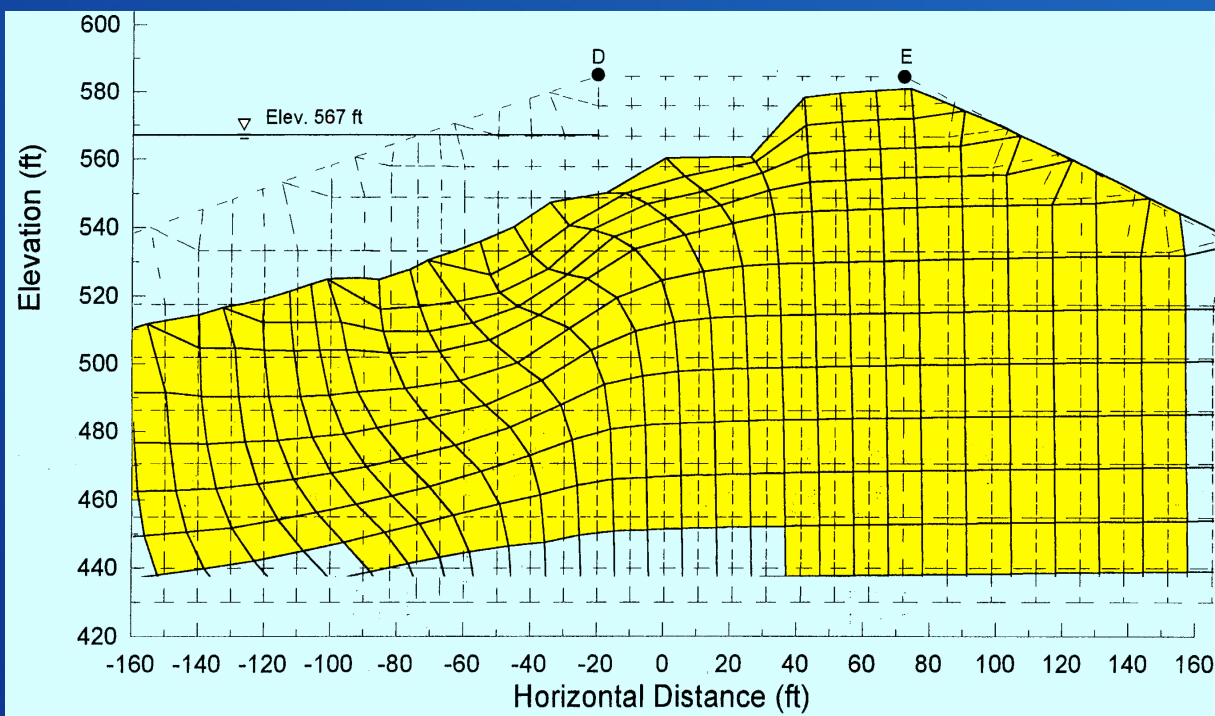# RECLAMATION
Managing Water in the West

Seismic Risk Analysis for Embankment Dams – An Introduction

U.S. Department of the Interior
Bureau of Reclamation

Reclamation's Risk-Based Decision Process

- **Formalized framework for engineering judgments, intended to provide consistency among projects.**

- **Seek balance between public safety, and cost to taxpayers and water users.**
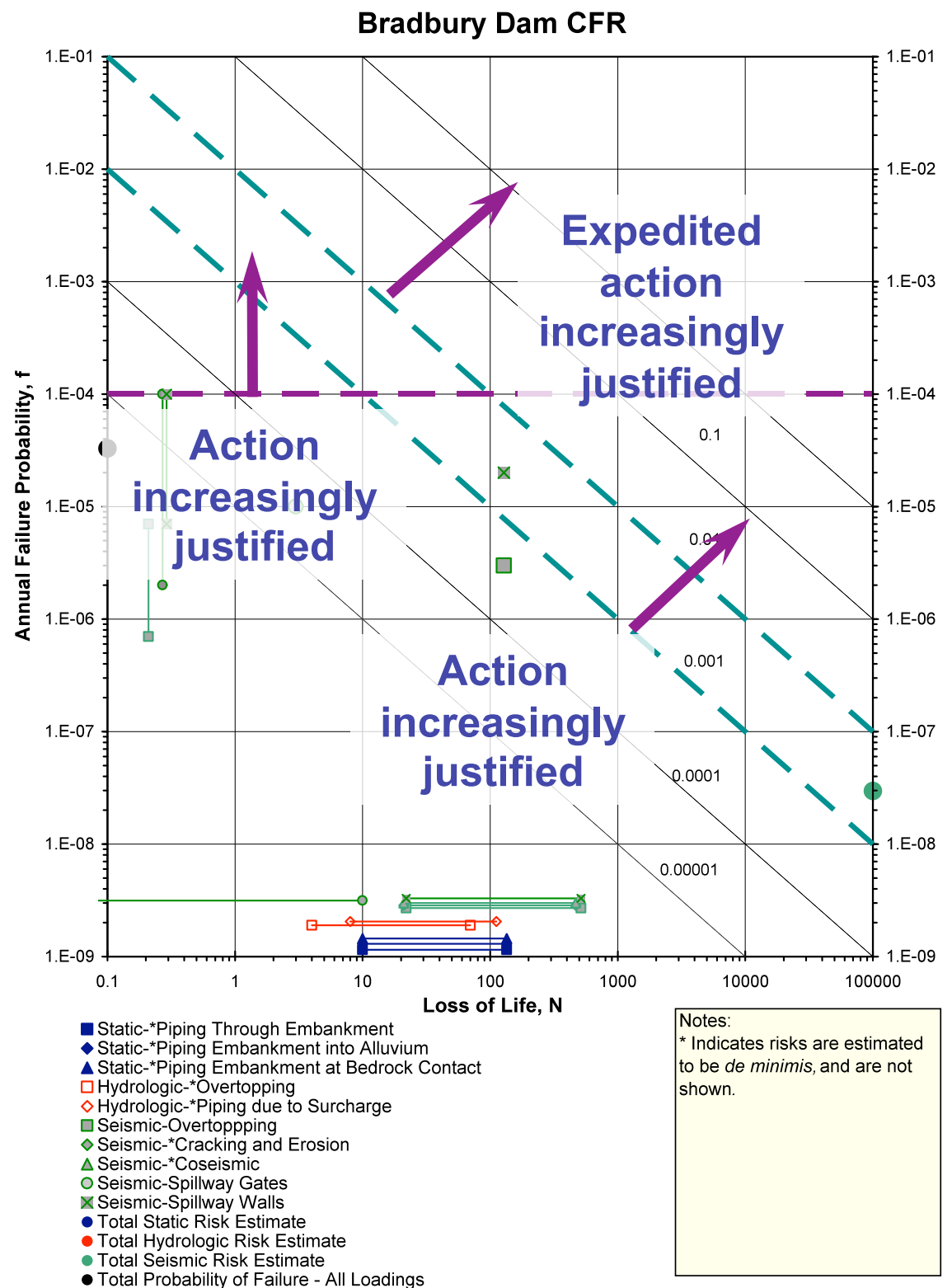
- **Prioritize dam-safety spending.**

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Definitions

- **Annual Probability of Failure (APF) =**

  $P_A(Loading_i)$ x $P(Failure|Loading_i)$

  [summed over all loadings]

- **Annualized Loss of Life (ALL) =**

  $P_A(Loading_i)$ x $P(Failure|Loading_i)$ x

  (Estimated Loss of Life)

  [summed over all loadings]
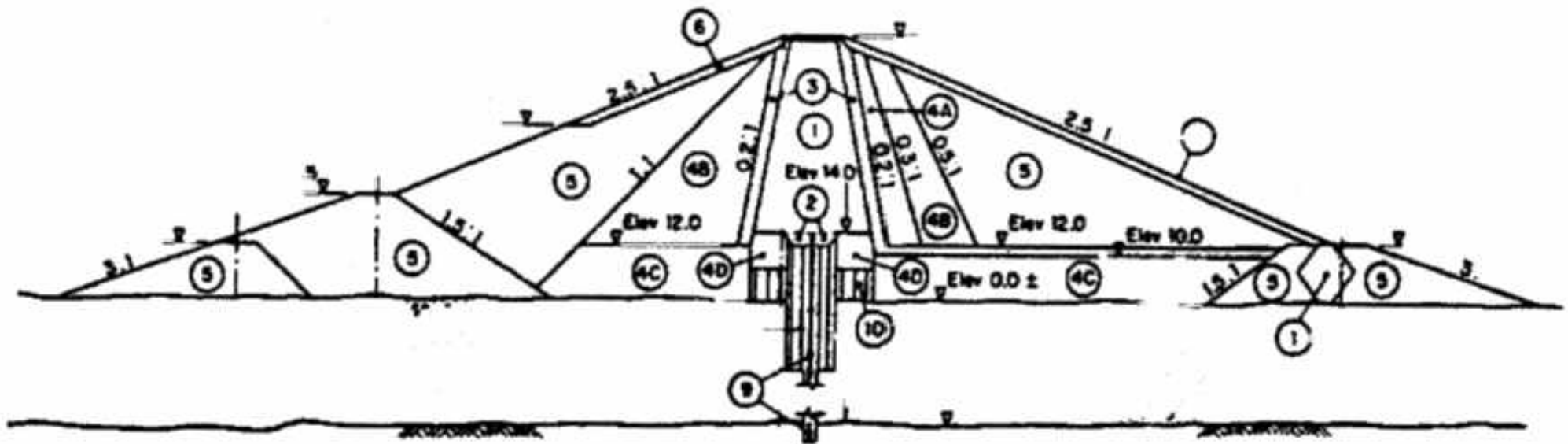
Public Protection Guidelines

- APF should be less than 1×10^{-4}.

- ALL should be less than 1×10^{-3}.

- Action to reduce risk is increasingly justified if either of these values are exceeded. Expedited action is needed if ALL exceeds 1×10^{-2}.

- Under Reclamation Safety of Dams Act, emphasis is on protection of human life, not economic loss.

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Guidelines Shown on f-N Chart

Bradbury Dam CFR

Annual Failure Probability, f

Loss of Life, N

Expedited action increasingly justified

Action increasingly justified

Action increasingly justified

- Static-*Piping Through Embankment
- Static-*Piping Embankment into Alluvium
- Static-*Piping Embankment at Bedrock Contact
- Hydrologic-*Overtopping
- Hydrologic-*Piping due to Surcharge
- Seismic-Overtoppping
- Seismic-*Cracking and Erosion
- Seismic-*Coseismic
- Seismic-Spillway Gates
- Seismic-Spillway Walls
- Total Static Risk Estimate
- Total Hydrologic Risk Estimate
- Total Seismic Risk Estimate
- Total Probability of Failure - All Loadings

Notes:
* Indicates risks are estimated to be *de minimis,* and are not shown.

Learning from Case Histories When Things Go Right

La Villita Dam, Mexico

60 m high, earth and rockfill on dense alluvial foundation
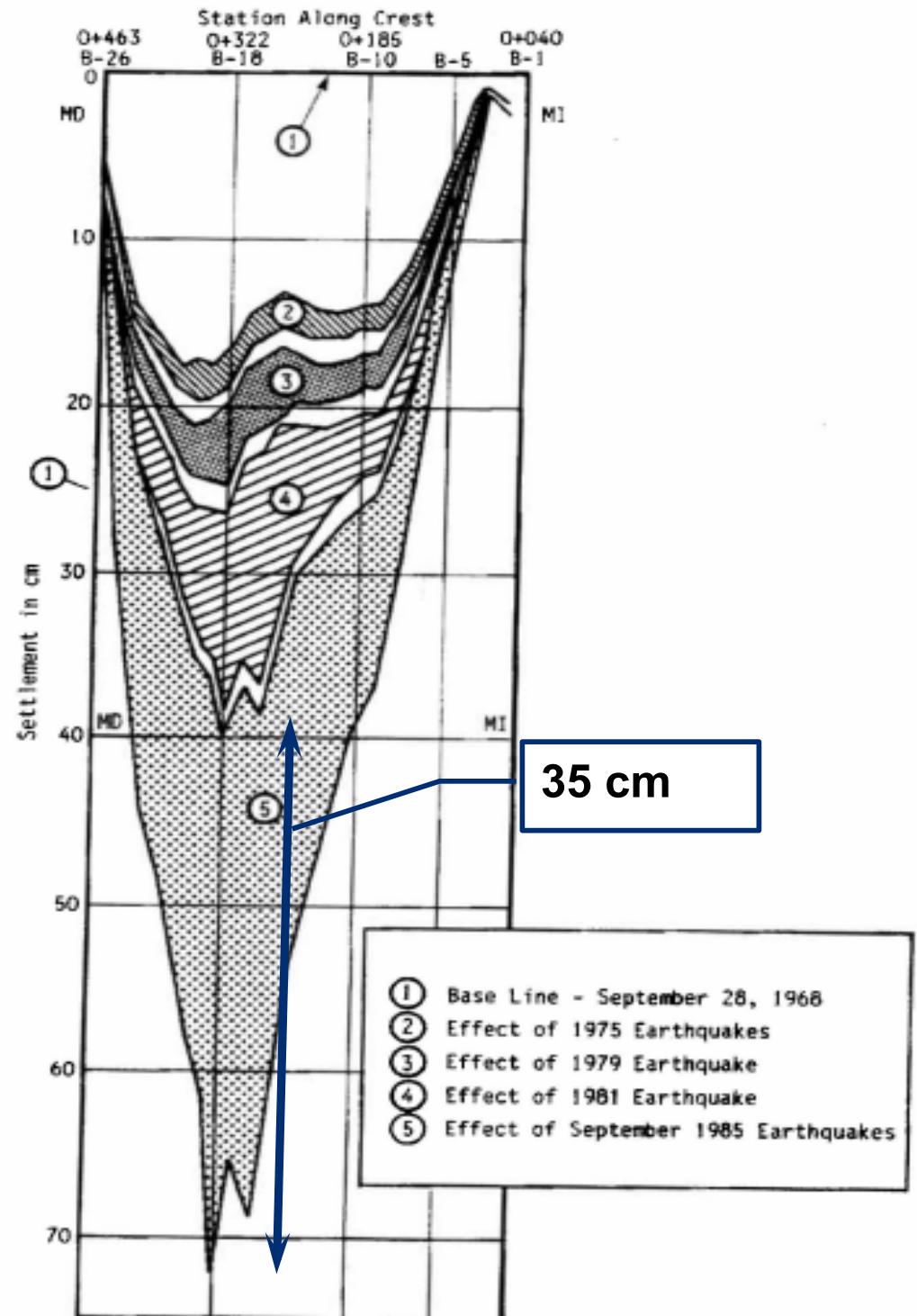
Elgamal *et al* (1990)
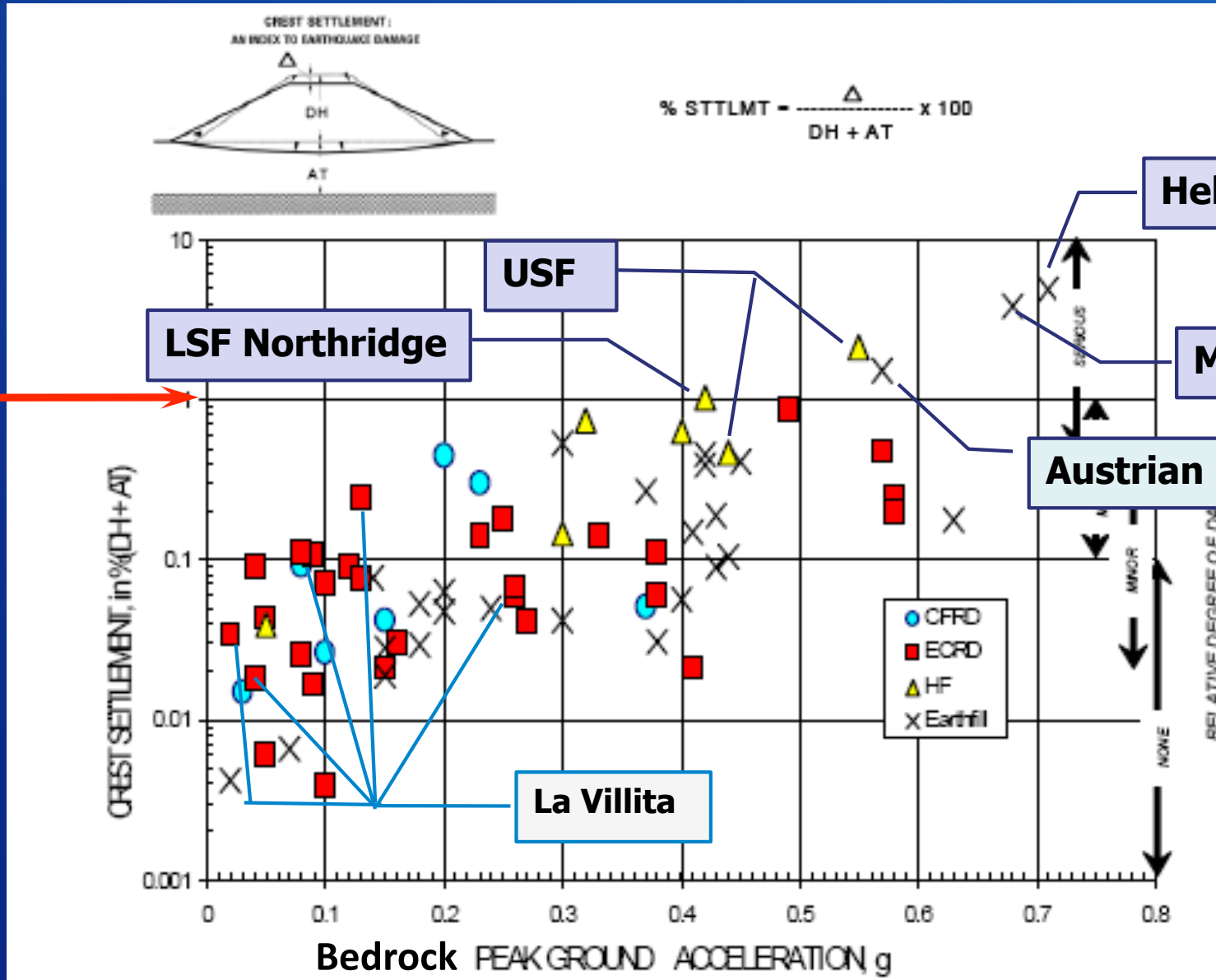
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Cumulative Settlement from 5 Events

35 cm from
[M 8.1, crest PHA 0.79]
and
[M 7.5, crest PHA 0.21]
combined

Crest PHA ≈ 6 times bedrock PHA.

Elgamal *et al* (1990)

35 cm

		Legend
①	Base Line - September 28, 1968	
②	Effect of 1975 Earthquakes	
③	Effect of 1979 Earthquake	
④	Effect of 1981 Earthquake	
⑤	Effect of September 1985 Earthquakes	

Embankment Dam Settlement

Modified from Swaisgood (2003)

Failure of Fujinuma Dam
2011 Tohoku Offshore Earthquake, Japan

Caused by weak/sensitive silt/clay in foundation?

Spring in Tuff Bedrock

Embankment Fill Layers

Black, Organic Silt/Clay Foundation Residual Soil Developed on Tuff Bedrock

GEER 2011 (photo: L. F. Harder)

Drainage Flow in Breach

GEER 2011 (photo: L. F. Harder)

Photos: Geotechnical Extreme Events Reconnaissance Association, 2011

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When Things Went Badly, but Could Have Gone Very Badly

- **Austrian Dam 1989 Loma Prieta Earthquake, M 6.9, PHA ≥ 0.57 g**

- **Numerous dams in 2001 Bhuj, India Earthquake, M 7.6**

- **Zipingpu Dam, Wenchuan, China Earthquake, M 7.9, 10 km from epicenter.**

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Austrian Dam

- Settlement ~ 2.5 feet along most of the crest (~1.5%).

- Extensive longitudinal cracking on both slopes, up to 14 ft deep.

- Transverse cracking within embankment, up to 10 ft deep, 8 in wide.

- Separation 23 ft deep at spillway "return" wall, apparently pull-away from downslope mvmt. (Normal freeboard 10')
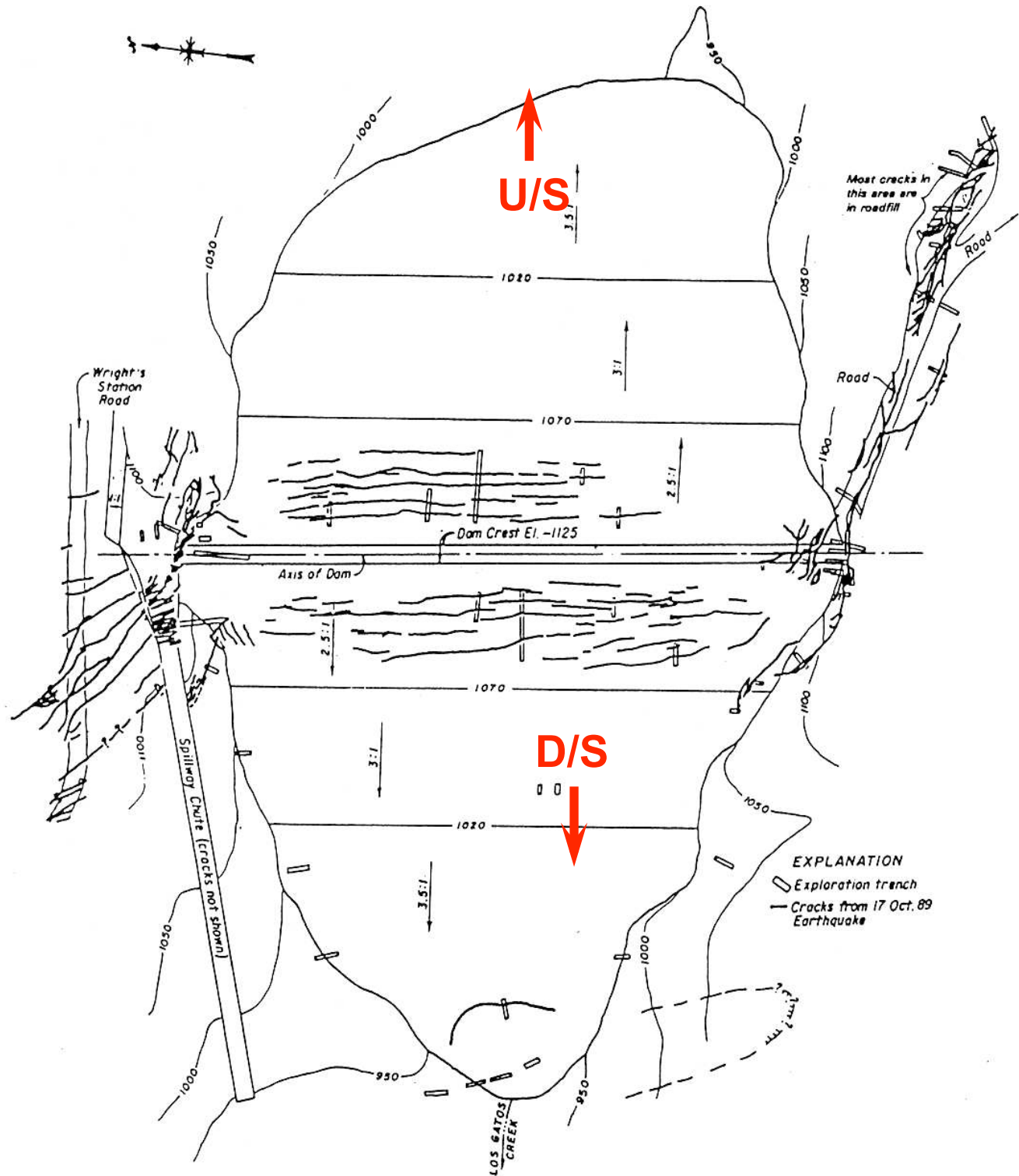
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Austrian Dam

1989 Loma Prieta Earthquake

M 6.9
PHA ≥ 0.57 g

USCOLD (1992)

Austrian Dam

- Cracks as deep as 27 feet in landslide material left in foundation.

- Sudden rise in piezometers, up to 55'.

- D/S mvmt. of embankment "stretched" spillway chute and broke seepage collars.

- Compaction measured in existing fill during repair averaged 93%. (Did that matter? Could it have mattered?)

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original
fill
height

Settlement and cracking in area of spillway wing wall. Note original fill height

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Cracking and settlement at 1st upstream left cutoff wall, Looking downstream

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How do we do analyze risk?

1. Develop list of plausible failure modes.

2. Decompose most likely ones into component conditions and events, typically shown on event trees.

3. Assign probabilities to component events and conditions. Except for load, each component probability assumes previous events/conditions have occurred.

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Discretize Earthquake Loading

In theory: For some loading L, integrate:

$$P_A(F) = \int P_A(L) \times P(F|L)\, d(L)$$

In practice: "Bin" loadings and sum:

$$\sum \left[P_{AE}(L_i) - P_{AE}(L_j) \right] \times \text{Avg. } P(F|L_i \text{ to } L_j)$$

4. Calculate individual APF for each path leading to failure.

5. Estimate consequences (single best estimate or probability distribution function) for each failure mode.

6. Calculate ALL = APF * Consequences for each path.

7. Report results on f-N diagram with text justifying estimates and conclusions.

Steps 3 and 5 may require "off-tree" calculations or Monte Carlo model.

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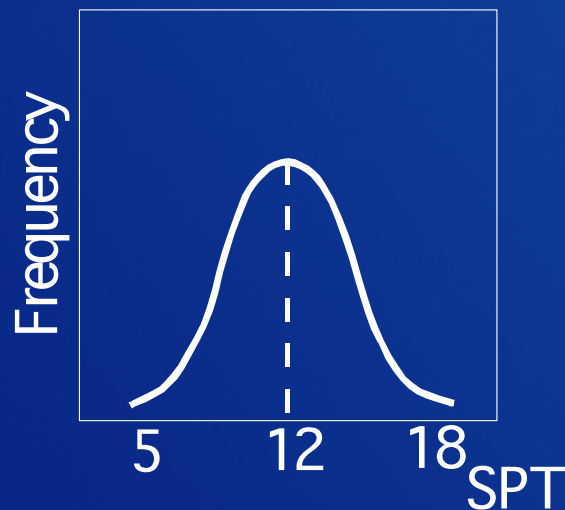# A Simple Seismic Event Tree for an Embankment Dam
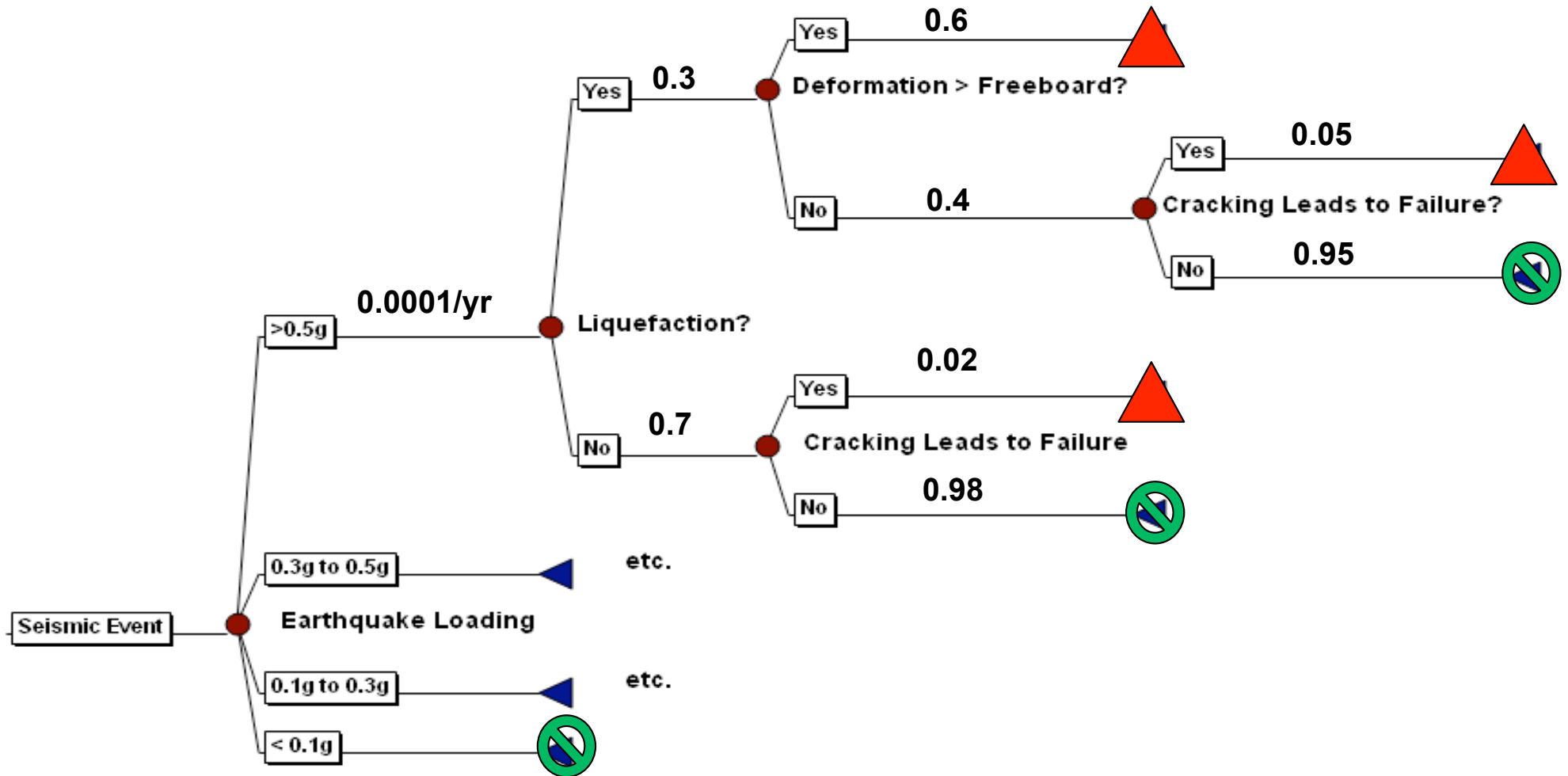
Event Trees

- Branches from each node are mutually exclusive and exhaustive, so probabilities must sum to 1.

- The probability for each outcome at each subsequent node is estimated *assuming that the previous branch has already occurred* (conditional probability).

- Loads usually "binned" with intent of fairly similar probability of the next event, within each bin.

- Sum APF and ALL for each path leading to failure to find total APF and ALL for that tree. (Other seismic failure modes may be on other trees.)
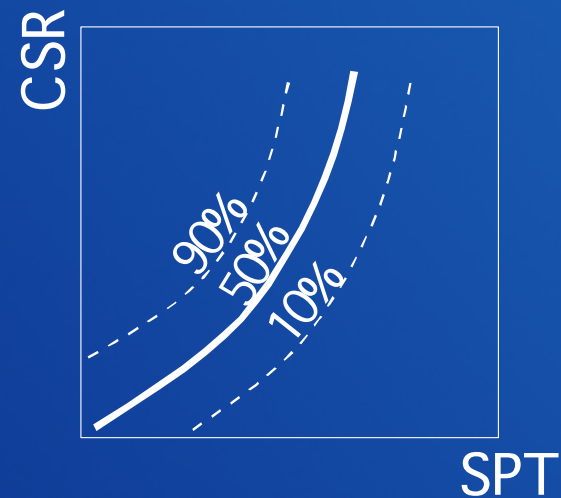
Seismic Loads

- **Probabilistic seismic hazard analysis at appropriate level of detail.**

- **Depending on level of study:**
  - **Select ground motions using PSHA (deconvolved to base of model). Perform numerical response or deformation analysis.**
  - **Estimate surface PHA for CSR and liquefaction probability using r_d.**
  - **Estimate probabilities for other PFMs as fns of PHA, 1-sec SA, or whatever, using simplified analyses (Mononobe-Okabe for spillway walls, Makdisi-Seed, Fell's correlations, etc.)**

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Probability of Liquefaction

- **Perform response analysis (or "simplified") for CSR.**

- **Identify representative blow count or CPT resistance, or develop PDF.**

- **Apply P(Liq'n) model (Liao *et al,* Youd and Noble, R. Seed *et al*, Idriss and Boulanger, others?) and *judgment.***
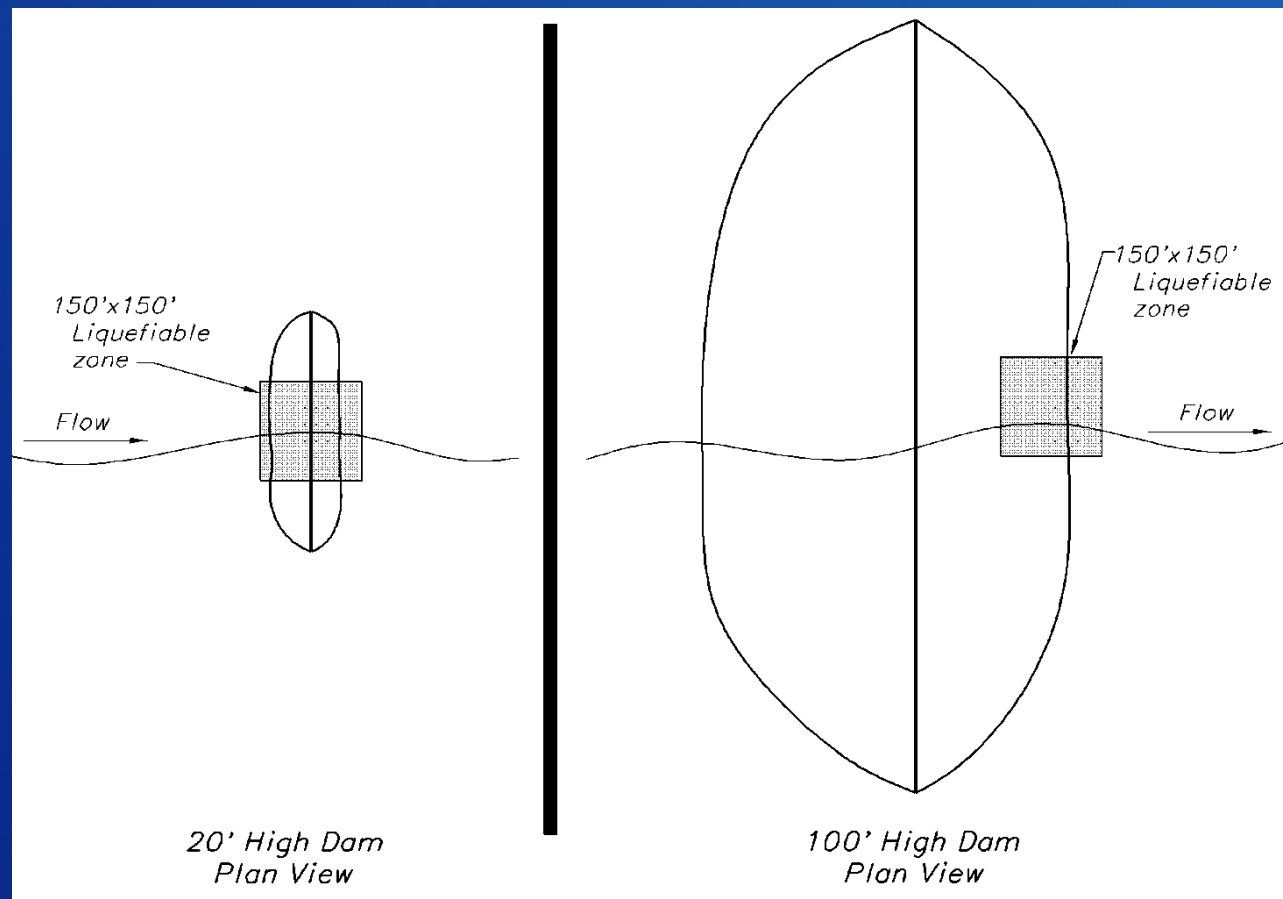
# Probability of liquefaction *over what area*? Enough to allow instability, with 3D effects.

150'x150'
Liquefiable
zone

Flow

20' High Dam
Plan View

150'x150'
Liquefiable
zone

Flow

100' High Dam
Plan View

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Deformation and Cracking (With or Without Liquefaction)

As appropriate:

- **Slope stability**
- **FEM deformation analysis**
- **Case histories**
- **Swaisgood's data on settlement**
- **Fell *et al* (2008) for cracking**
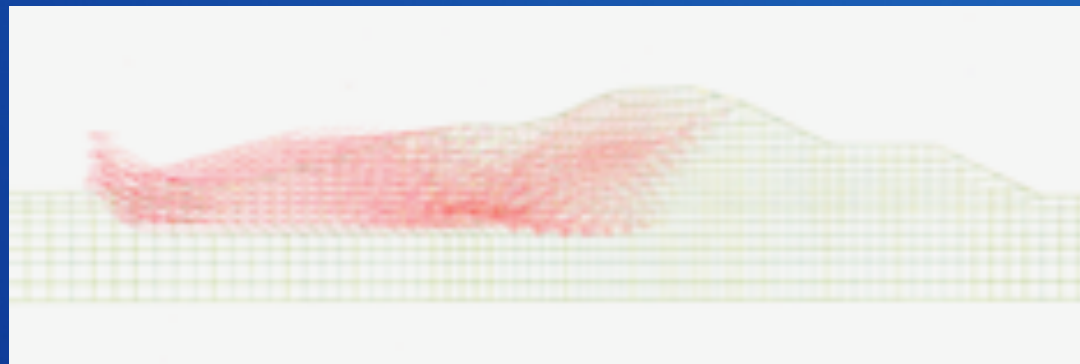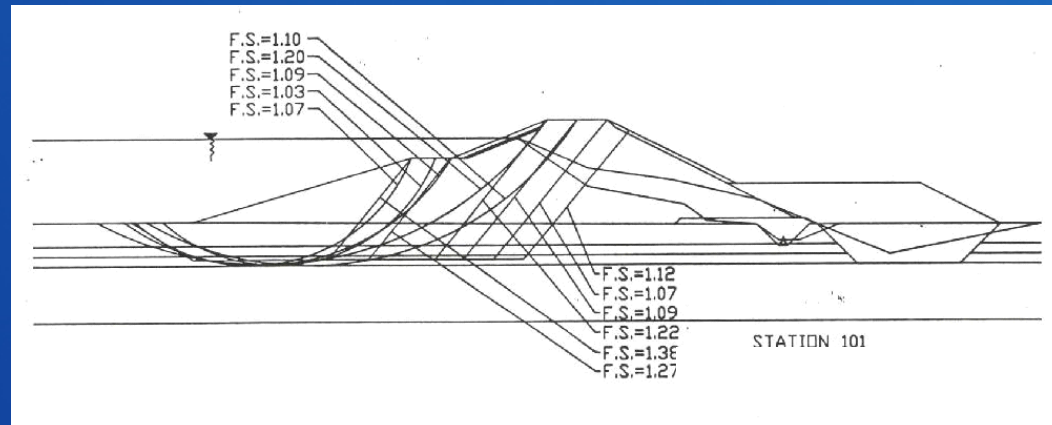
Verbal Scale for Subjective Probability

• **Virtually Certain**	• **0.999**
• **Very Likely**	• **0.99**
• **Likely**	• **0.9**
• **Neutral**	• **0.5**
• **Unlikely**	• **0.1**
• **Very Unlikely**	• **0.01**
• **Virtually Impossible**	• **0.001**

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Fundamentally, all probability estimates are subjective.

- Purely degree of belief if data base is small. Base DOB on geologic data, *case histories*, sensitivity of numerical models to input parameters, mechanics of breaching, etc.

- Even with large statistical data base, must judge - subjectively – what it means for this dam. Statistics give *guidance*, not *answers*.

- Both epistemic and aleatory uncertainty in models, judgments, foundation data, etc.

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Estimating Consequences

– **Identify potential failure modes; analyze breach outflow and inundation (location, depth, velocity, arrival time) for each scenario.**

– **Determine populations at risk for various cases of warning and severity, considering variation with time of day and time of year.**

– **Point estimates or PDFs for each PFM.**

  • **Empirical fatality rates**

  • **Detailed models (Life Safety Model, LifeSim, etc.)**

  • **Yup! Subjective again.**

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- **Semi-empirical fatality rates from 40 floods but none due to earthquake. Fujinuma Dam should be added.**

A Procedure for Estimating
Loss of Life Caused by Dam Failure

DSO-99-06

Sedimentation & River Hydraulics

September 1999

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RECOMMENDED FATALITY RATES FOR ESTIMATING LIFE LOSS FROM DAM FAILURE

Flood Severity	Warning Time	Flood Severity Understanding	Fatality Rate	
			Specific Value	**Range**
High	None		0.75	0.30 to 1.0
	15 to 60 minutes	Vague	Use the values shown above and apply to the number of people who remain in the floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	60 minutes or more	Vague		
		Precise		
Medium	None		0.15	0.03 to 0.35
	15 to 60 minutes	Vague	0.04	0.01 to 0.08
		Precise	0.02	0.005 to 0.04
	60 minutes or more	Vague	0.03	0.005 to 0.06
		Precise	0.01	0.002 to 0.02
Low	None		0.01	0.0 to 0.02
	15 to 60 minutes	Vague	0.007	0.0 to 0.015
		Precise	0.002	0.0 to 0.004
	60 minutes or more	Vague	0.0003	0.0 to 0.0006
		Precise	0.0002	0.0 to 0.0003

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Next Simplest: Event Tree with PDFs on Probability
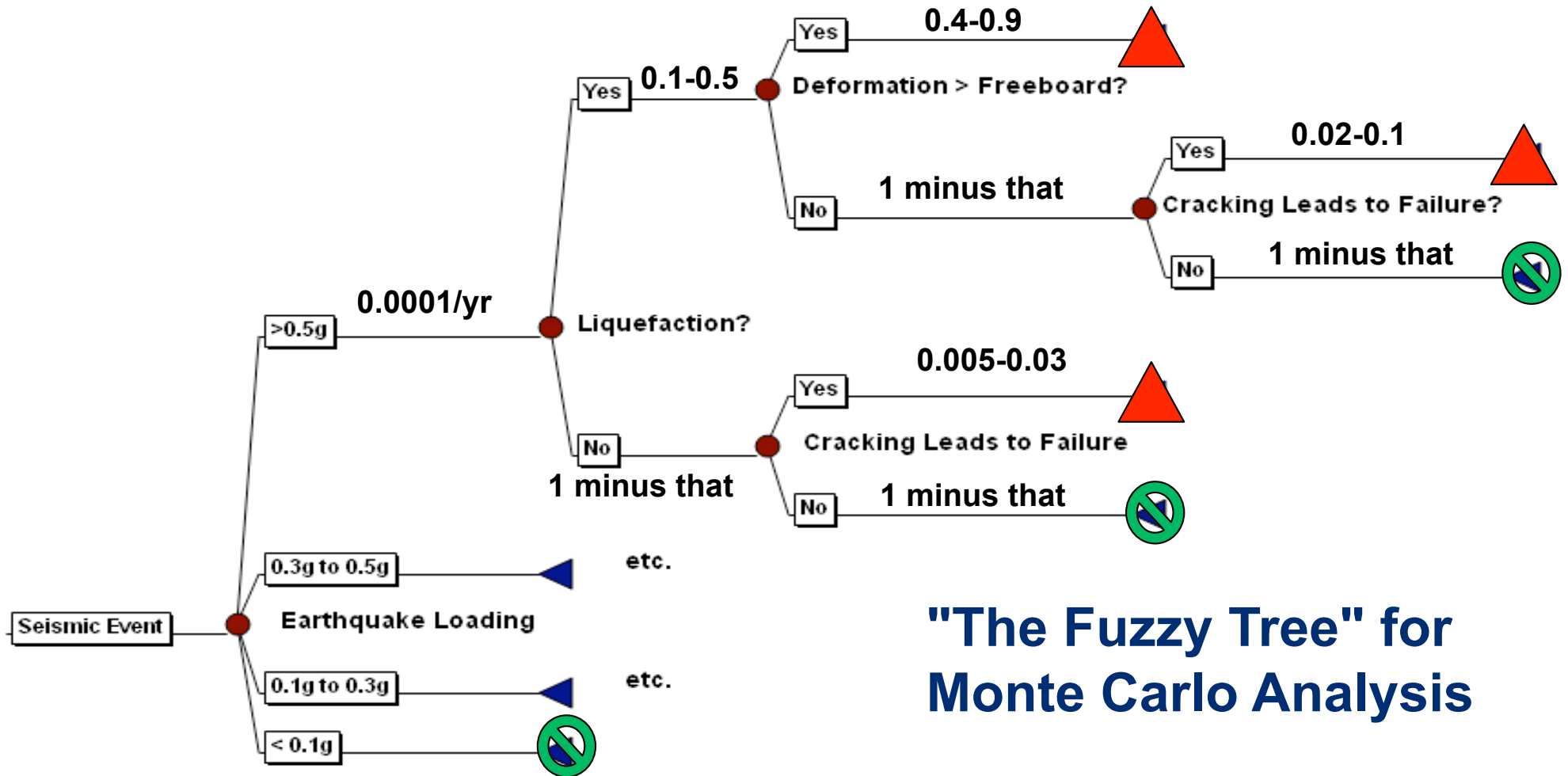
"The Fuzzy Tree" for Monte Carlo Analysis

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Monte Carlo Analysis with PDFs on Probabilities Only

- In simplest form of MC analysis, a PDF is estimated for some or all branch probabilities in an event tree.
- Then, for each iteration of the MC model, a probability is sampled from each PDF, and the failure risk is calculated for the whole tree.
- Repeat 9,999 times (typically), for a total of 10,000 estimates of APF and annualized loss of life.
- *Each iteration provides an estimate of APF.*
- Mean risk for each PFM from 10,000 iterations is usually what's used in the decision process.
- Scatter indicates level of confidence in the mean.

What does a PDF on an event probability mean?

- How high or low would you make your estimate if I gave you an additional drill log that shows loose sand? Or if I pulled out another research report that disagrees with the ones you've already read? Or if I ran the response analysis with a different set of ground motions and got a different result?

- Diversity of opinion within the team.

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Accounting for Uncertainty

- **Aleatory uncertainty – what's effectively random (reservoir level at the time of the earthquake). Irreducible.**

- **Epistemic uncertainty – what we don't know (continuity of low-angle fault seen in two out of three drill holes). Reducible with additional data, improved analysis, etc.**

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PDF on event probability

- **Coin toss: 0.48 to 0.52 probability of heads on the next toss.**

- **Baseball: 0.2 to 0.8 probability that the National League will pennant in 2022.**

- **In neither case is there much reason to favor one over the other, but between now and October 2022 we expect to gain additional information that could change our estimate by a lot. Unlikely to find good evidence that coin is strongly biased.**

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MC Results from Simple Event Tree with Distributions on Branch Probabilities Only

(Note "compact" cloud.)

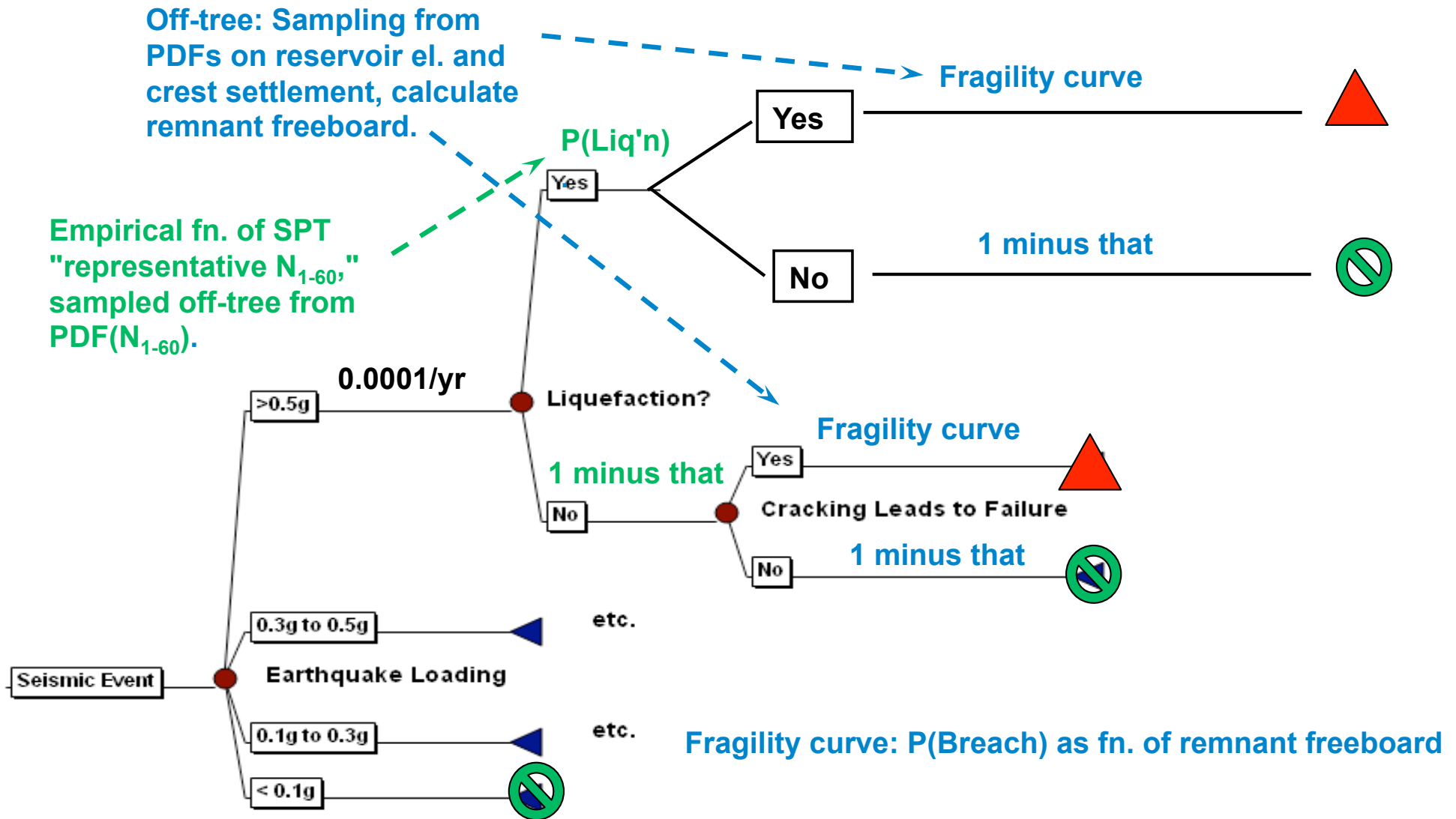
Concrete Dam
Seismic Risk
Sliding of Left Abutment Block
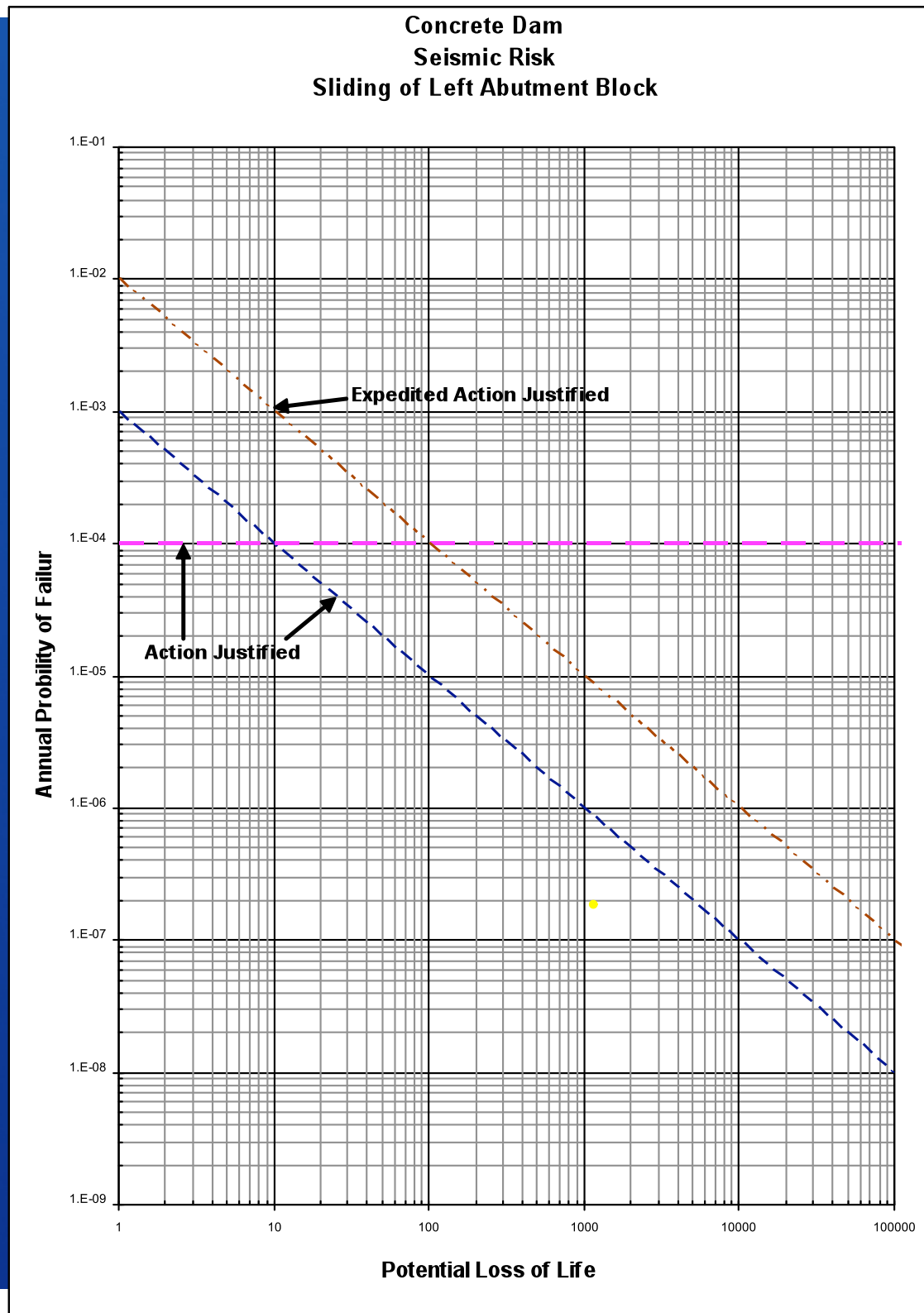
The Next Step Up: MC with PDFs on Physical Parameters

- Why? Makes it more manageable when branch probabilities are very sensitive to physical parameters (e.g., amount of settlement and pre-earthquake freeboard) which may in turn depend on material properties, model uncertainty or bias, etc.

- Otherwise, size of event tree to cover all possibilities would get too large.
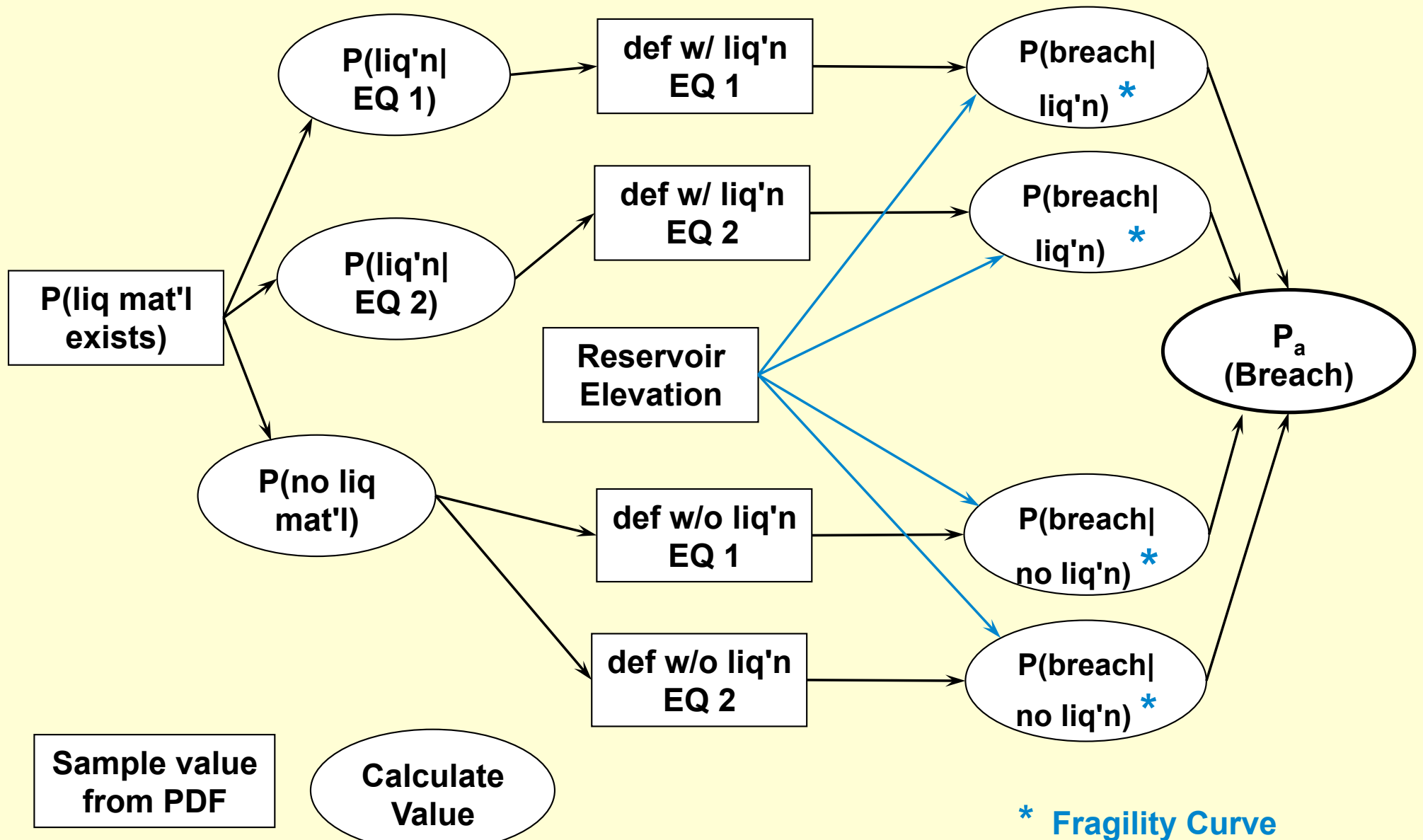
40

MC Analysis with PDFs on Physical Parameters

- MC analysis can be used as an alternative to creating an event tree with many, many branches.

- Enter parameters/probabilities (or PDFs on parameters/probabilities) as functions of physical parameters.

- For earthquake loading on spillway gates:
  - Fit equation giving axial force in gate arms as fn. of PHA and reservoir level.
  - Estimate fragility curve giving p(buckling) as fn. of axial force. Can be *family of curves* that give PDF on p(buckling).
  - For each iteration, sample from PDF on reservoir levels, and calculate p(buckling) directly from fragility curve, or sample it from PDF defined by family of curves.

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MC with Physical Parameters

Off-tree: Sampling from PDFs on reservoir el. and crest settlement, calculate remnant freeboard.

Empirical fn. of SPT "representative N_{1-60}," sampled off-tree from $PDF(N_{1-60})$.

P(Liq'n)

Fragility curve

Yes

No

1 minus that

0.0001/yr

>0.5g

Liquefaction?

1 minus that

Yes

Fragility curve

Cracking Leads to Failure

No

1 minus that

0.3g to 0.5g

etc.

Earthquake Loading

Seismic Event

0.1g to 0.3g

etc.

< 0.1g

Fragility curve: P(Breach) as fn. of remnant freeboard

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Example Monte Carlo Flow Chart

P(liq'n| EQ 1) → def w/ liq'n EQ 1 → P(breach| liq'n) *

P(liq mat'l exists) → P(liq'n| EQ 1)

P(liq mat'l exists) → P(liq'n| EQ 2) → def w/ liq'n EQ 2 → P(breach| liq'n) *

P(liq mat'l exists) → P(no liq mat'l)

Reservoir Elevation

P_a (Breach)

P(no liq mat'l) → def w/o liq'n EQ 1 → P(breach| no liq'n) *

P(no liq mat'l) → def w/o liq'n EQ 2 → P(breach| no liq'n) *

Sample value from PDF

Calculate Value

* Fragility Curve

Off the Tree

- **Residual freeboard = Pre-earthquake freeboard minus crest settlement**

- **May create "fragility curve" giving P(Breach) as fn. of remnant freeboard.**

- **Negative freeboard => overtopping, high P(Breach).**

- **P(Breach) by erosion in crack decreases with increasing freeboard.**

  – **Consider embankment design/construction and case histories - Rogers Dam failed by cracking (we think); LSF and La Marquesa didn't, despite major damage. Some embankments have survived flood overtopping.**

  – **May have separate fragility curves for different conditions – more-or-less intact crest *vs* major damage like LSF.**

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- Repeat 9,999 times (typically), for a total of 10,000 estimates of APF and annualized loss of life.

- *This time, each individual iteration does not provide a complete estimate of APF,* only an estimate of APF assuming specific conditions, e.g., reservoir at elevation 654.2; 10 kA earthquake causes 17.3 feet of settlement, etc.

- APF is numerically equal to the mean of 10,000 iterations. (Actually, it's the sum of APF from a tree with 10,000, 20,000, 30,000 or 40,000 paths to failure.)

f-N Chart from MC Analysis with PDFs on Material Properties and Reservoir Level

(Note vertically elongated cloud with few dots above mean. Statistics on the dots may not mean much!)
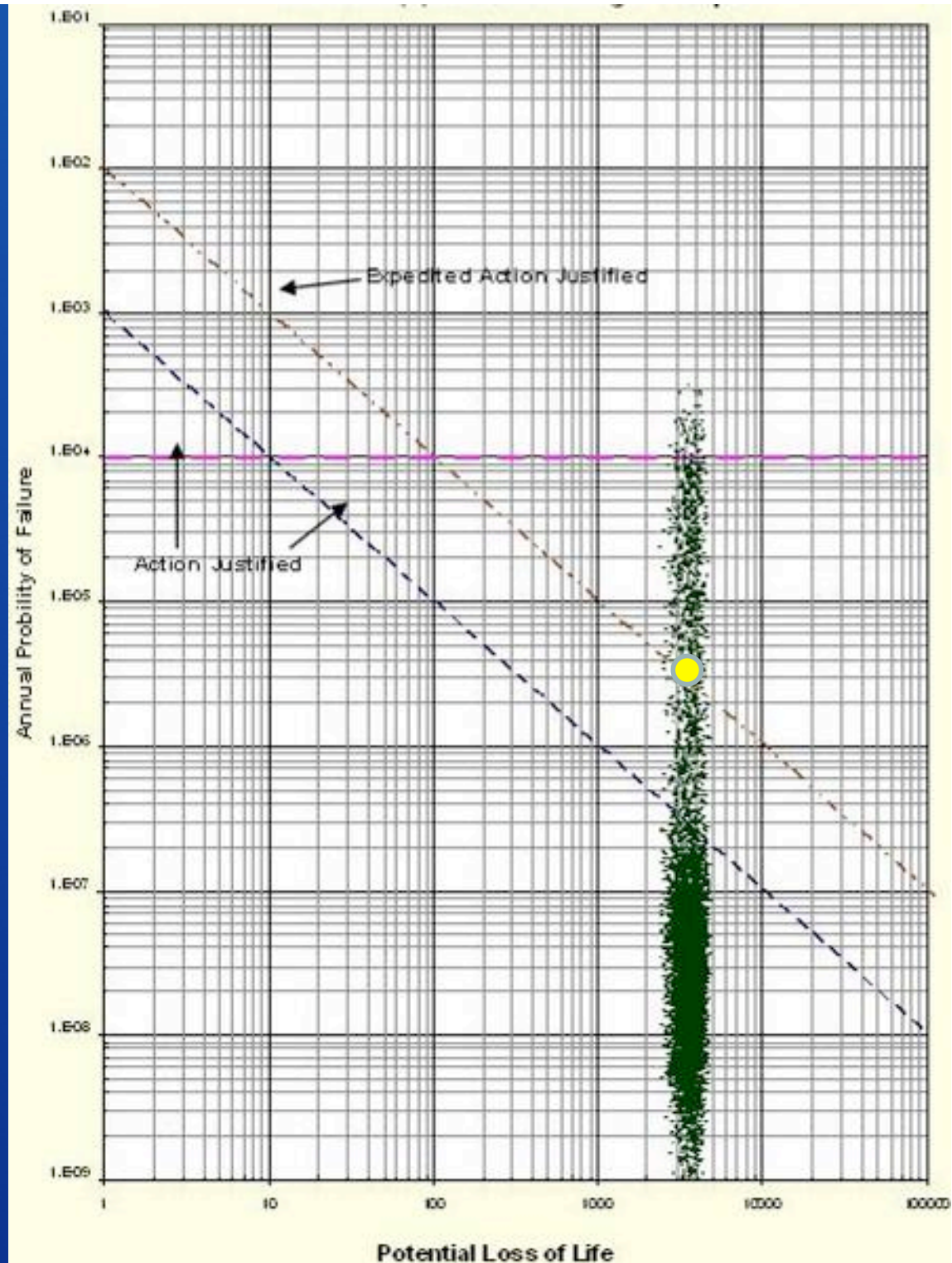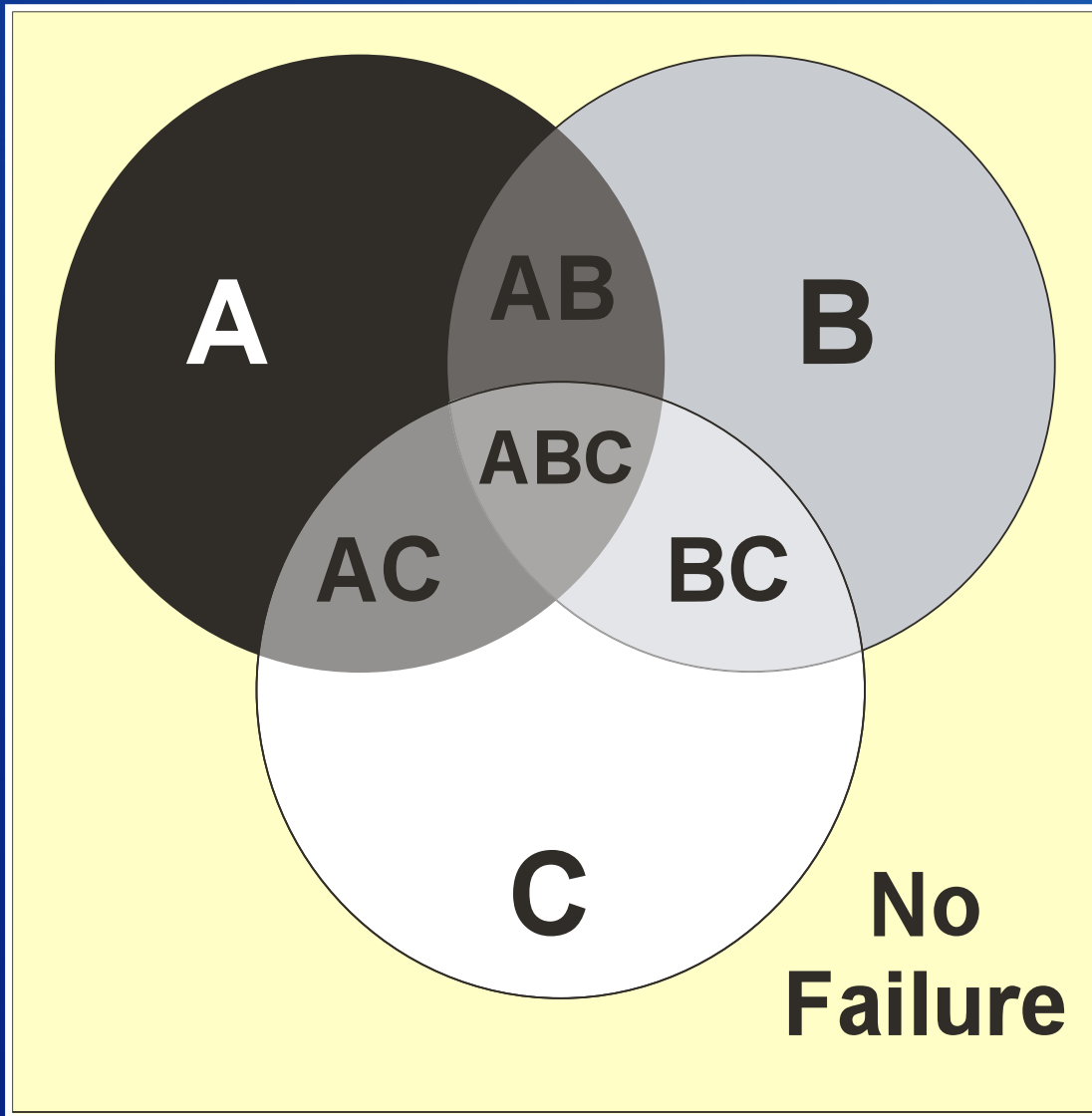
System Failure Probability

- In dam-safety risk analysis, the system is typically defined as all the components of the project that retain the reservoir, failure of which would affect a common population.

- Usually we treat it as a "series system," like links in a chain– if one component fails, the system fails.

- The failure probability of a system, p_{fs}, must be $\leq$ 1.0. By unimodal bounds theorem, its value is between the highest single failure mode probability (max p_i), and the total failure probability of the system considering all of the (n) potential failure modes to be independent:

Max $p_i \leq p_{fs} \leq 1 - [(1 - p_1)(1 - p_2)\ldots(1 - p_n)]$

"Common-Cause" Adjustments

- **Needed for seismic and flood failure modes that result from the same initiating event (the common cause)** *but are not part of the same event tree.*

- **Example - three independent failure modes:**
    - *p*(A - sliding of concrete section | EQ) = 0.7
    - *p*(B - buckling of spillway radial gate arm | EQ) = 0.5
    - *p*(C - fndn. liq'n, overtopping at earthfill wing dam | EQ) = 0.5

- **There are seven possible failure outcomes, but we usually want to assign the probability of failure to individual failure modes, not to combinations.**

- **Treat the failure modes as independent components of a system, then distribute system failure probability proportionally among A, B, and C.**

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"Common-Cause" Adjustment

- The probability of "no failure" for the system is:

  p(No Failure) = [1 - p(A)] x [1 – p(B)] x [1 – p(C)]

  = [1 - 0.7] x [1 - 0.5] x [1 - 0.5]

  = 0.3 x 0.5 x 0.5 = 0.075

- System failure probability is 1 – 0.075 = 0.925

- To allocate probability among individual failure modes only, adjust individual probabilities thusly:

  p_{adj}(A) = (0.925/1.7) * 0.7 = 0.381

  p_{adj}(B) = (0.925/1.7) * 0.5 = 0.272

 p_{adj}(C) = (0.925/1.7) * 0.5 = <u>0.272</u>

  0.925

Where are we?

- Our ability to calculate probability is way ahead of our ability to determine "representative blowcount" and other material properties, predict depth of cracking and performance of zoning, etc.

- High degree of subjectivity in nearly every part of the process.

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- **Still, probabilistic risk analysis is a useful tool for setting priorities and comparison with societal tolerance for risk (Public Protection Guidelines).**

- **The *process* may be more important than the result.**

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Discussion?

Fatehgadh Dam
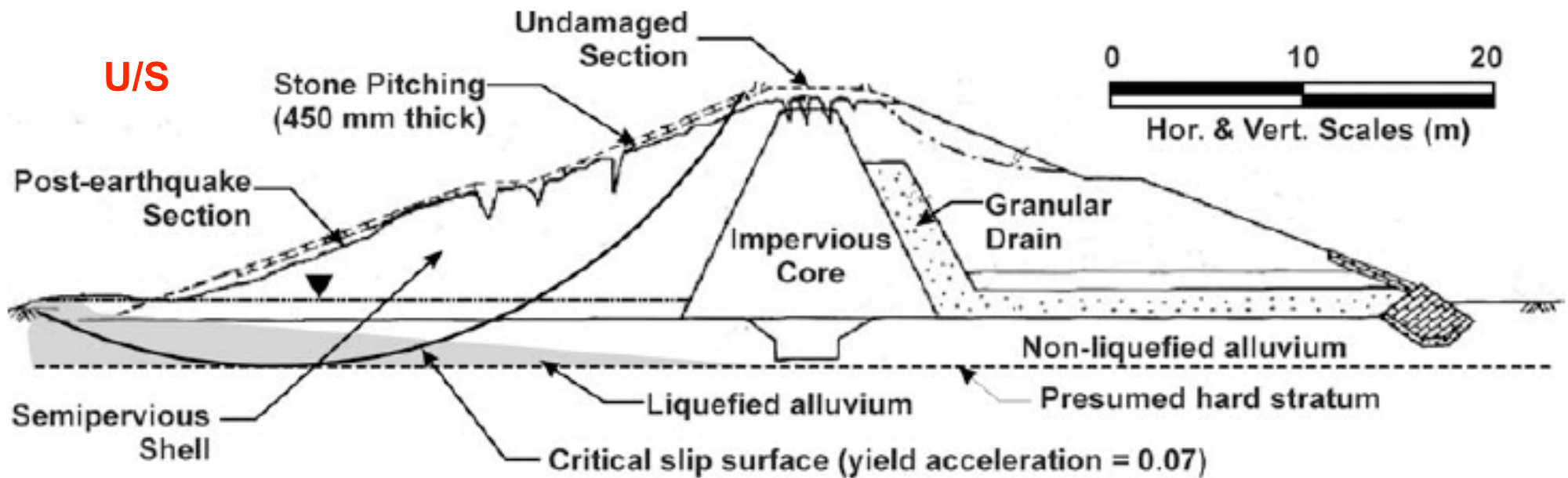
Singh, Roy, and Jain (2004)

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