially ignoring the intersection event, but still counting the probability
- For the purposes of calculating the total AFP, the adjusted PFMs can thus be treated as ME and summed. Note this does <u>not</u> make them ME. The PFMs remain SI



Common Cause Adjustment

- For two PFMs, the adjustment is easy, since P(AB) = P(A)*P(B) for SI events
- For more than two PFMs, formula for the intersection is more complicated, so easier to use de Morgan's rule





Common Cause Adjustment

- Consider three SI potential failure modes A, B, and C

  P(A) = 0.3

  P(B) = 0.1

  P(C) = 0.2
- Approximate total probability of failure by summation

  0.3 + 0.1 + 0.2 = 0.6
- Total probability of failure by de Morgan's rule:
  1 – [(1-0.3) (1-0.1) (1-0.2)] = 0.496
- Approximation error
  - (0.6-0.496) / 0.496 = 20%

Common Cause Adjustment

- Probability adjustment
  - The corrected total probability is thus 0.496
  - For reporting purposes, need to adjust the individual PFM probabilities as well (since we usually do not consider intersection events):

$$P' = P * \text{Total Probability} / \text{Unadjusted Sum}$$

$$P'(A) = 0.3 * 0.496 / 0.6 = 0.248$$

$$P'(B) = 0.1 * 0.496 / 0.6 = 0.083$$

$$P'(C) = 0.2 * 0.496 / 0.6 = 0.1655$$

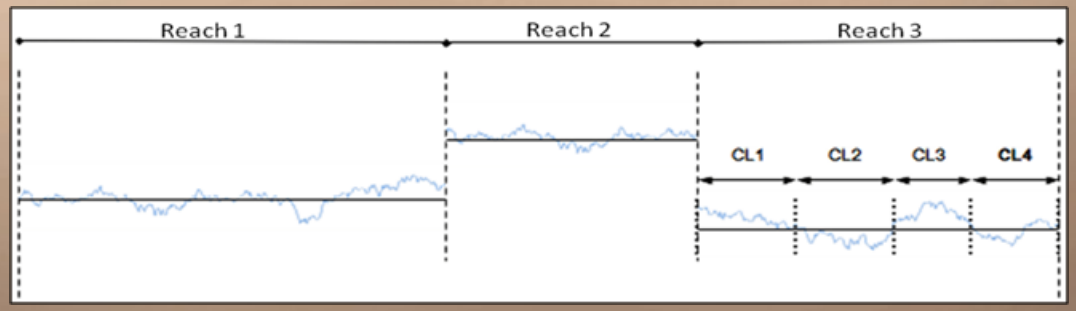
- Summation of adjusted probabilities (double-check): 0.248 + 0.083 + 0.165 = 0.496

Length Effects

- Issue arises in context of levees and long dams
- If sufficient information exists to identify all potential weak spots with confidence, then length is irrelevant
- If not, then our knowledge uncertainty leads to a longer system having a higher likelihood of encountering a weak spot
  - Divide system into homogeneous reaches
  - Estimate system response for each reach
  - Subdivide long reaches into characteristic lengths
  - Combine probabilities for characteristic lengths

Characteristic Length

- Minimum length for which performance of adjacent lengths is statistically independent
  - Easier said then done
- Statistical analysis of spatial correlation, analogy to other similar projects, or expert judgment



Cascading Failure

- Downstream direction
  - If failure of the dam and/or levee being assessed would result in overtopping and subsequent breach of downstream dams and/or levees, then the risk associated with these cascading failures would typically be attributed back to the dam being assessed.
- Upstream direction
  - If failure of an upstream dam would result in overtopping and breach of the dam or levee being assessed, then changes in the magnitude and frequency of the loading caused by failure of the upstream dam would not typically be included in the risk estimate.

Intervention

- BOR directly considers the potential benefits of pre-failure intervention in its risk estimates
  - Does not necessarily mean intervention is likely to succeed
- USACE portrays risks for two different scenarios
- 1. Assuming intervention actions are possible:
  - Estimate probabilities in same manner as BOR
  - Probably a better representation of actual situation
- 2. Assuming intervention actions do not occur:
  - Helps to improve understanding of apparent reliance on intervention to manage risk

Incremental Risk

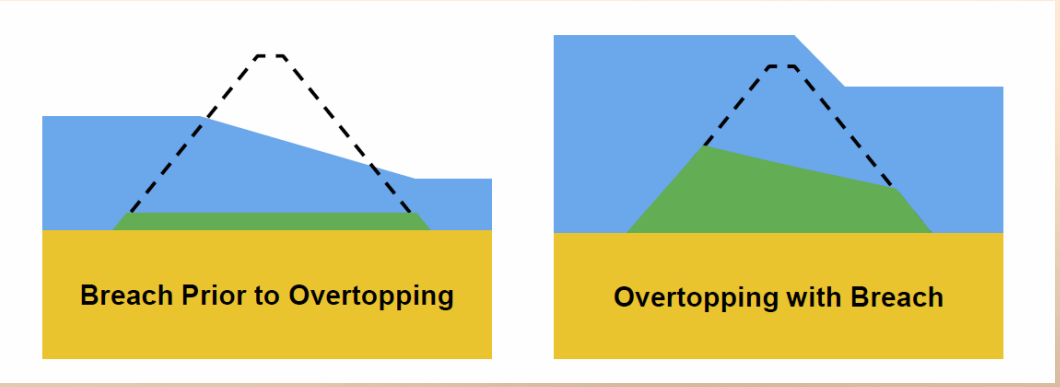
- For flood PFMs, BOR practice is to consider the entire breach inundation PAR as a starting point
  - The possibility of people leaving before the breach as a result of spillway releases is often considered
- USACE practice is to distinguish between the risks imposed by the dam or levee and inherent flood risk
  - Improves understanding of the benefits of the dam/levee
- In the event tree, incremental consequences are estimated as the difference between the failure consequences and the non breach consequences

Non Breach Risk

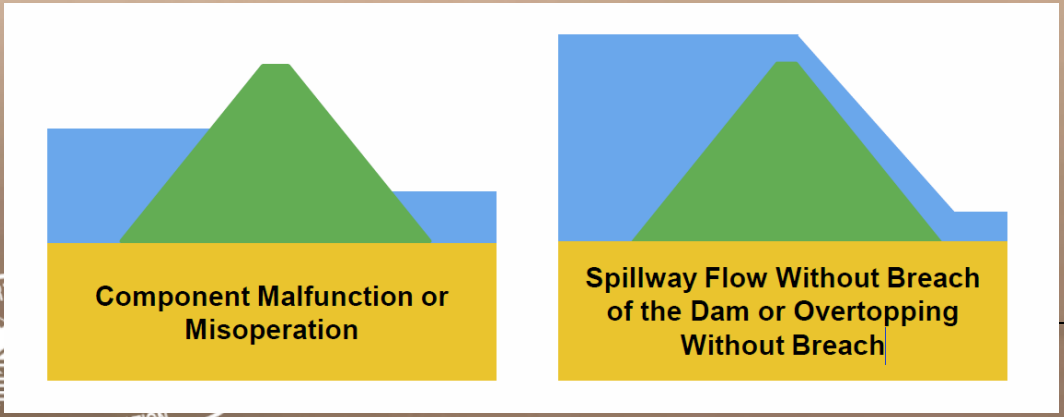
- BOR typically does not consider PFMs that do not involve an uncontrolled release of the reservoir
  - For example, controlled spillway releases in excess of the safe channel capacity are not typically developed as PFMs
- USACE practice is to assess and communicate the inundation risk that remains even if the infrastructure operates and performs as intended
  - Many USACE facilities are designed for flood control, so spillway releases (for example) can be very large
- Inundation maps for non breach scenarios typically included in the EAPs for USACE facilities

Breach versus non-breach risk

- Examples of breach scenarios associated with flooding

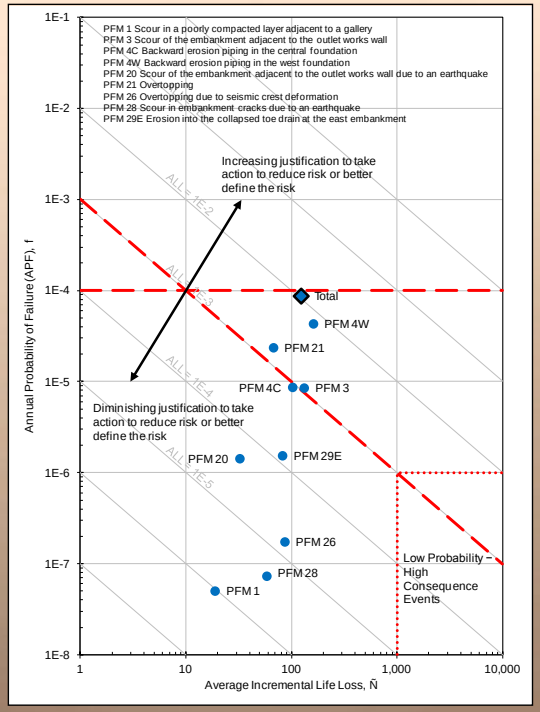


- Examples of non-breach flood inundation scenarios

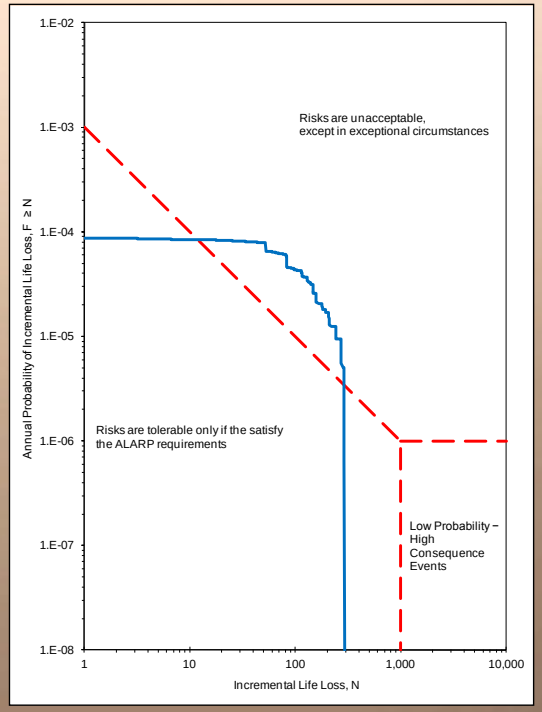


Portraying Risk

- What is the nature and magnitude of the risk?
- How does it compare with risk guidelines?



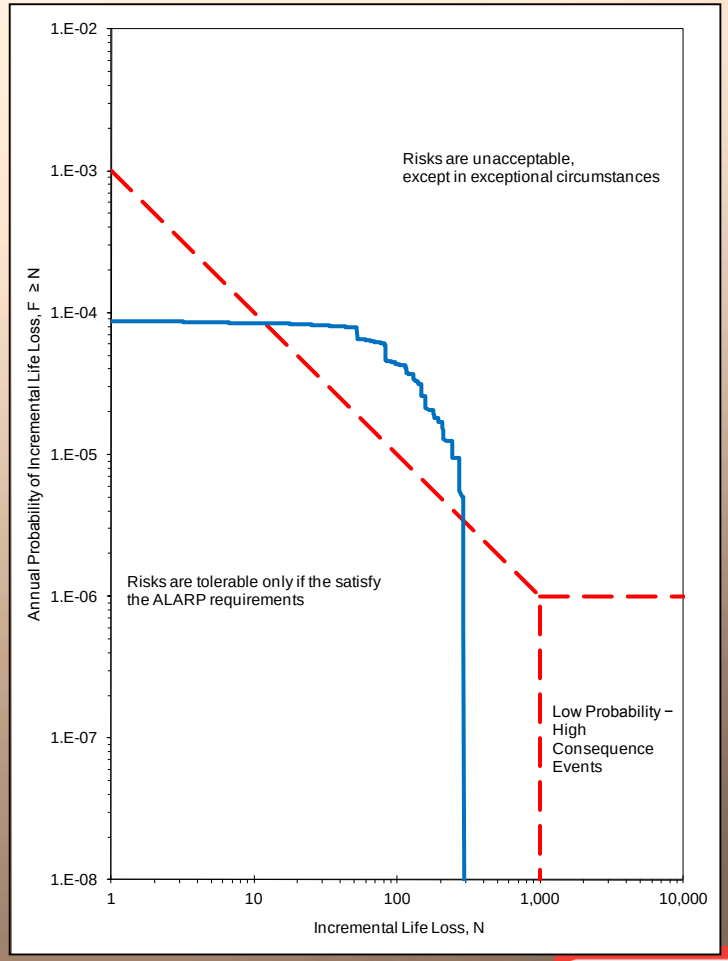
f-Ñ Chart



F-N Chart

Cumulative risk portrayal (FN)

- Used by USACE and others
- PFMs are broken out by load range and sorted in order of decreasing life loss
- Cumulative AFP (F) reported for each unique value of life loss (N)
- For each point on the curve, y-axis gives the probability of N or more lives being lost

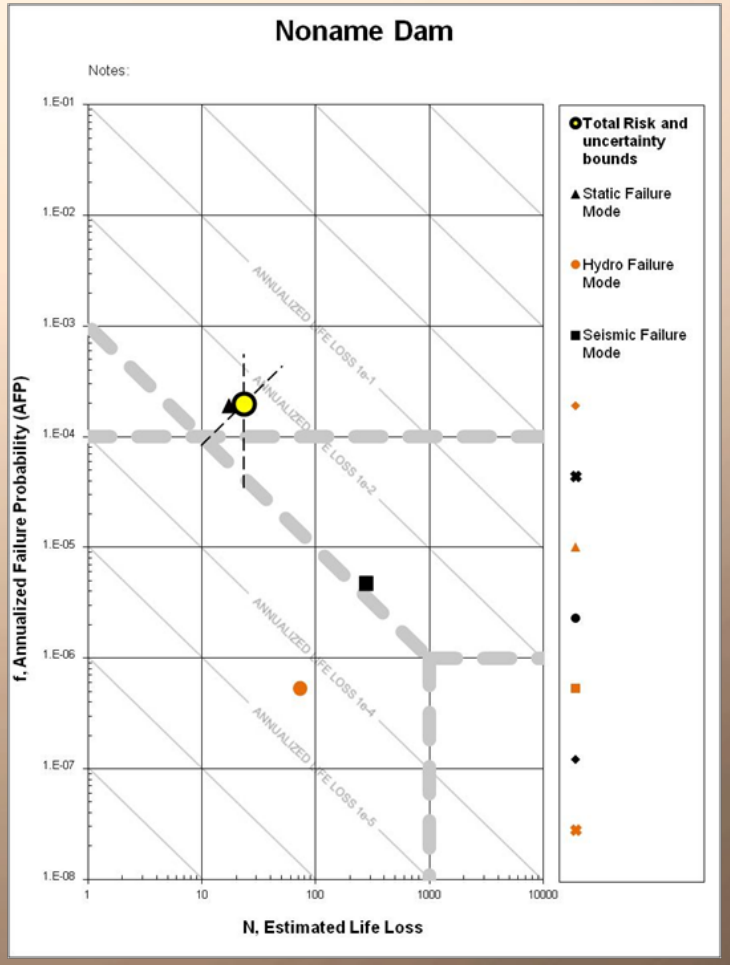


Cumulative risk portrayal (FN)

- Advantages of separating the load ranges
  - Event tree models often assume that failure occurs at the peak demand
  - Breaking out the PFMs by load range can help identify other system states where capacity < demand
  - E.g. makes it easier attribute risk to different conditions associated with a certain load range, e.g. pre- versus post-overtopping failure given a 5000-year flood
- Advantages of plotting the cumulative AFP curve
  - highlights the range of life loss outcomes (associated with individual PFMs and load ranges) that likely control the risk

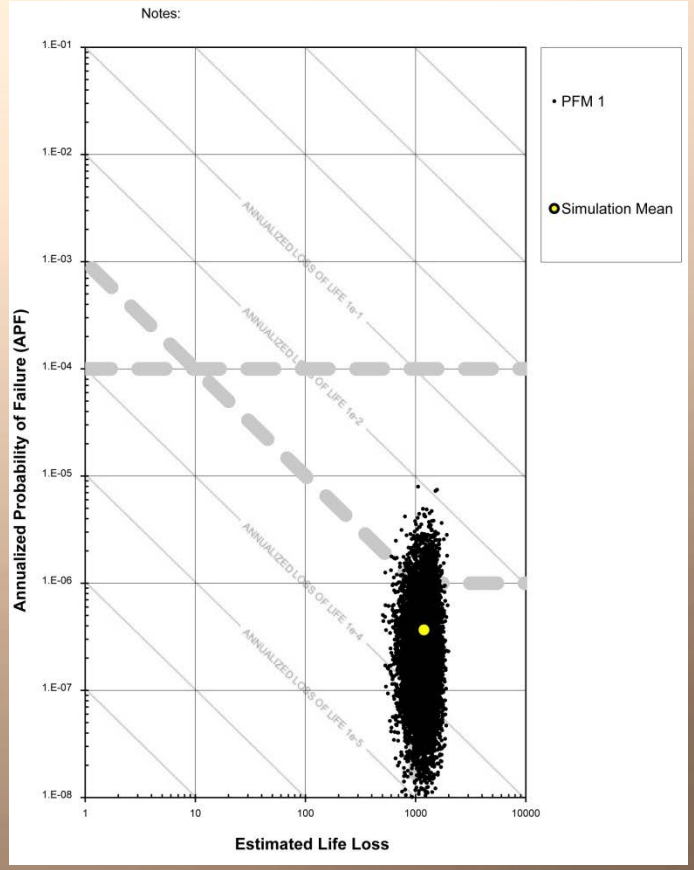
Individual PFM risk portrayal (fN)

- Used by BOR, USACE, and others
- PFMs are shown as individual markers plotted at their mean estimated AFP and mean estimated life loss
- Total risk is shown a “whiskered” marker whose plotted at the total mean AFP and total mean <u>annualized</u> life loss (triaxial plot)
- Whiskers denote uncertainty



Individual PFM risk portrayal (fN)

- Advantages of plotting individual (vs. cumulative) risk estimates
  - Uncertainty can be easily shown by superimposing Monte Carlo point cloud over the mean marker
  - Whiskers show uncertainty over the total mean risk estimate (often controlled by one or two PFMs)
  - Presumably, the fN chart guidelines represents “expected” values, so this format provides a convenient means of direct comparison



Communicating Uncertainty

- How does the nature and magnitude of the uncertainty affect the decision?
  - What do we know with reasonable certainty? What don't we know? How confident are we in the results?
  - How sensitive are the risk estimates to potential new information? Does the estimated risk have the potential to change significantly with new information?
- Would new information actually help improve the decision, or simply fill gaps in the model?
  - Additional analysis results?
  - Additional field exploration data?

Options for Portraying Uncertainty

- Plotting a Monte Carlo point cloud on the f-N chart
  - Shows uncertainty in estimated AFP and life loss for PFM
- Performing sensitivity studies
  - Can be used to highlight which risk estimates control AFP
- Discussing percentiles, standard deviations, and other measures of dispersion
  - A variety of measures can be used to represent the upper and lower bound risk estimates
  - Order of magnitude bounds often used for non-MC studies
- Important that uncertainty effectively communicated

Exercise: 5 conditionally SI PFMs

Potential Failure Mode (given the occurrence of a flood)	Conditional Probability of Failure
Sliding at base of gravity spillway section	0.23
Seepage erosion through wing embankment above core	0.14
Radial gate arm buckling due to trunnion friction	0.06
Spillway wall overtopping erosion and headcutting back to reservoir	0.31
Stilling basin failure and undermining erosion with headcutting back to reservoir	0.17

- Estimate the percent error that will result if the conditional AFPs are summed directly (hint: apply the common cause adjustment)

Exercise Solution

- Unadjusted sum

  0.23 + 0.14 + 0.06 + 0.31 + 0.17 = 0.91

- Total probability by de Morgan's rule

  1 – [(1-0.23) (1-0.14) (1-0.06) (1-0.31) (1-0.17)] = 0.64

- % Error

  100 * (0.91 – 0.64) / 0.64 = 41%