Best Practices in Dam and Levee Safety Risk Analysis

I-9. Decision Documents and Building the Case

December, 2014

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Outline

- What needs to be built
- Where we get the evidence to build it
- How we fit it into decisions

The main thing we need is to start citing the evidence that supports the case for why the risk estimates (both likelihood of failure and consequences) make sense, and therefore why the recommendations make sense.

Six Questions Needing Answered:

- Do risks agree with DSAT's understanding of current conditions and the ability to withstand future loads?
- Do recommended actions agree with portrayed risks?
- Is it reasonable to continue operating until the next CR?
- What are the most appropriate future actions?
- Do recommendations sufficiently capture needed actions?
- Does the overall report and its conclusions make sense?

QCC Questions

Charge Questions for Issue Evaluation Studies:

- Are the background, design, construction, and performance adequately explained?
- Are the hydrologic and seismic loads adequately characterized? Was the uncertainty appropriately considered and portrayed?
- Are potential failure modes adequately described and evaluated? Are there other potential failure modes that should be considered? Are the risk driving failure modes appropriate? Are there any failure modes that were excluded that should not have been? Has enough information been included for failure modes that were excluded from the report? Was the uncertainty appropriately considered and portrayed?
- Are consequence estimates well supported and reasonable? Was the uncertainty appropriately considered and portrayed?

QCC Questions (Cont.)

- Are interim risk reduction measures (IRRM) reasonable? Do you suggest consideration of other IRRMs?
- Do the portrayal and level of risks agree with your understanding of the facility's current condition and its ability to withstand potential loads, based on your review of information provided? Are risk analyses well supported and reasonable? Are there branches in risk event trees that require further evaluation, reassessment or investigation before being judged as a reasonable representation of the risk?

QCC Questions (Cont.)

- Has the team identified aspects of the load, failure modes, or consequences that influence the results and have they identified which items they are least confident in? Do the recommended actions agree with the risks as they are portrayed in the documents provided for your review? In your professional opinion, what are the most appropriate actions to pursue for either reducing uncertainties, confirming risks, or reducing risks?
- What are the urgency of actions related to this structure in the context of the Dam Safety Action Classification?
- Do you have any other comments?

Building the Case

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

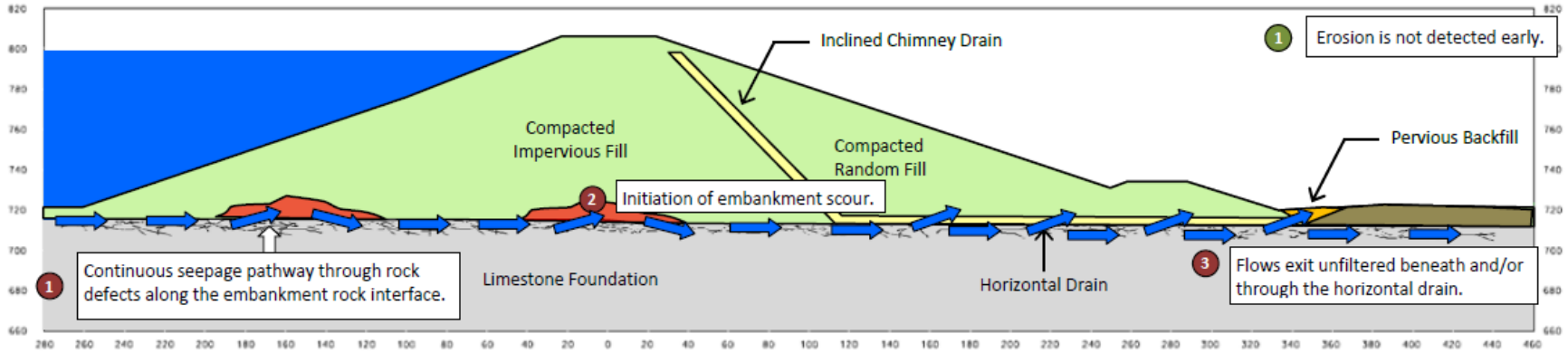
Teams must consider each factor to rigorously build the case for each potential failure mode.

Where do we get the Evidence to Build Cases?

Where we get the Evidence to Build Cases

- Case histories of failures
- Site characterization (geologic details)
- Empirical data
- Design precedents
- Design details
  - Key defenses (multiple, many made to address past incidents)
  - Construction details
- Performance
- Inspections and observations
- Analysis
- Other PFMA's and risk analysis
- Poor performance at other structures today

Simple Example PFM on Cross Section



Simple Argument

- Claim:
  - Chimney drain material filters the impervious fill.

- Evidence:
  - Gradation tests show filter criteria met (provide figure)
  - There were a large number of tests (report number)
  - Zone 2 material doesn't easily segregate (calculation)
  - Construction control procedures were excellent (describe)

Embankment placed on untreated overburden foundation

Embankment placed on top of rock (non-special treatment)

Embankment placed on special treatment zone bedrock

The area of concern for this potential failure mode is at both the left and right interfaces of the concrete and the embankment where material was placed directly on the exposed bedrock (shaded yellow), particularly in the areas adjacent to blast damaged rock beneath the concrete center spillway section. Potential seepage paths are shown as solid blue lines. Seepage observed during 2003 and/or 2005 flood events are shown as dotted blue areas.

Figure 2-10: Typical Foundation after Overburden Removal

Good Example

Failure Mode Description: A continuous network of rock defects (jointing, bedding planes, small scale irregularities along the rock surface, and blast damage) exists at the embankment/rock interface from upstream to downstream with an exit at the ditch near the embankment downstream toe ***(Flaw).*** *At all* reservoir levels ***(loading)***, the rock is charged and the resulting flow through the network of defects is of sufficient velocity and hydraulic gradient to scour the embankment core material at the interface ***(Initiation)****. These* flows exit unfiltered beneath and/or through the horizontal drain and scour erosion continues ***(Continuation).*** *The impervious embankment material upstream of the horizontal drain supports a roof to* the developing pipe and there is no upstream zone that would clog or limit flow into it ***(Progression)****.* Detection and intervention are unsuccessful (*Unsuccessful Detection and Intervention*)*. With the* expanding of the pipe, the resulting inrush of water blows out the downstream horizontal drain and the downstream portion of the embankment collapses. The collapsed material is progressively removed by these flows until the crest collapses below the reservoir level resulting in overtopping breach and significant downstream consequences ***(Breach)****.*

Where do we get the Evidence to Build a Specific Case

- Specific risk analysis results
  - Detailed Failure Mode Description
  - Drawings and figures
  - **Event tree - key branches(outline)**
  - **"More likely and less likely" factors**
  - **Rationale for risk estimates of nodes**
  - **Likelihood of failure**
  - **Estimated Consequences**

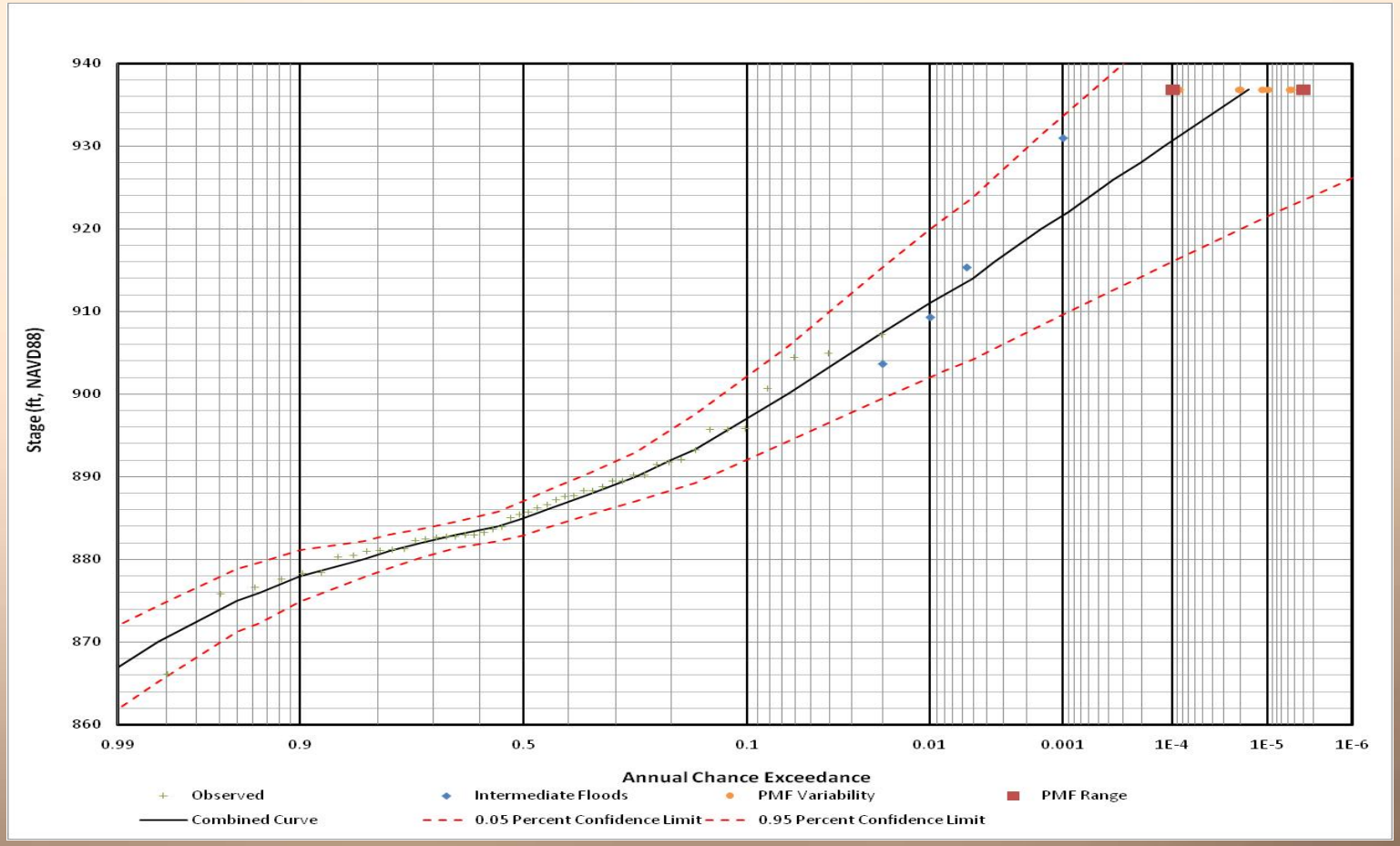
Building the Case

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

Teams must build the case for all potential failure modes.

What are the essential elements of building the case for the loading estimate?

Reservoir Elevation Frequency Curve



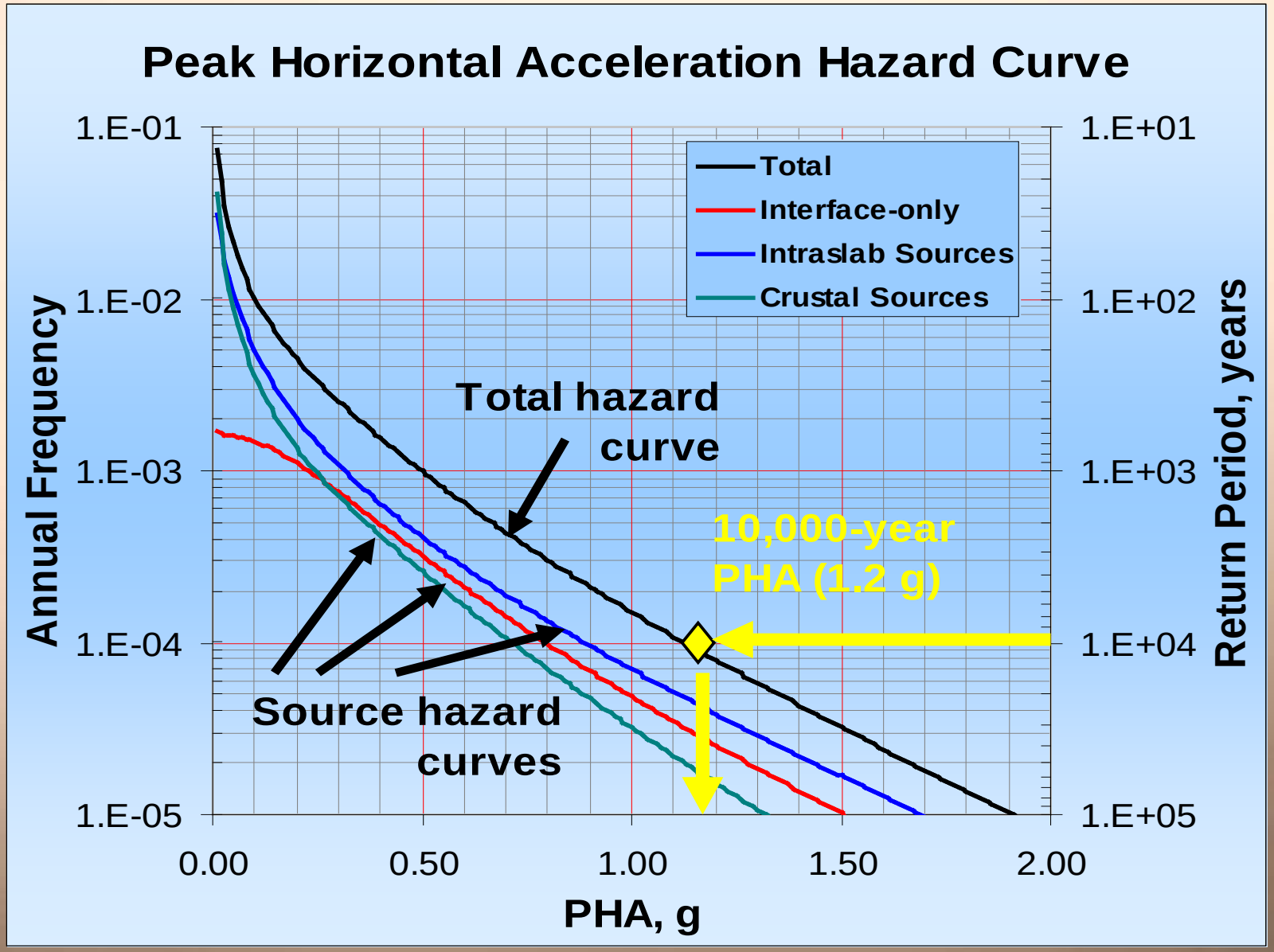
Stage Frequency curve with uncertainty

Flood Event Tree Partitions

Flood Intervals

- EL 1671.5, P=0.5
- EL 1673.5, P=0.4
- EL 1679.2, P=0.09
- EL 1685.5, P=0.009
- EL 1691.5, P=0.0009
- EL 1695.0, P=0.0001

Elevation			Probability		
Lower Bound	Upper Bound	Index Value	Lower Bound	Upper Bound	Probability
n/a	1671.5	1671.5	1	0.5	0.5
1671.5	1675.5	1673.5	0.5	0.1	0.4
1675.5	1683.0	1679.2	0.1	0.01	0.09
1683.0	1688.0	1685.5	0.01	0.001	0.009
1688.0	1695.0	1691.5	0.001	0.0001	0.0009
1695.0	n/a	1695.0	0.0001	0	0.0001


Peak Horizontal Acceleration Hazard Curve
Annual Frequency
Return Period, years
PHA, g
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
0.00
0.50
1.00
1.50
2.00
Total
Interface-only
Intraslab Sources
Crustal Sources
Total hazard curve
10,000-year PHA (1.2 g)
Source hazard curves

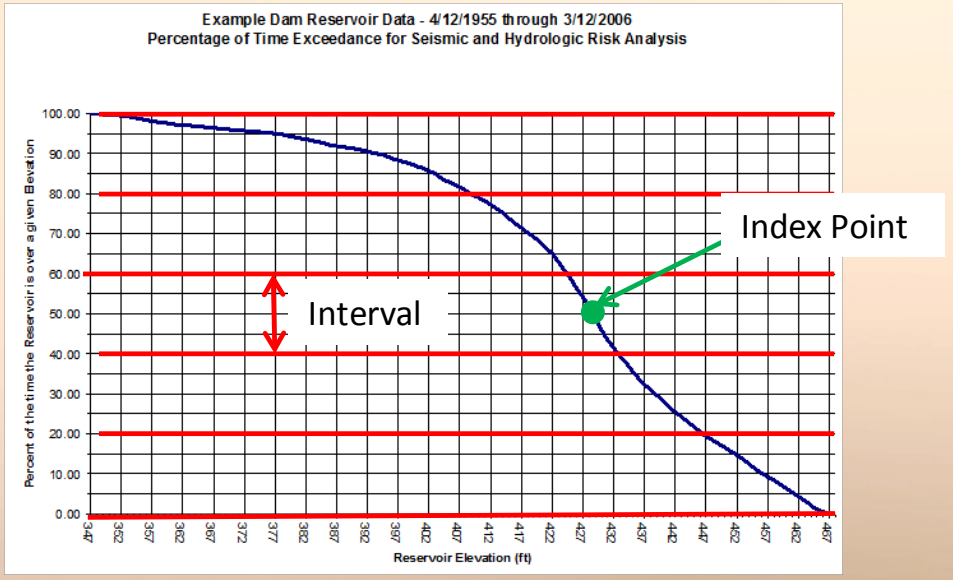
Seismic Loading

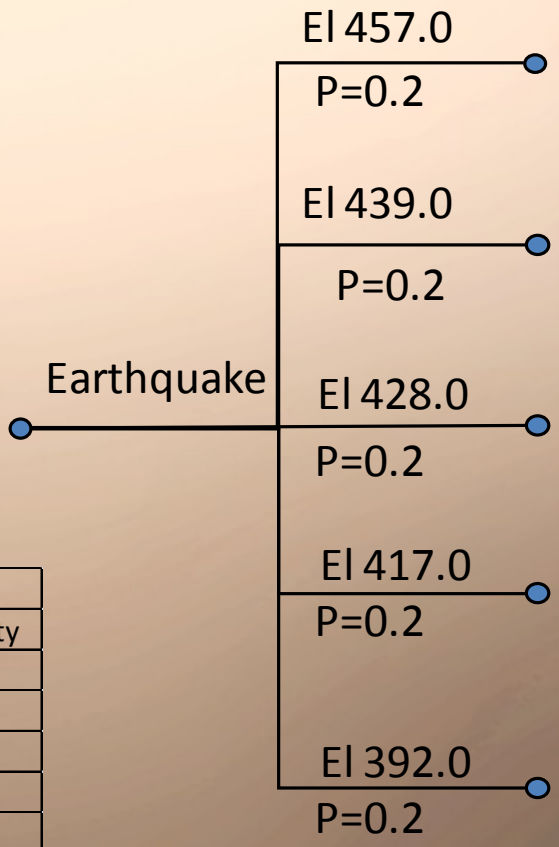
- Probabilistic ground motions are required for quantitative risk analysis

$$Rate(loading) = Rate(EQ) \times \Pr(loading \mid EQ)$$

- First key factor in determining the hazard is the earthquake rate of the controlling source
  - Geologically determined slip rate
  - Historical seismicity
  - Geodesy and GPS
- Second key factor is determining the range of possible ground motions, given a likely set of scenario earthquakes

Seismic Event Tree Partitions





Elevation			Fraction of Time Exceeded		
Lower Bound	Upper Bound	Index Value	Lower Bound	Upper Bound	Probability
447.0	467.0	457.0	0.2	0	0.2
432.0	447.0	439.0	0.4	0.2	0.2
424.0	432.0	428.0	0.6	0.4	0.2
409.0	424.0	417.0	0.8	0.6	0.2
347.0	417.0	392.0	1	0.8	0.2

Keys to Partitioning of Loading

- Historic performance of dams
- Threshold events
- Pool of record
- Performance during past events
- Enough to get a well defined relationship

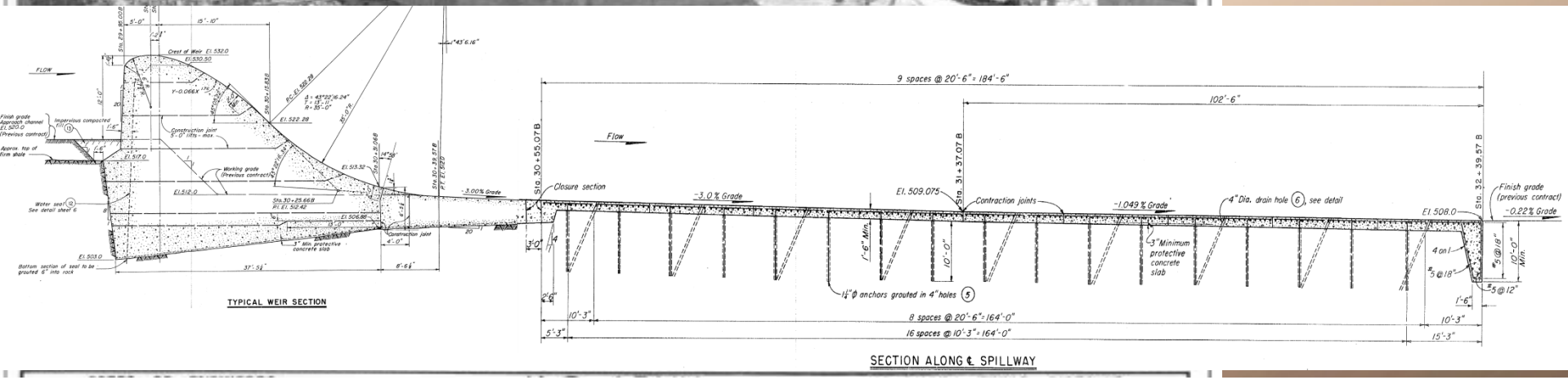
Building the Case

$$\text{Risk} = \sum \left[\begin{matrix} \text{Probability} \\ \text{of the Loadin} \end{matrix} \right] \left[\begin{matrix} \text{Probability of Failure} \\ \text{Given the Loading} \end{matrix} \right] \left[\begin{matrix} \text{Consequences} \\ \text{Given Failure} \end{matrix} \right]$$

Teams must build the case for all potential failure modes.

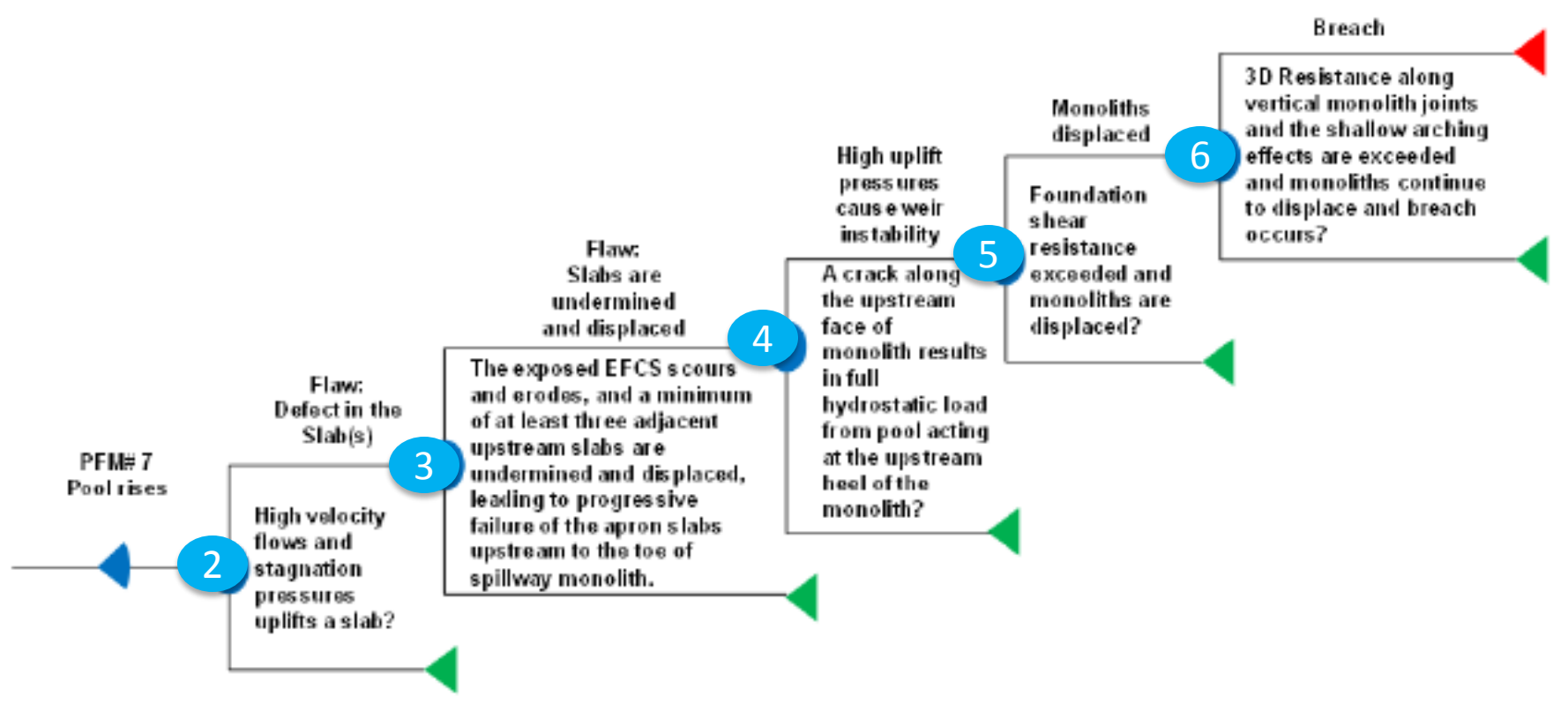
Given the loading, what are the essential elements of building the case for the probability of failure?

Multi-discipline Example



PFM 7 Spillway weir instability due to failure of the spillway apron slabs during high velocities and high stagnation pressures in the existing offset joints in the apron slabs leads to sliding of the spillway weir and uncontrolled loss of reservoir.

PFM 7



NO INTERVENTION NODE SHOWN

Simple Arguments

- Claim:
  - Each finding should establish claims
- Evidence:
  - Needs to be validated
  - Should substantiate the claim

PFM 7 (Node 2)

High velocity spillway flows generate stagnation pressures at a projecti uplifts and displaces an apron slab.

Elicited likelihood estimates:

Spillway Crest El 532.0: 0.000
POR (536.7): 0.01
Pool El 539: 0.05
Pool El 541.2: 0.100
Pool El 547.0: 0.300
PMF (554.1): 0.500

*There are no dowels or any type of interlocking system between slabs along joints.

* Velocities are estimated to range from 30 – 50 fps along the apron slabs for reservoir elevations above pool of record (El. 536.7).

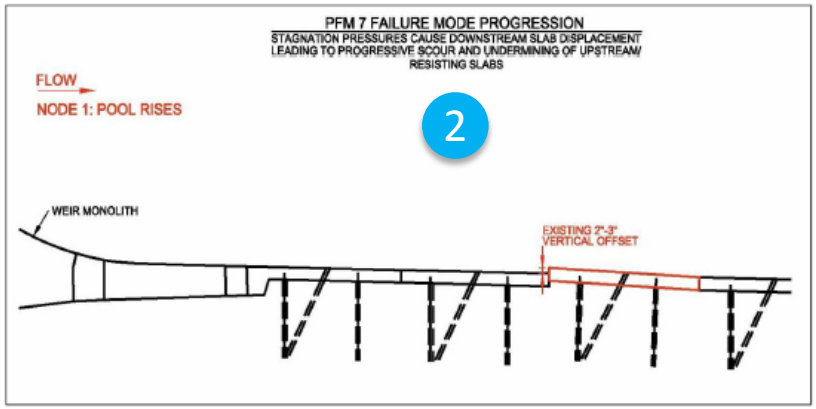


Figure 9-44: PFM 7 Flaw

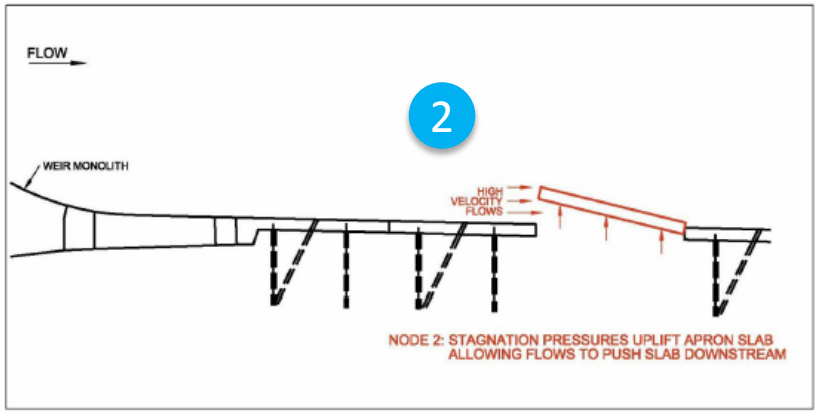


Figure 9-45: PFM 7 Initiation

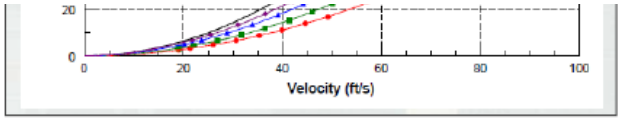


Figure 9-59: Best Practices USACE/USBR Stagnation Pressure Relationship to Flow Velocity

PFM 7 (Node 3)
The exposed EFCS scours and erodes,
upstream slabs are undermined and di
apron slabs upstream to the toe of spil

Elicited likelihood estimates:

Spillway Crest El 532.0: 0.000
POR (536.7): 0.001
Pool El 539: 0.01
Pool El 541.2: 0.05
Pool El 547.0: 0.10
PMF (554.1): 0.20

Conditions making PFM Likely

- *The 1982 event was reported to have eroded 7-8 feet at the downstream end the spillway slabs.

Figure 2-16: Lewisville Dam. Turbulent flow in the spillway channel just downstream of spillway weir resulted in severe erosion (Photo taken around October 1981)

7

3

PFM 7 (Node 4)

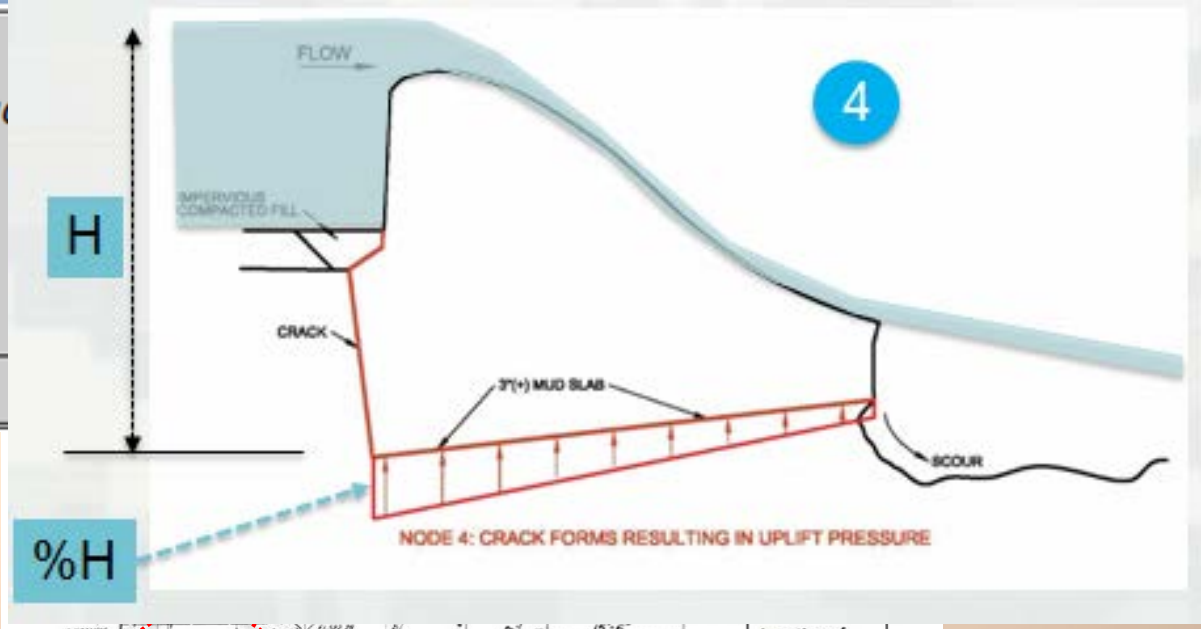
Uplift pressure distribution (0-33%; 33-67%; 67-1

Elicited likelihood estimates:

0-33% = 0.65
33-67% = 0.25
67-100% = 0.1

Conditions Making PFM Likely

- *There are no foundation drains in the weir structure.



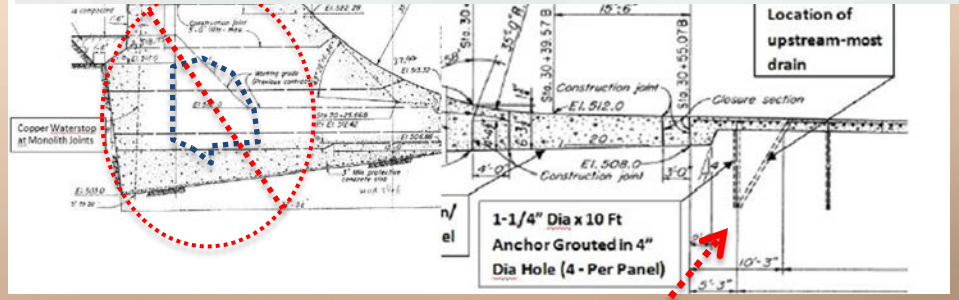


Figure 9-56: Typical Clogged Spillway Apron Slab Drain Condition (Jan 2014)

PFM 7 (Node 5a, 5b, 5c)

Foundation shear resistance exceeded and monoliths d
resistance).
0-33%; 33-67%; 67-100%

Elicited likelihood estimates:

Spillway Crest El 532.0: 0.000
POR (536.7): 0-33% = ; 33-67% = ; 67-100% = 0.25
Pool EL 539: 0-33% = ; 33-67% = ; 67-100% = 0.60
Pool EL 541.2: 0-33% = ; 33-67% = ; 67-100% = 0.75
Pool El 547.0: 0-33% = ; 33-67% = ; 67-100% = 0.90
PMF (554.1): 0-33% = ; 33-67% = ; 67-100% = 0.95

Conditions Making PFM Likely | ***Conc***

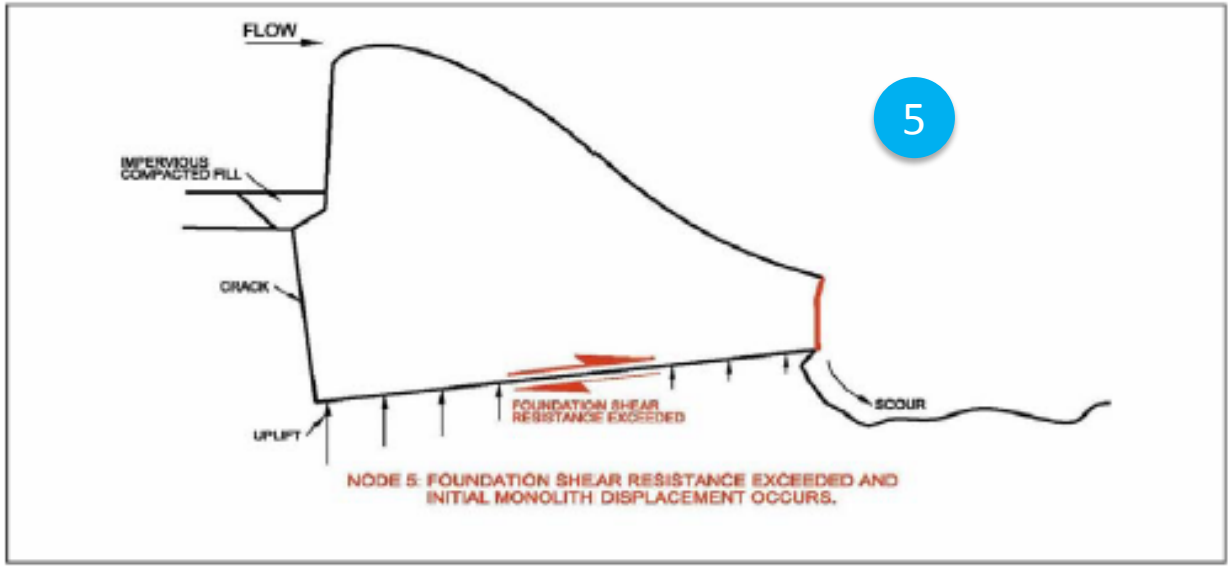


Figure 9-48: PFM 7 Progression Leading to Failure of Weir Monolith

- *Downstream movement of the monoliths may result in an open crack along the upstream face of the monolith resulting in full hydrostatic load from pool acting at the upstream heel of the monolith.
- *The risk of safety factors below 1.0 with no slab resistance reach, or nearly reach 100% as the uplift and pool event/ headwater increase.

539	0	539	0%
541.2	0	541.2	2%
547	7%	547	41%
554.1	46%	554.1	89%
33-67% Uplift with Apron Resistance		**33-67% Uplift without Apron resistance**	
Headwater	**Risk SF < 1.0**	**Headwater**	**Risk SF < 1.0**
536.7	0	536.7	1%
539	2%	539	14%
541.2	7%	541.2	47%
547	56%	547	98%
554.1	96%	554.1	100%
67-100% Uplift with Apron Resistance		**67-100% Uplift without Apron Resistance**	
Headwater	**Risk SF < 1.0**	**Headwater**	**Risk SF < 1.0**
536.7	6%	536.7	51%
539	26%	539	89%
541.2	52%	541.2	99%
547	97%	547	100%
554.1	100%	554.1	100%

PFM 7 (Node 6)
3D Resistance along vertical monolith joints and the sl
exceeded and monoliths continue to displace and brea

Elicited likelihood estimates:

Spillway Crest El 532.0: 0.000
POR (536.7): 0.005
Pool EL 539: 0.010
Pool EL 541.2: 0.200
Pool El 547.0: 0.300
PMF (554.1): 0.600

Summary Statement: *Due to the loss of the three consecut*
additional load transfer will occur between the adjacent spillway
adjacent spillway apron slabs. The loss of the three downstrean
a loss of restraint of up to an estimated 600 kips (60 feet x 10k/ft
used during the original design were unrealistic due to the use o
angle of 21 degrees. The abutments of the spillway monoliths a
would not offer the same restraint to translation and rotation as a
monoliths should act as a shallow arch and provide significant re

Conditions Making PFM Likely | ***Con***

6

- "Three rows of apron slabs have been removed immediately downstream of a spillway monolith near the middle of the structure.

- "Due to the removal of downstream apron slabs, additional loading would be transferred to the adjoining monoliths and adjacent intact apron slabs.

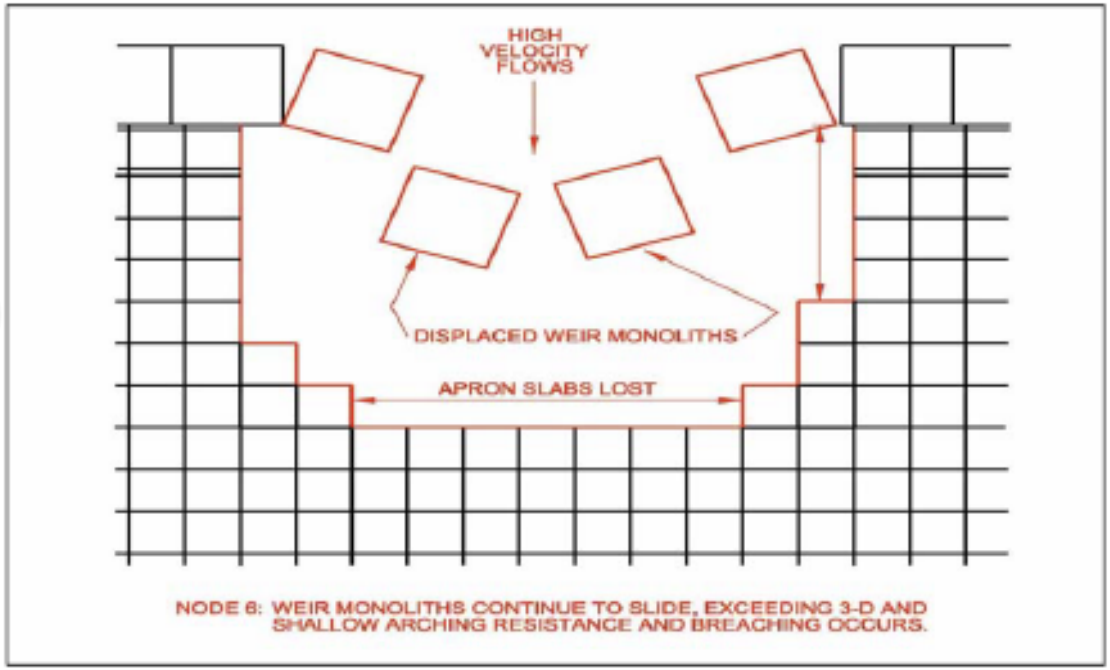


Figure 9-49: PFM 7 Progression Leading to Breach

Building the Case

$$\text{Risk} = \sum \begin{bmatrix} \text{Probability} \\ \text{of the Loading} \end{bmatrix} \begin{bmatrix} \text{Probability of Failure} \\ \text{Given the Loading} \end{bmatrix} \begin{bmatrix} \text{Consequences} \\ \text{Given Failure} \end{bmatrix}$$

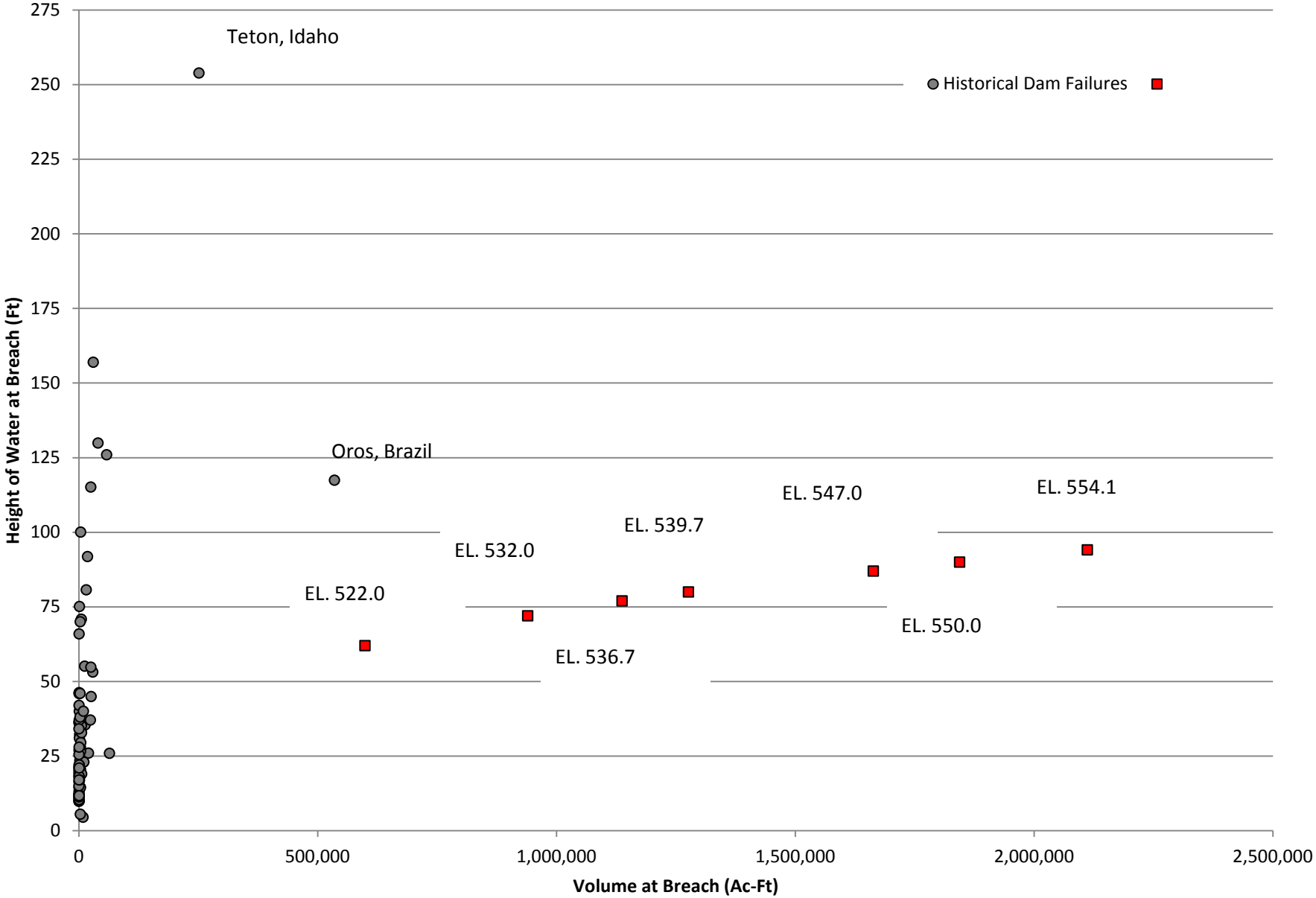
Teams must build the case for consequences as rigorously as done for potential failure modes.

What are the essential elements of building the case for the consequence estimate?

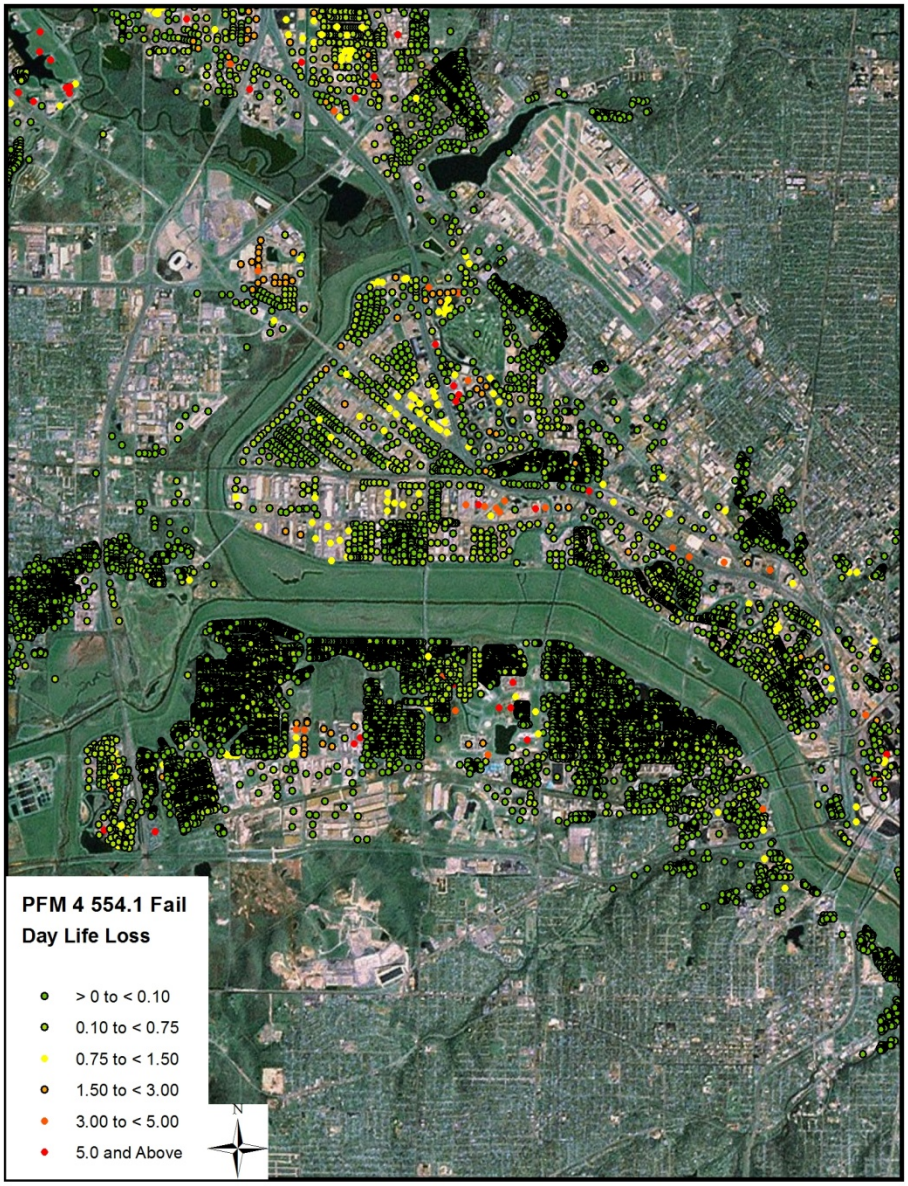
Making Sense of Consequence Analysis Results

- Characterize Flooding
  - Present assumptions regarding breach time/size, arrival time, depths and velocities, rate of rise
- Population at Risk
  - Show where they are, how common attributes were grouped in HEC/FIA and LifeSim, transient PAR considerations
- Detection, Warning, Flood Wave Travel Time
  - Provide expected /best case/worst case assumptions on detection, decision to notify, notification process, decision to evacuate, evacuation process. Why is expected result where it is?
- Results
  - Show how many & where & sensitivity to assumptions

Historic Breach Characteristics



PFM 4 554.1 Fail Dot Plot



Essential Elements of Building the Consequences Case

- Initial distribution of people
- Redistribution of people (evacuation effectiveness)
- Flood characteristics
- Shelter provided by final location

Passed Tech Review

- If you have a good day at QCC/DSAT, it is probably because:
  - Your failure modes adequately described and understood by everyone in attendance
  - You portrayed the current condition of the dam (design, analysis, construction, structural behavior) and its ability to withstand future loadings
  - You adequately supported the risk estimate numbers with the reasons why they make sense
  - The state of the facility, the risk numbers, and the recommendations are consistent with each other

Decisions

- Four Basic Pieces of Information
  - Risk Estimate
  - Estimated Range of Uncertainty (and Confidence)
  - Case to Support Risk Estimate
  - Recommended Course of Action
- Strategy
  - Use the risk estimate in relation to the risk guidelines and the safety case to support rational consistent decisions

Details

- Three main components:
  - The risk is tolerable or intolerable
  - The need for action is urgent or not
  - The uncertainty is great and additional investigations has a good chance of changing perceptions of risk tolerability or urgency

Dam Safety Case:

- A Logical Set of Arguments…
  - Recommending additional safety-related action is justified, or no additional safety-related action is justified.
  - Routine activities continue no matter what

- Is convincing when readers sense that the following are coherent:
  - the dam's existing condition and ability to withstand future loading,
  - the risk estimates,
  - and the recommended actions.

Conclusions Requiring Justification

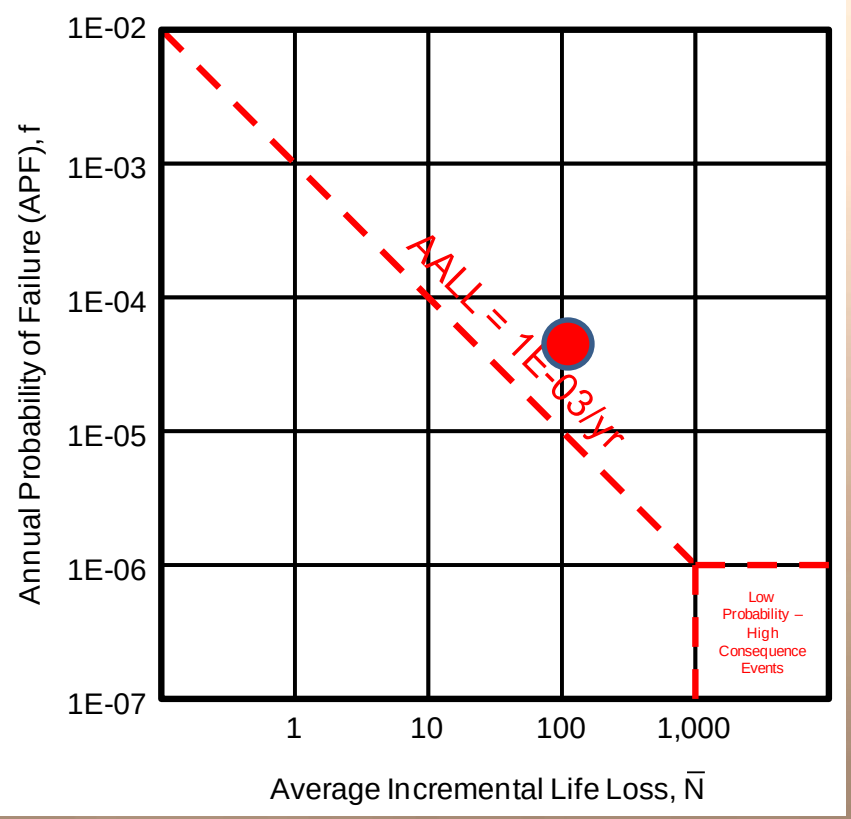
Risk	Confidence	Action
Tolerable	High	No further actions or studies necessary
Tolerable	Low	It might be reasonable to expect additional information could increase the risk estimate such that risk might not be tolerable.
Not Tolerable	High	Move directly into MOD study
Not Tolerable	Low	It might be reasonable to expect additional information could decrease the perceived risk such that the perceived risk may be tolerable
Tolerable	High	There might be reasonable and prudent actions to reduce risk

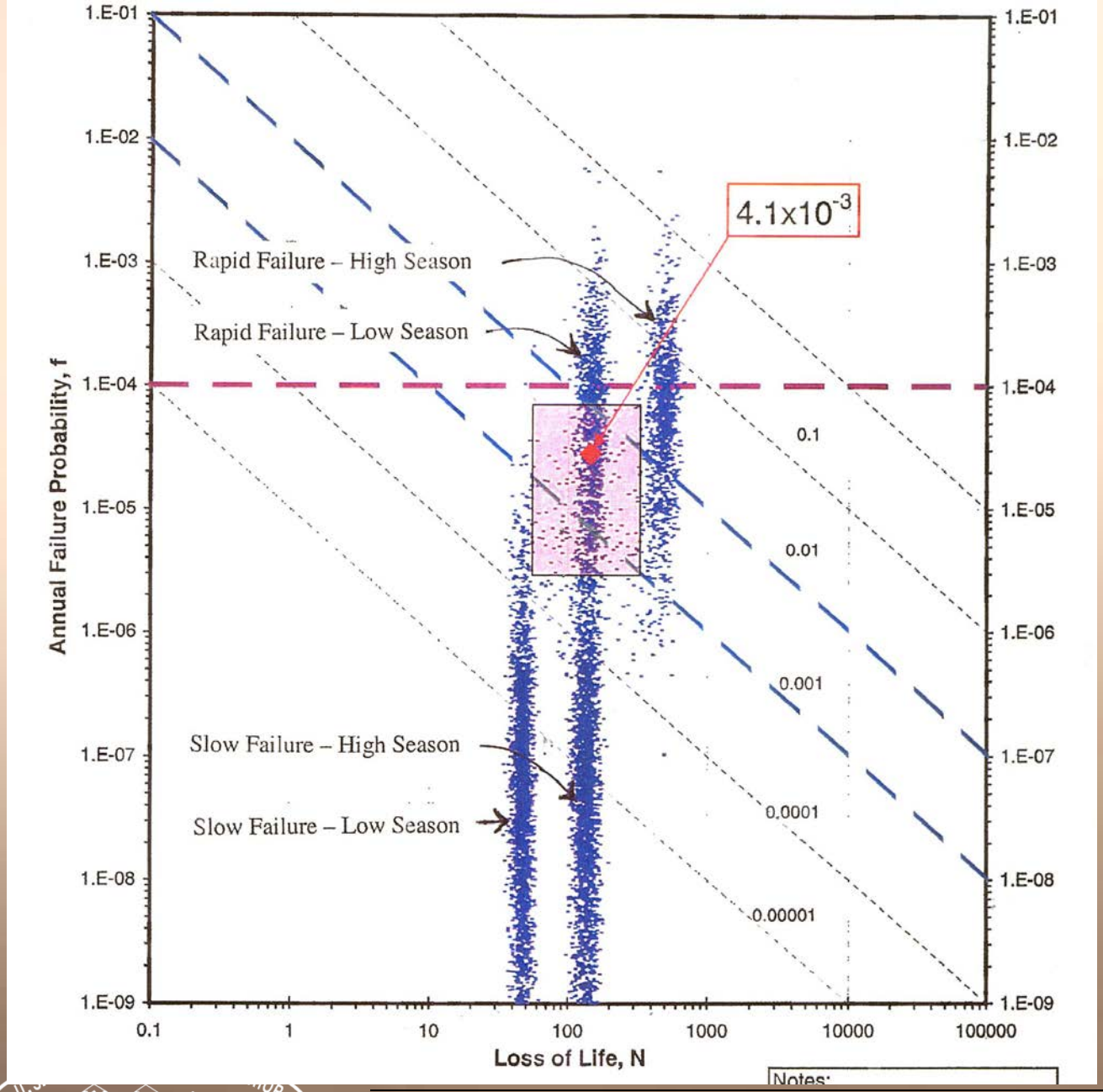
To be updated

Justification to Recommend Investigations to Reduce Uncertainty

- Any actions proposed based on uncertainty must address the sensitivity of the mean risk estimate to that uncertainty.
- Moving the mean estimate changes the justification category
- There is a good likelihood the recommended investigation can reduce the uncertainty

Example - Incremental Life Safety Risk Matrix





Blow Count

Mean: 16

Std. Dev.: 8

Six Boreholes

Unfortunate

Locations

Blowcount 16 OK

Low Blow Count Hits Drove Up The Risk

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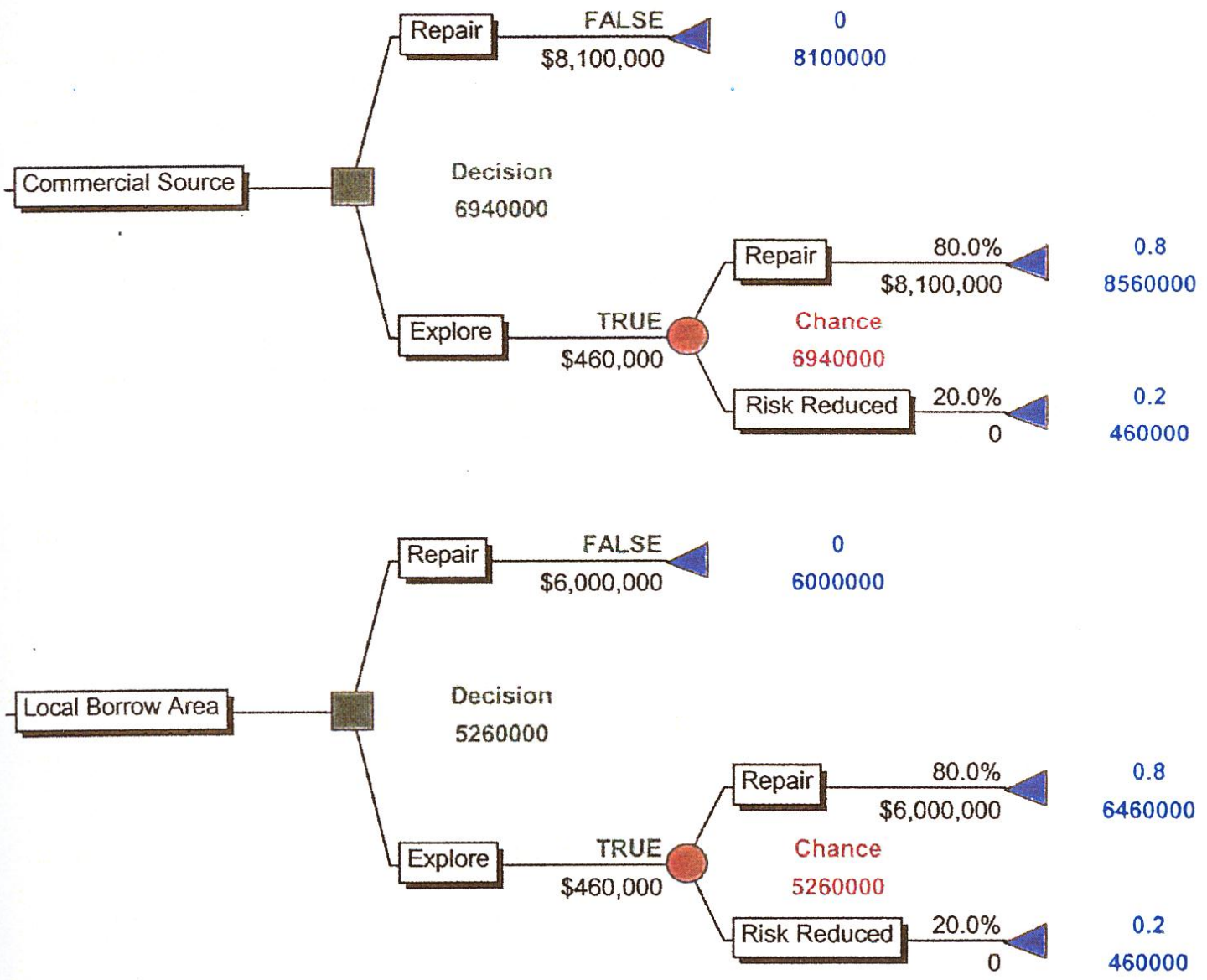
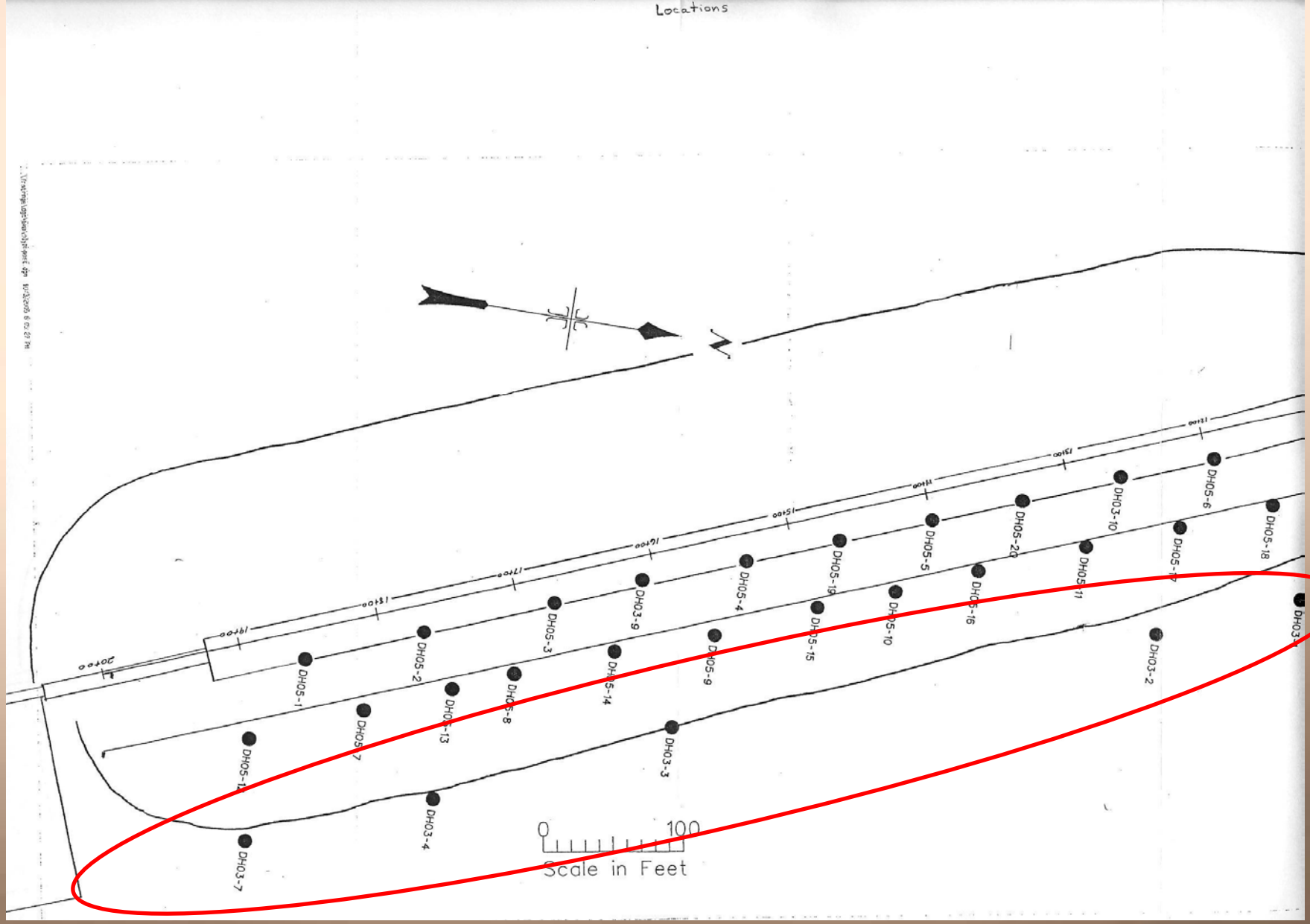
Justification to Recommend Investigations to Reduce Uncertainty

- The mean estimate of risk was shown to be sensitive to the blow count uncertainty.
- The likely change in the mean estimate impacted the justification category.
- There was strong evidence the recommended investigation could reduce the uncertainty.
- It looked like a good economic deal.


Commercial Source
Decision
6940000
Repair
FALSE
$8,100,000
0
8100000
Explore
TRUE
$460,000
Chance
6940000
Repair
80.0%
$8,100,000
0.8
8560000
Risk Reduced
20.0%
0
0.2
460000
Local Borrow Area
Decision
5260000
Repair
FALSE
$6,000,000
0
6000000
Explore
TRUE
$460,000
Chance
5260000
Repair
80.0%
$6,000,000
0.8
6460000
Risk Reduced
20.0%
0
0.2
460000

Locations



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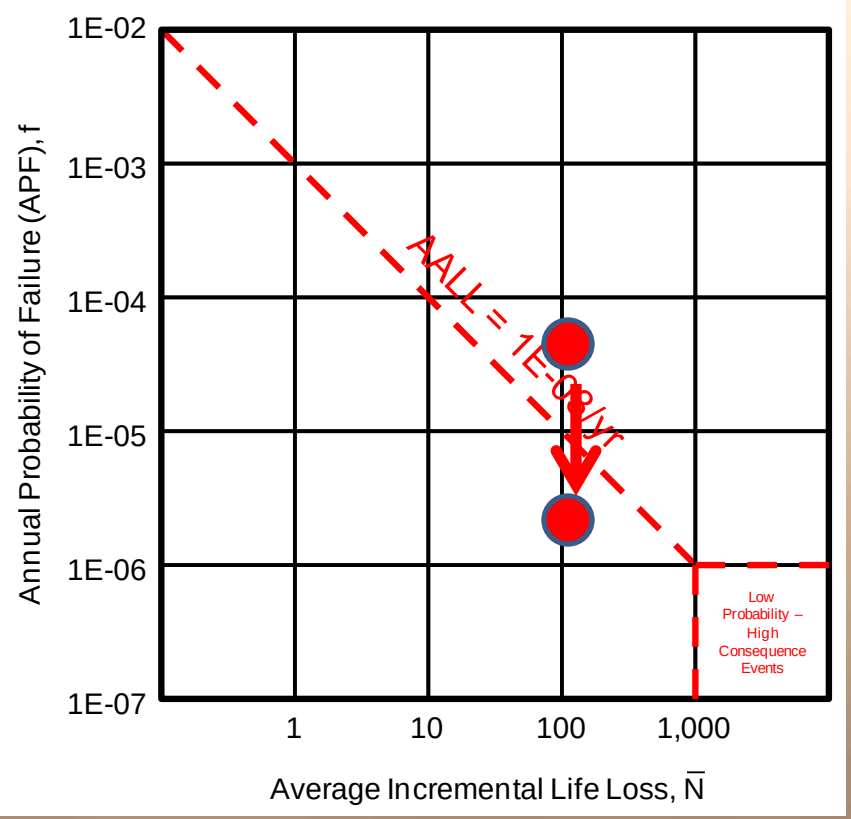
Incremental Life Safety Risk Matrix

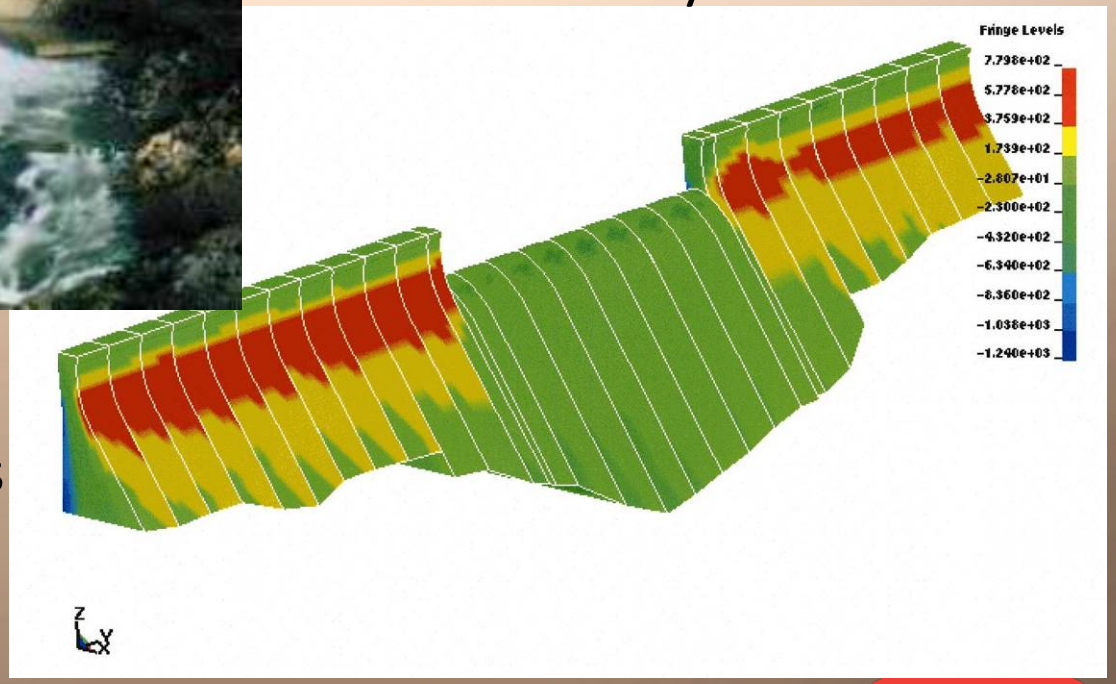


Take Away

- Dam Safety Case – structured arguments developed to have the facility's condition, risk estimates, and recommended actions make sense
- Show the evidence as to why it is reasonable to believe the Risk and APF numbers. Do not use the risk value as sole basis.
- Fully develop the justification to take action
- Address the sensitivity of the mean to key parameters, the likelihood a change justification class, and likelihood of success when recommending additional studies to reduce uncertainty

Example to Illustrate Process

MCE Analysis



Red – tensile stresses exceed strength

Build the Case

- Claim:
  - The lift joints near the spillway crest are well bonded and have significant strength. This leads to a low likelihood (0.1 or less) of cracking through the section at 1/10,000 AEP or smaller ground motions.
- Evidence:
  - All lift joints near the spillway elevation were recovered intact in core drilling
  - There were a large number of tests indicating high tensile strength across joints (report numbers)
  - Construction control procedures were excellent (describe)
  - Stresses are less than estimated strength (enumerate)