# Best Practices in Dam and Levee Safety Risk Analysis

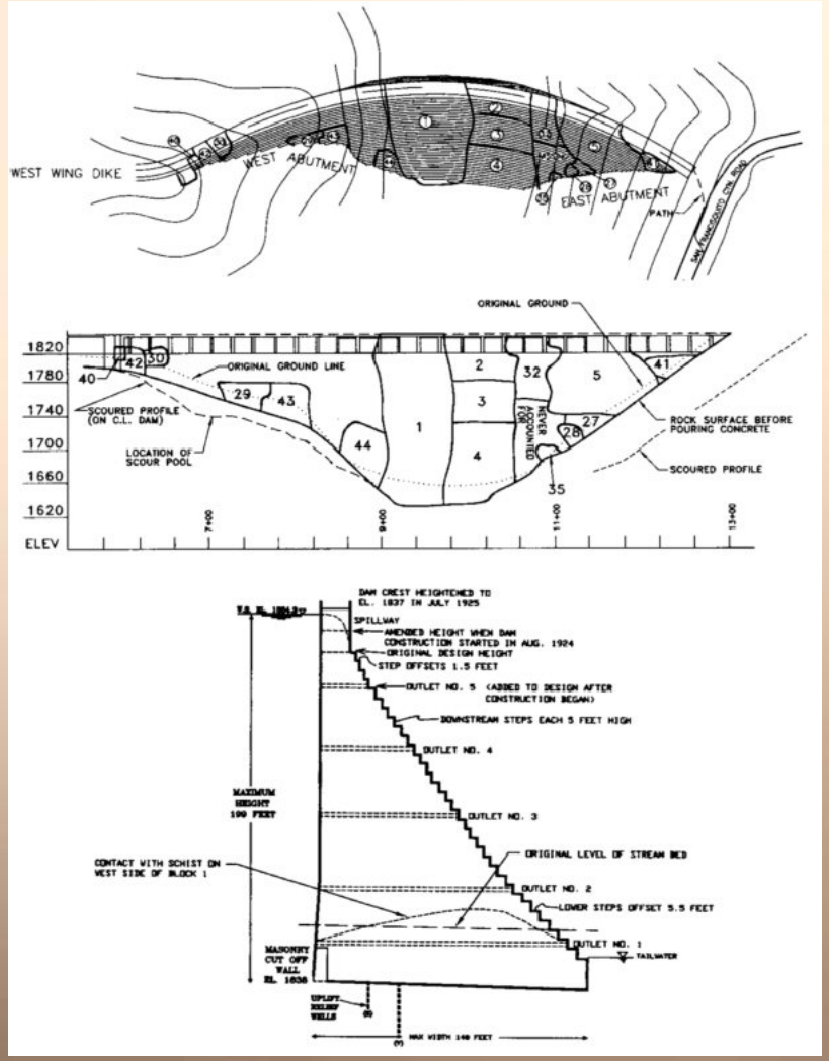
## V-3. Concrete Arch Dams

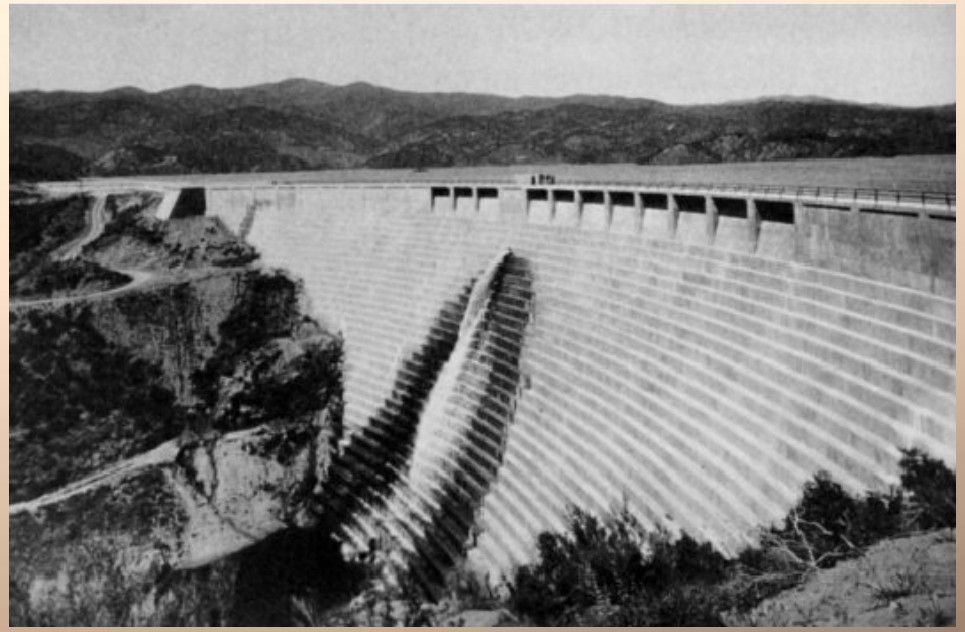
12 June 2015

RECLAMATION
*Managing Water in the West*

US Army Corps of Engineers
BUILDING STRONG®

# St. Francis Dam, CA



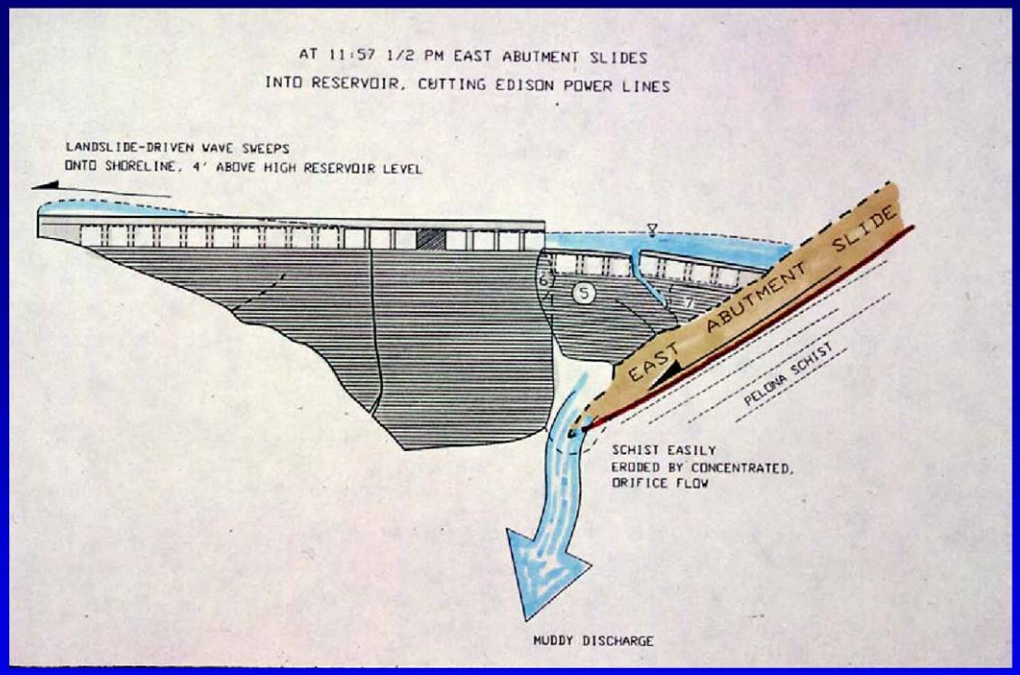



- 205’ high curved gravity dam

# St. Francis Dam

- Collapsed suddenly March 1928 with reservoir 3 in from spillway
- 470 lives lost

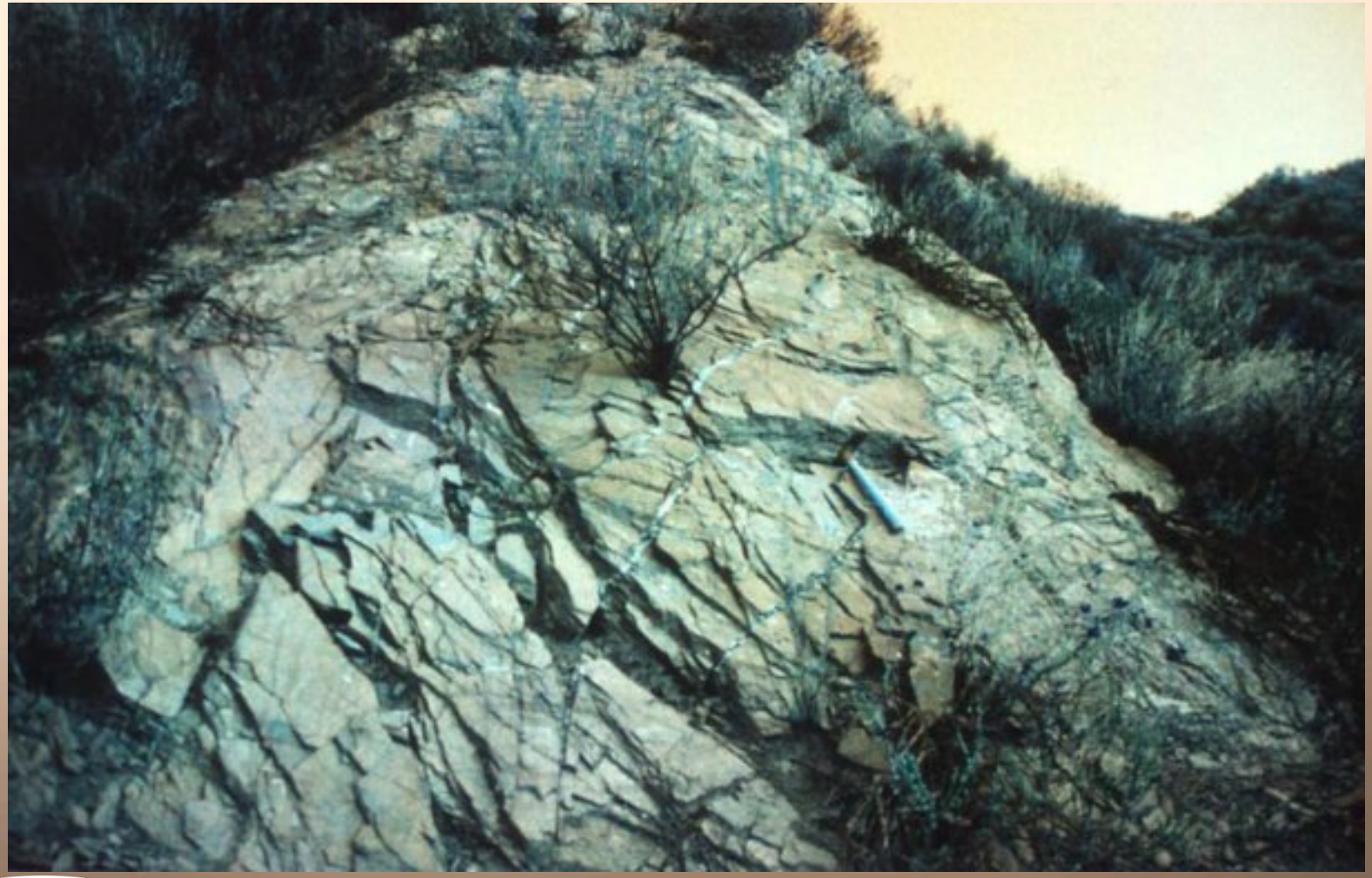
# St. Francis Dam




- Around 11:57-1/2 PM a massive landslide of the dam's eastern abutment initiated, severing the SoCal Edison Lancaster power lines.
- The entirety of the dam's left abutment was carried across the downstream face of the main dam.
- A landslide-driven displacement wave washed flotsam 4 ft above the reservoir high water line 3/4 mile to the north

Courtesy Prof. David Rogers

# St. Francis Dam



Foliation planes at St. Francis Dam

# St. Francis Dam

470 Lives Lost

# Malpasset Dam, France

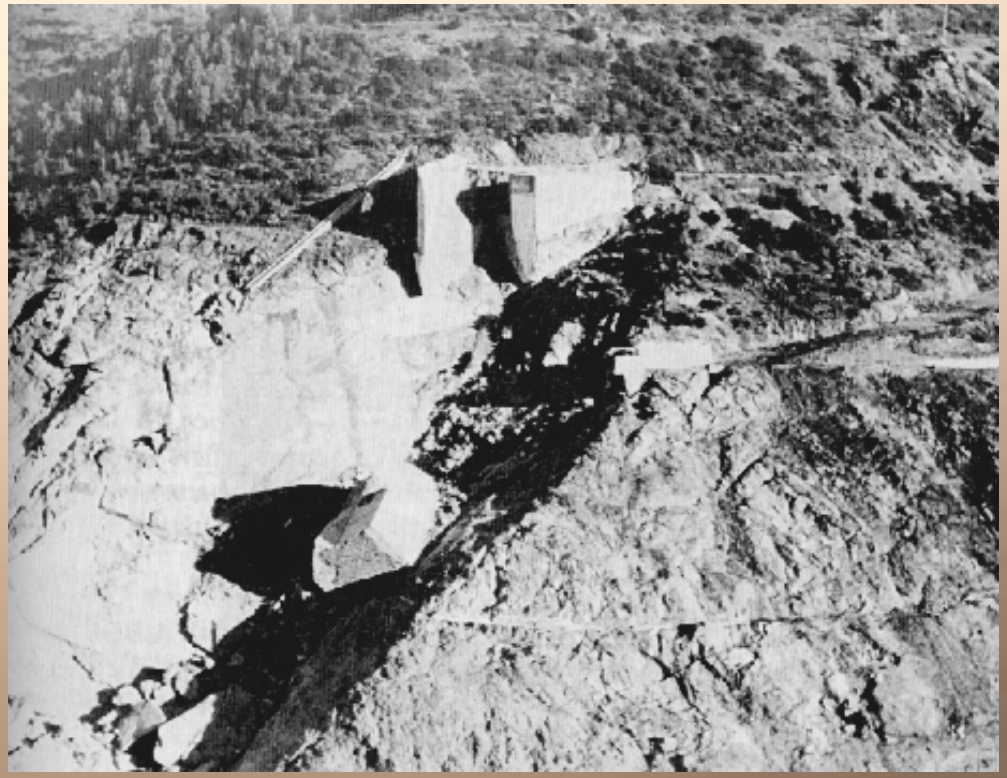
**Arch dam 216.9 ft high and ONLY 22 ft thick at base**

# Malpasset Dam

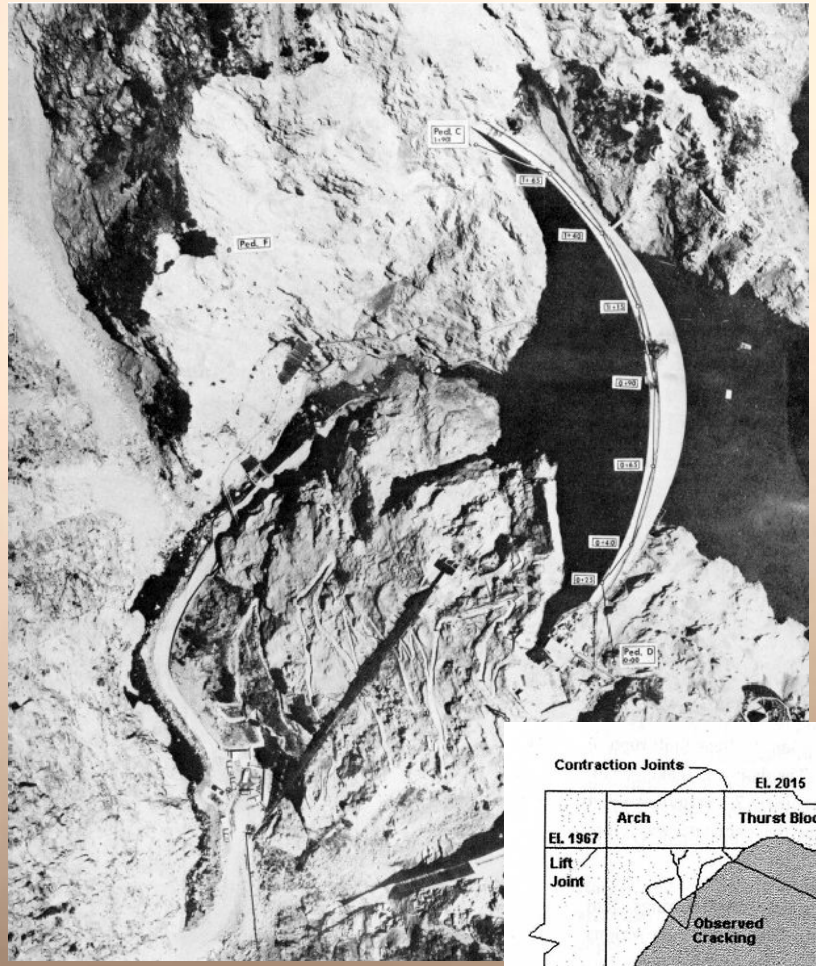
Collapsed suddenly in 1959
421 deaths and total destruction for 6.8 miles to the Mediterranean Sea

# Malpasset Dam

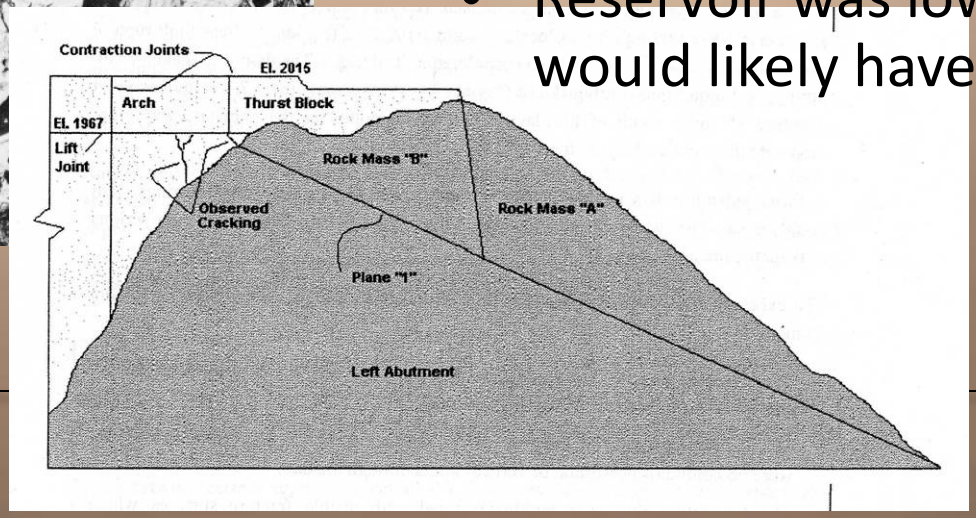
- U/S dipping fault and D/S dipping foliation shear formed lt abut block
- Arch thrust in direction of foliation decreased permeability
- Tensile stress at u/s face opened foliation shear
- Nearly full uplift developed on foliation
- Block slid out on fault (phi = 30$^{o}$) and dam went with it



# Pacoima Dam, CA



- 370’ high flood control arch dam
- 1971 M6.6 San Fernando and 1994 M6.8 Northridge eq’s
- Opening of joint between dam and left thrust block, cracking of thrust block, left abut rock movements
- Reservoir was low, or dam would likely have failed

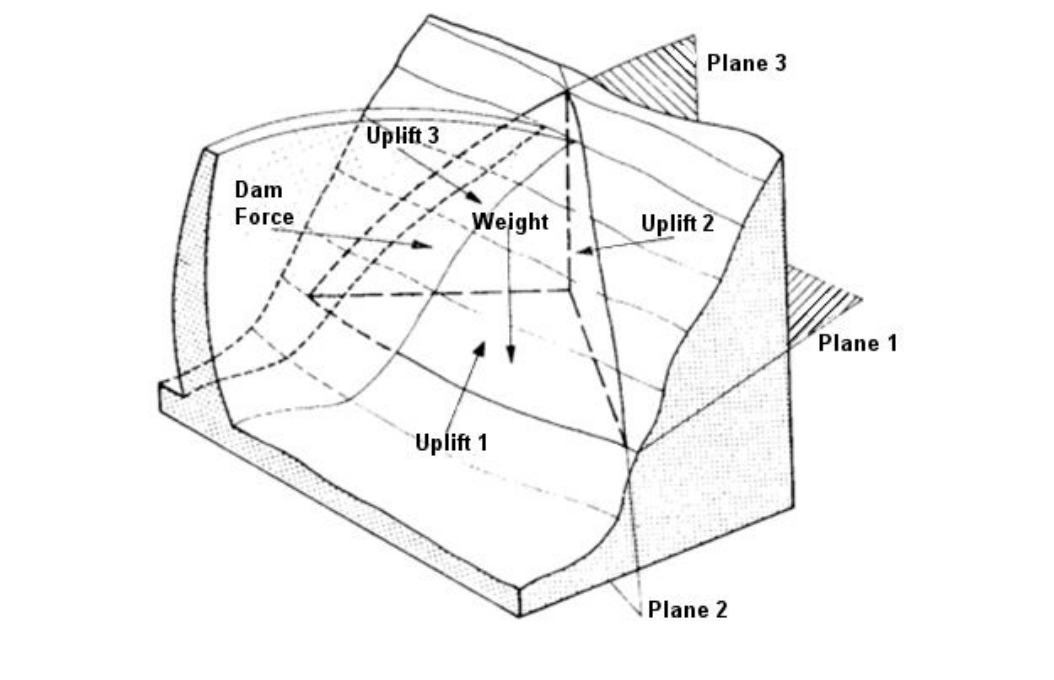


# Key Concepts

- Arch dams are forgiving structures – if one area is overstressed, load can be redistributed and transferred by arch action to the abutments
- Sliding on weak foundation discontinuities primary cause of arch dam failures
- Foundation drainage can add to stability (if functioning)
- No known failures of arch dams due to structural distress or seismic loading
- Tensile strength of concrete is important
- Estimating risks is difficult, relies primarily on traditional analyses and judgmental probabilities

# Normal Operations

- What could change? Increased uplift on foundation planes?
- 3-D rigid block stability equations can be programmed in spreadsheet for reliability analysis




If block is unstable and moves, it takes dam with it. Enough displacement can rupture dam.

# Normal Operations

- If analyses indicate good behavior expected, no indications of problems or clear potential failure modes identified, may want to consider failure likelihood negligible
- If there is a well defined sequence that could lead to a potential failure mode, develop an event tree and estimate branches

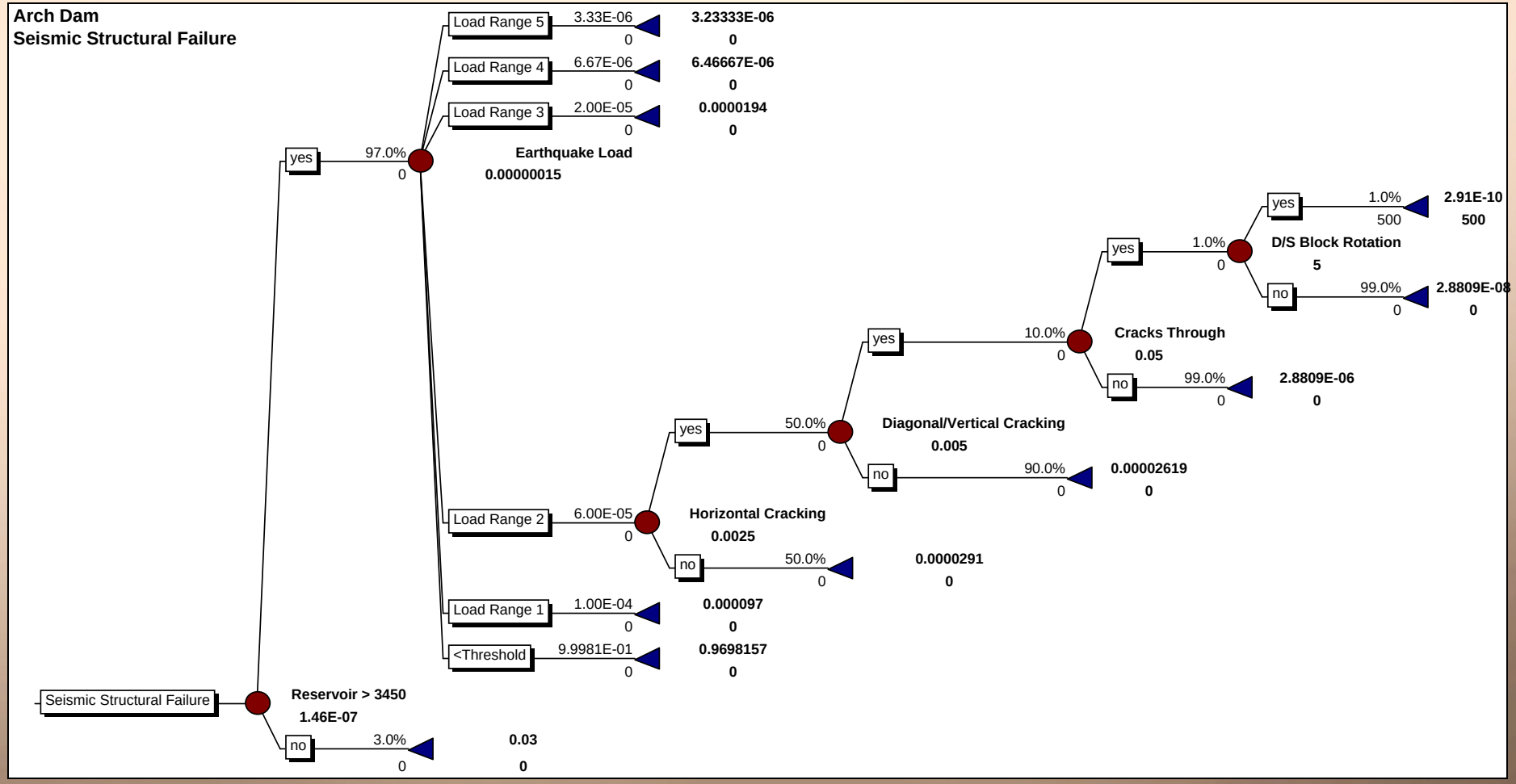
# Flood Loading

- Stability of abutment blocks could be compromised – increased loading from arch plus increased uplift forces – consider event tree
- Abutment erosion due to overtopping is a potential vulnerability
- If arch structure handles static load, unlikely additional hydrostatic pressure from flood loading will increase structural risks when flood load probability is considered

# Seismic Structural Failure

- No known arch dam failures during earthquakes
- Shake table model studies show structural failure mode
- Horizontal cracking near center
- Diagonal cracking parallel to abutments
- Rotation of isolated blocks

# Seismic Structural Failure

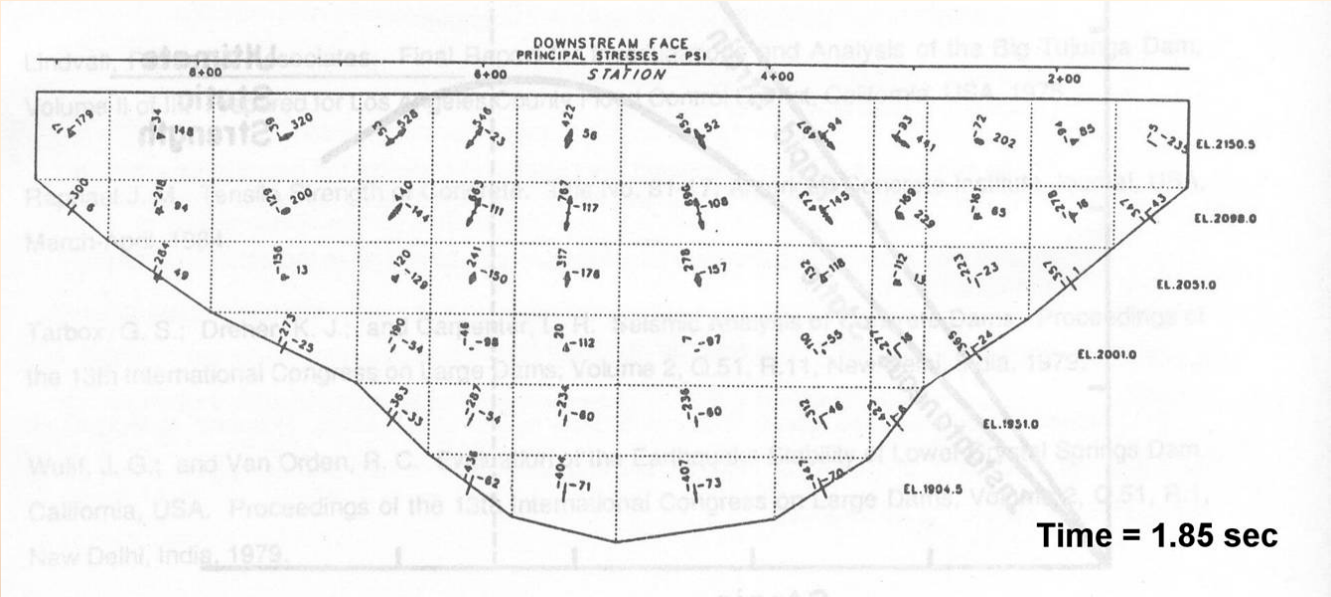



Note: only one reservoir range critical, temperature ranges not shown – Refer to pg. V-3-14

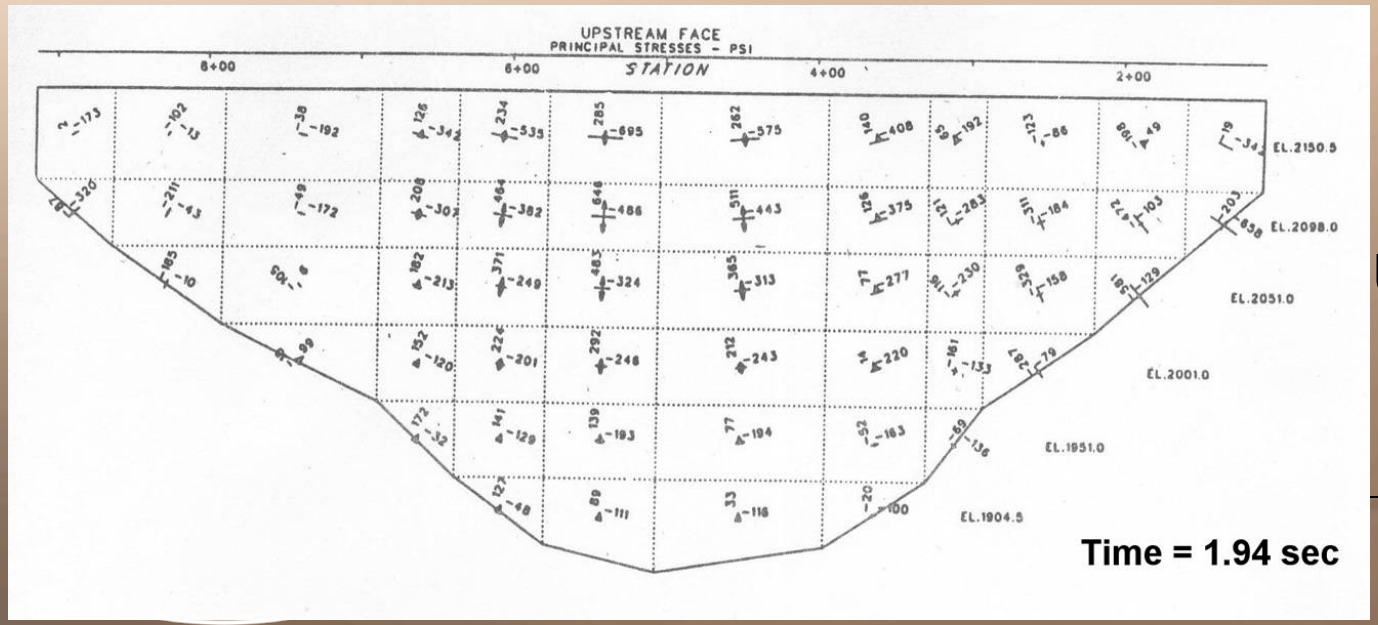
# Seismic Structural Failure

- 3-D time-history finite element analyses needed (consider variations in reservoir, temperature, and seismic load)
- Examine principal tensile stresses (vertical and diagonal) in relation to tensile strength
- (note that if rapid loading strength is used, one excursion can crack concrete, but is it over large enough area? – also can consider apparent strength if linear elastic properties used)

# Seismic Structural Failure

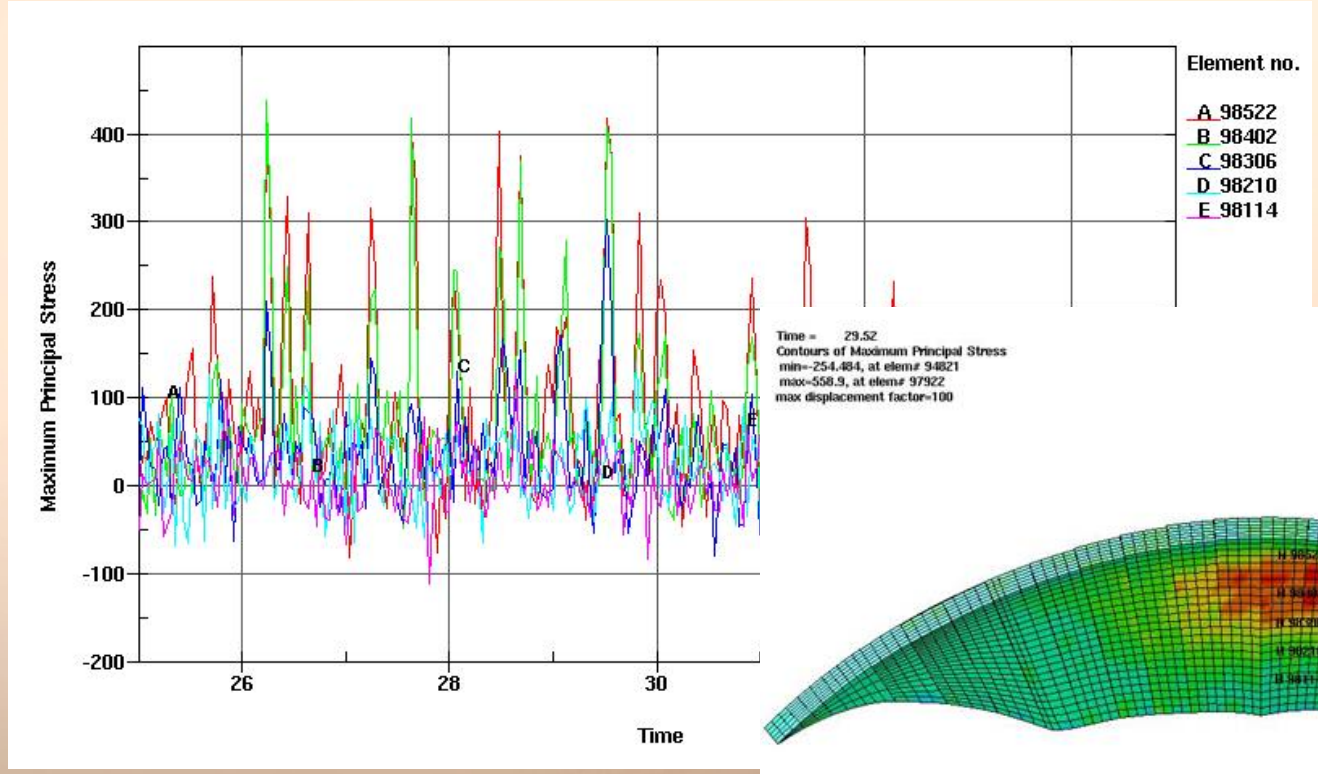


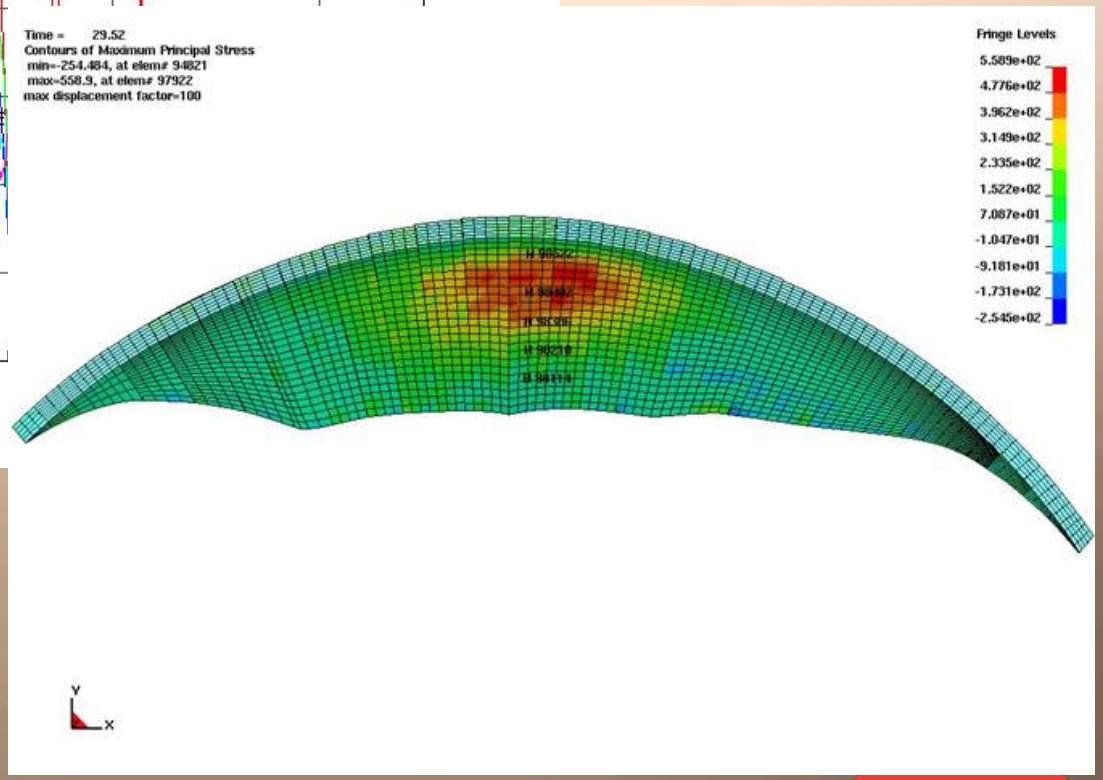

D/S face




U/S face

# Structural Failure




Principal stresses and associated histories from nonlinear analysis (contraction joints can open)

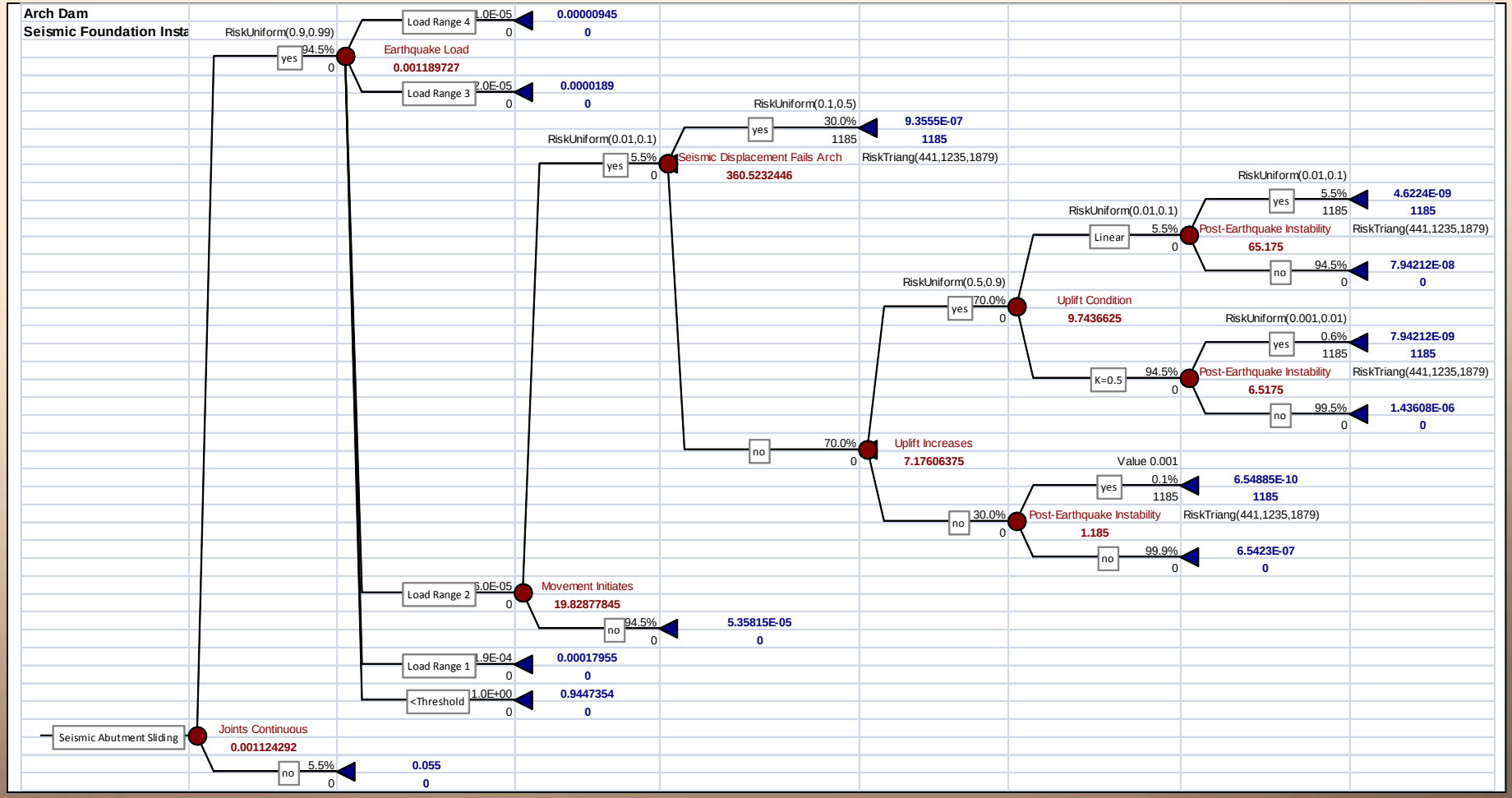
# Seismic Structural Failure

- If arch cracks all the way through:
  - How likely is it that the cracking pattern will be adverse enough to allow block displacement (i.e. semicircular cracking pattern smaller on u/s face than d/s face)?
  - How likely is it that the cracked condition would manifest early in the earthquake such that there would still be sufficient earthquake energy to displace and rotate the block?

# Seismic Foundation Failure

- Historically foundation failure is most significant failure mode
- Earthquake could provide “first loading” and trigger foundation block sliding

# Arch Seismic Foundation Failure




Note: Reservoir and temperature ranges not included, Refer to pg. V-3-17

# Seismic Foundation Risks

- Foundation block planes continuous
  - Field evidence weighed and judgments made
- Seismic Loads from hazard curves
- May also need reservoir load ranges and temperature load ranges

# Movement Initiates

- Uncoupled analysis
  - Time-history loads extracted from finite element analysis and applied to block in separate rigid block analysis (along with weight, water loads, and inertia loads)
- Coupled nonlinear analysis
- Perform sensitivity studies to help with estimates
- Factor in conditions not captured by analysis

# Movement Magnitude

- Estimate potential earthquake displacements
- “Newmark” type uncoupled analysis
- Nonlinear coupled finite element analysis
- If displacement during earthquake shaking is sufficient to fail dam, include likelihood in event tree
- Estimate movement and likelihood it will lead to increased water loads and potential post-earthquake instability

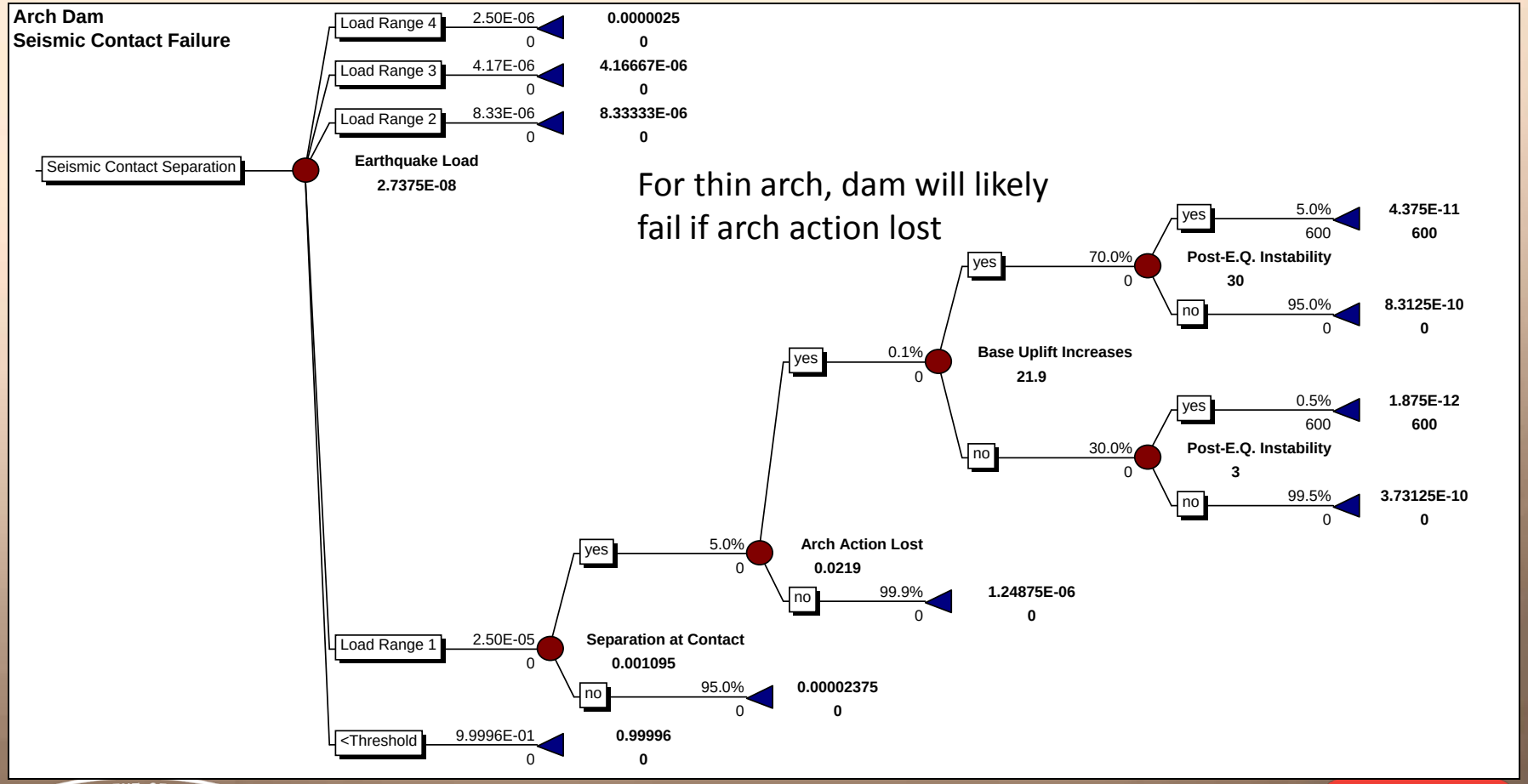
# Likelihood of Post-E.Q. Instability

- May have different uplift conditions to evaluate
  - Drains intact
  - Drains intact but reduced efficiency
  - Drains sheared or overwhelmed
  - Uplift increases due to pinching of downstream seepage exit points and opening of upstream discontinuities
- Perform reliability analysis of post e.q. conditions for simple blocks
- Subjective estimates for complex blocks

# Contact Failure/ Sliding

- Typically only a concern for non-radial abutments that “open up” in downstream direction
- Under strong shaking, the contact can be broken and monoliths can slide at their base
- If upper blocks move, arch action can be lost
- Loss of arch action will likely result in failure of a thin arch
- A thick arch may be stable two-dimensionally

# Thick Arch Seismic Contact Failure/Sliding




Refer to pg. V-3-18

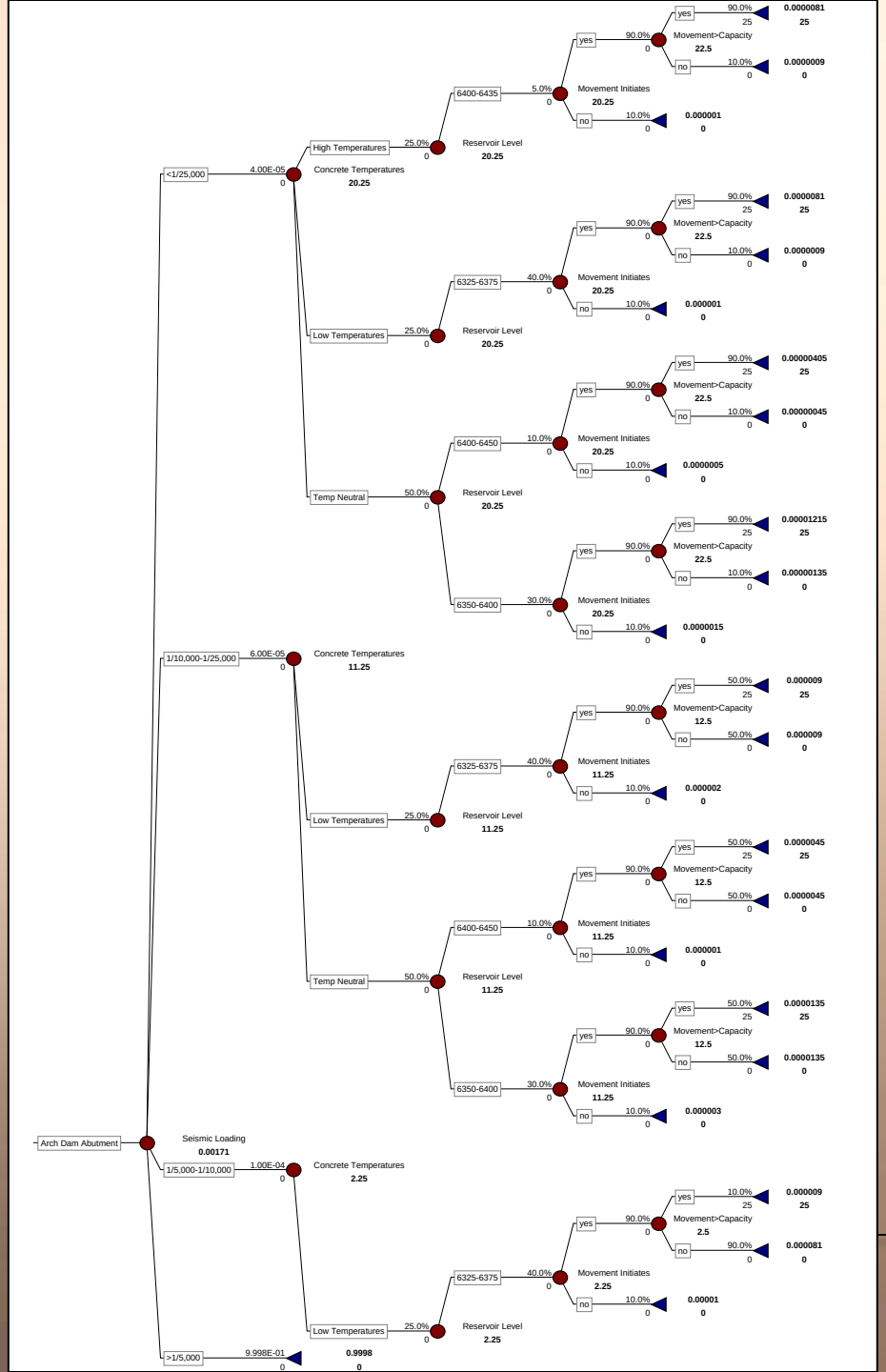
# Contact Failure/Sliding

- Nonlinear analysis can be used to look at contact separation and subsequent sliding
- Otherwise base judgment on calculated stress levels
- Enough displacement to lose arch action?
- Post e.q. stability could be important for thick dams

Nodes that separated for 50k earthquake at 5% damping

# Exercise

- Develop an event tree for the seismic abutment failure of a thin concrete arch dam where the block response is calculated to be sensitive to the reservoir level and concrete temperature. During the winter, when the reservoir typically fluctuates between elevations 6325 and 6375, displacements are predicted for the 5,000-year earthquake ground motions and greater with the reservoir at elevation 6375. In the summer, when the reservoir typically ranges from elevations 6400 to 6435, block displacements are not calculated until the seismic loading reaches about the 25,000-year level with the reservoir at elevation 6435. In the spring when the reservoir typically fills to elevation 6450, block displacements are calculated at about the 10,000-year earthquake level with the reservoir full. During the fall, when the reservoir is on the way down, typically between elevations 6350 and 6400, block displacements are again calculated at the 10,000-year earthquake level and the reservoir at elevation 6400.




# Possible Exercise Solution