Concrete Arch Dams

Best Practices in Dam and Levee Safety Risk Analysis

Part E – Concrete Structures

Chapter E-4

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US Army Corps of Engineers®
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Department of Energy Federal Energy Regulatory Commission
TVA

Outline

- Objectives
- Key Concepts
- Case History
- Normal and Flood Loading
- Seismic Loading
- Takeaway Points

Objectives

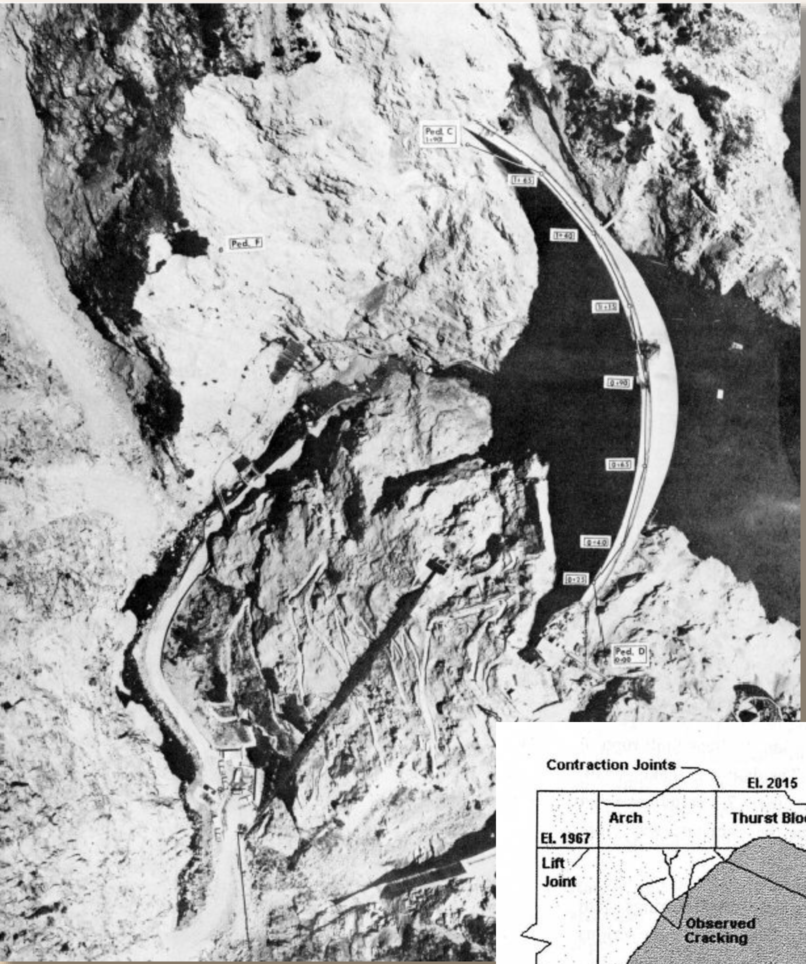
- Understand the mechanisms that affect arch dam failure.
- Understand how to construct an event tree to represent arch dam failure.
- Understand how to estimate event tree branch probabilities and probability of breach.

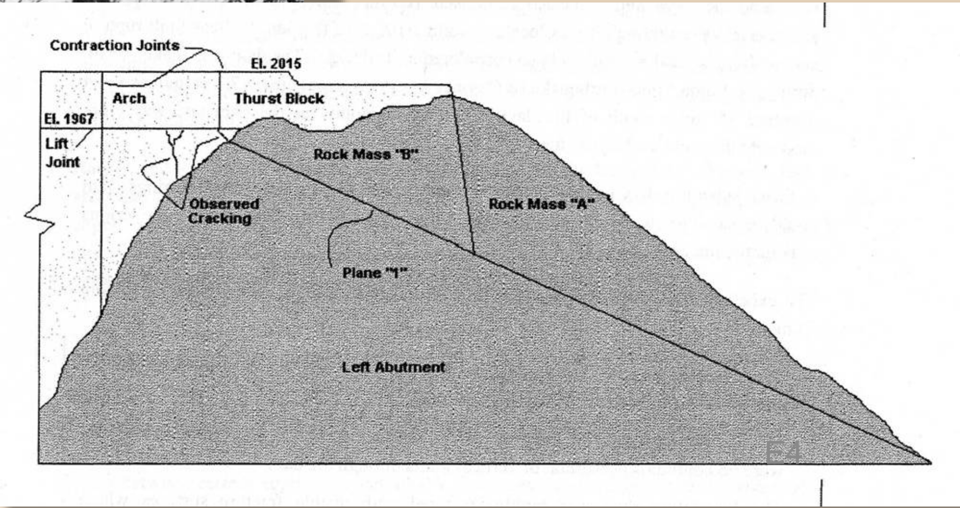
Key Concepts

- Load can be redistributed and transferred by arch action to the abutments if one area is overstressed.
- Abutments relied upon for load transfer and stability.
- Sliding on weak foundation discontinuities primary cause of historical arch dam failures (covered in *Chapter D-7, Foundation Risks for Concrete Dams*)
- No known failures of arch dams due to structural distress or seismic loading
- Seismic potential failure modes typically most important from structural risk perspective
- Concrete properties are important (covered in *Chapter E-1, Concrete Property Considerations*)
- Estimating risks is difficult, relies primarily on traditional 3-D finite element analyses and judgmental probabilities
- Cracking does not equal failure

Case History

Pacoima Dam, CA





- 370' high flood control arch dam
- 1971 M6.6 San Fernando and 1994 M6.8 Northridge earthquakes
- Opening of joint between dam and left thrust block, cracking of thrust block, left abutment rock movements (both earthquakes, even with remediation after 1971 event)
- More movement of left abutment in 1994
- Reservoir was low, or dam may have failed

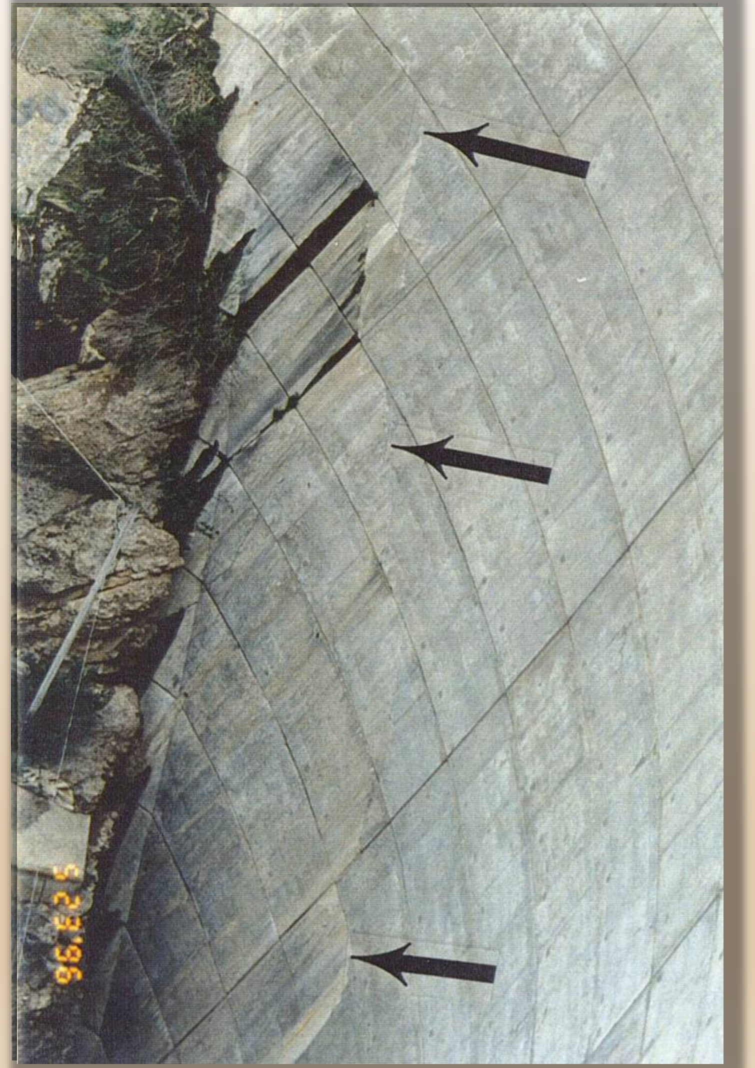
Normal and Flood Loading

Normal Operations

- If analyses predict favorable structural behavior, no indications of problems or clear potential failure modes identified, failure likelihood could be considered negligible.

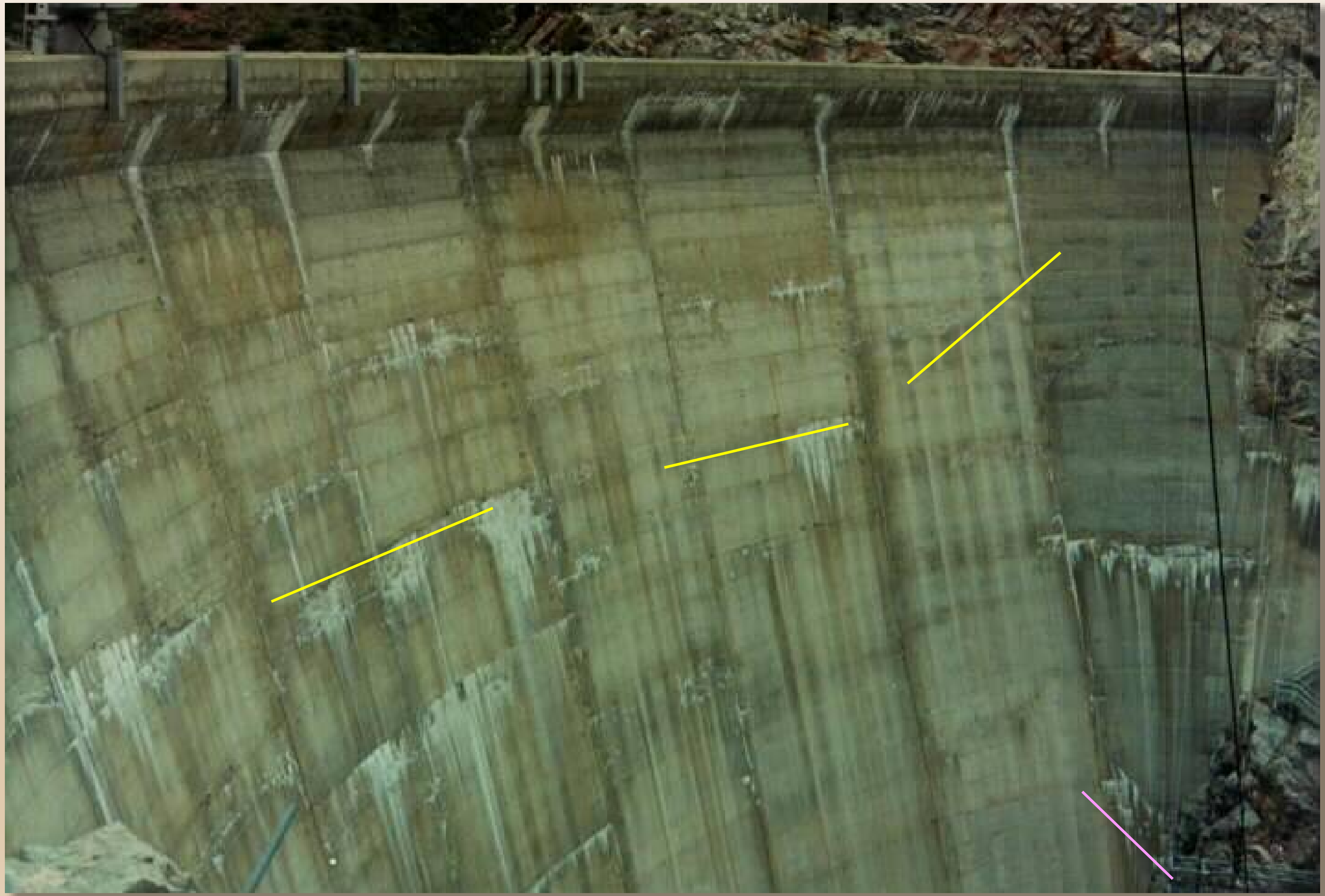
- If there is a well defined crack pattern or sequence that could lead to a potential failure mode, develop an event tree specific to that potential failure mode (covered in another chapter) and estimate branches based on analysis results.

Potentially Adverse Cracks



Cracks in **thin arch** dam from low reservoir and high temperature parallel to abutment. Upstream movement caused moment and tension on downstream face.

Cracking (ASR and Abutment Protrusion)



- Alkali Silica Reaction causes the concrete expand resulting in potentially adverse cracking patterns for an arch dam (yellow)
- Cracks at abutment protrusions are common but seldom problematic (pink)

Flood Loading

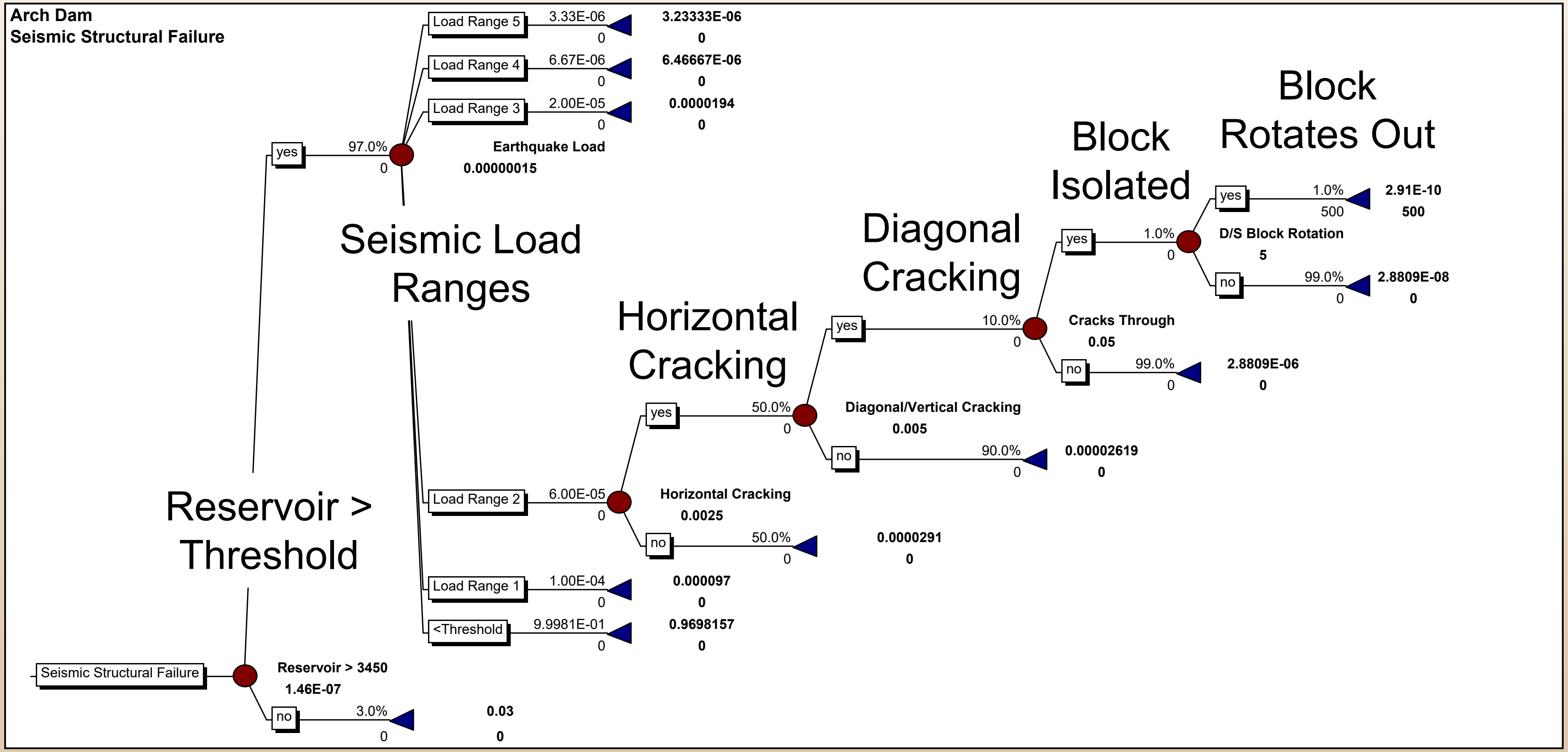
- Abutment erosion due to overtopping is a potential vulnerability (covered in another chapter).
- Adverse cracking could become critical under increased loading.
- Generally, if arch structure handles static load, additional hydrostatic pressure from flood loading is unlikely to increase structural risks when flood load probability is considered.

Seismic Loading

Seismic Structural Failure

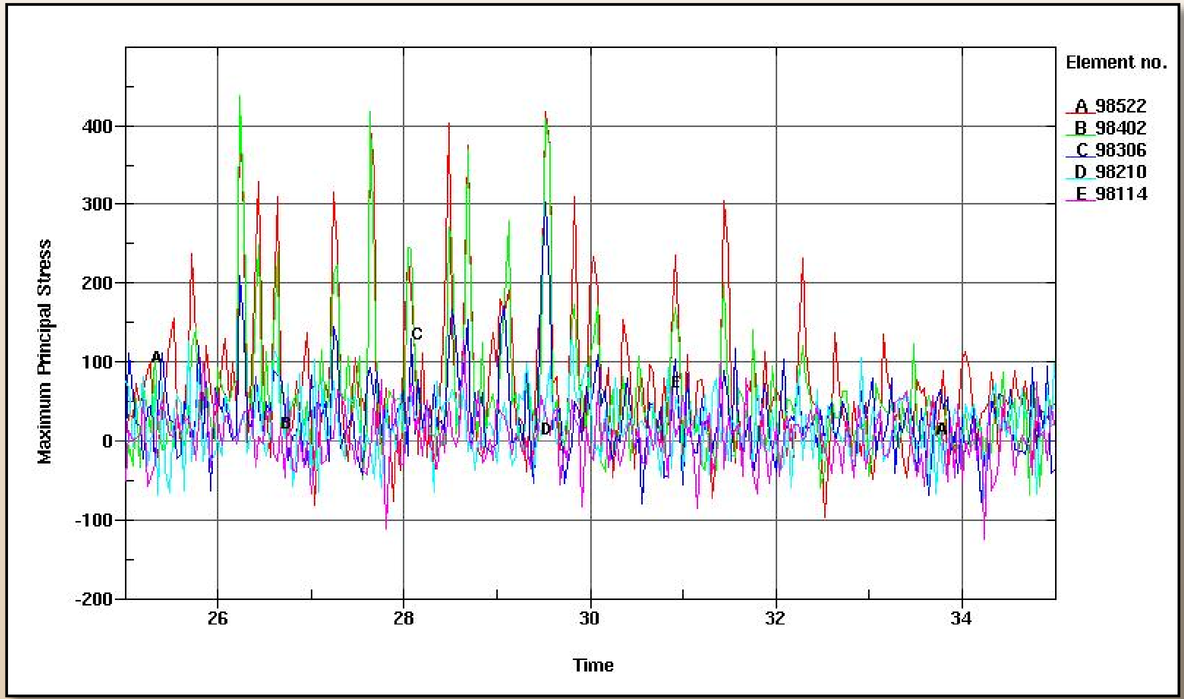
- No known arch dam failures during earthquakes
- Shake table model studies show structural failure mode
- **Horizontal cracking** near center
- **Diagonal cracking** parallel to abutments
- **Rotation** of isolated blocks

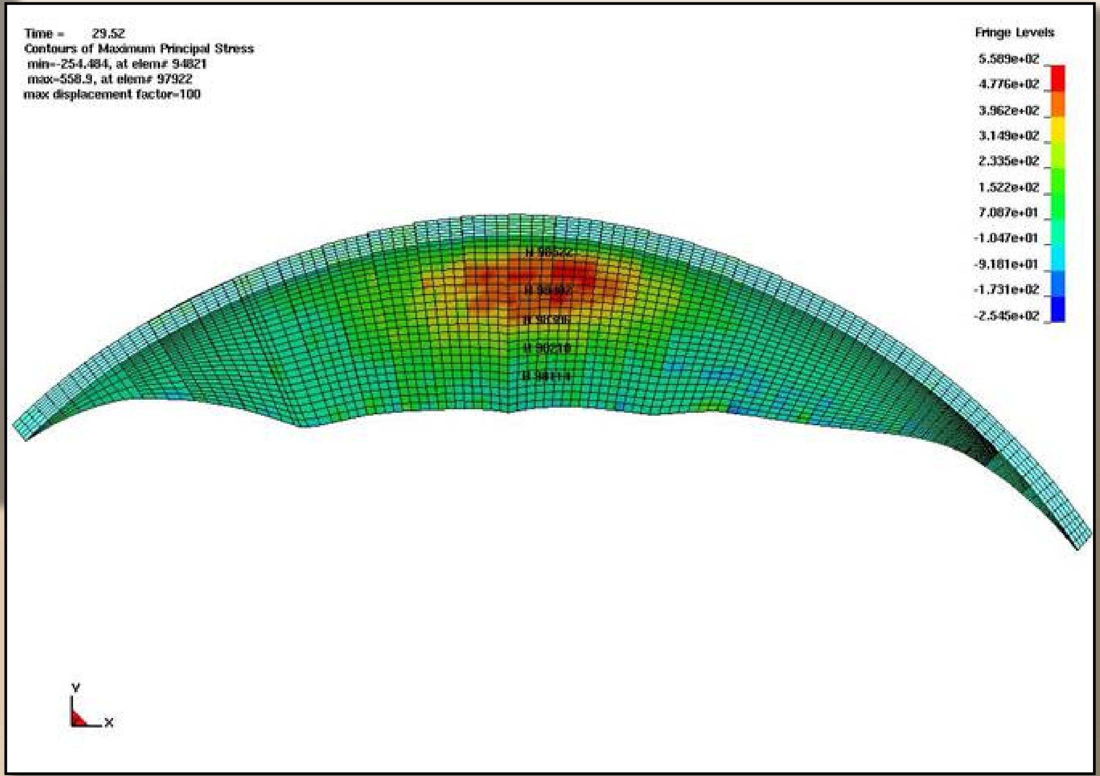
Seismic Structural Failure



Note: Only **one** reservoir range is critical in this example. Analyses may indicate diagonal cracking occurs first (adjust event tree), Temperature ranges not evaluated.

Seismic Structural Failure

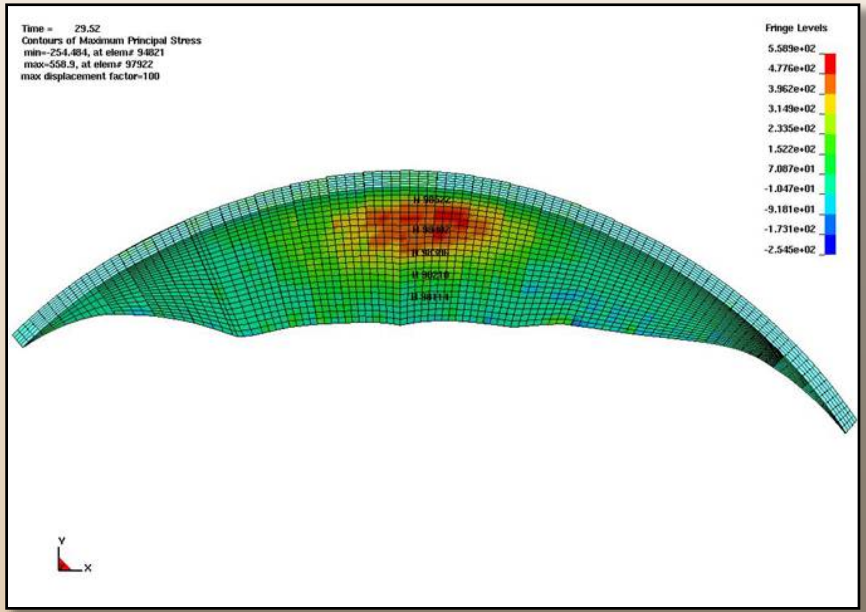




Principal stresses and associated histories from nonlinear analysis (*contraction joints can open*)

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?

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.

Takeaway Points

- Forgiving structures if abutments can carry the transferred load. If an arch dam has performed well, the chance of structural failure under normal conditions or small increases in reservoir load is small.

- Most risk-driver potential failure modes are related to seismic loading although no arch dams are known to have failed during an earthquake.

- Shake table model tests provide insight for the potential failure progression.

- 3-D dynamic finite element analyses are typically needed to evaluate dynamic behavior and probability of failure.

Questions or Comments?

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