Folsom Gravity Dam Analyses:
What are Acceptable Displacements?

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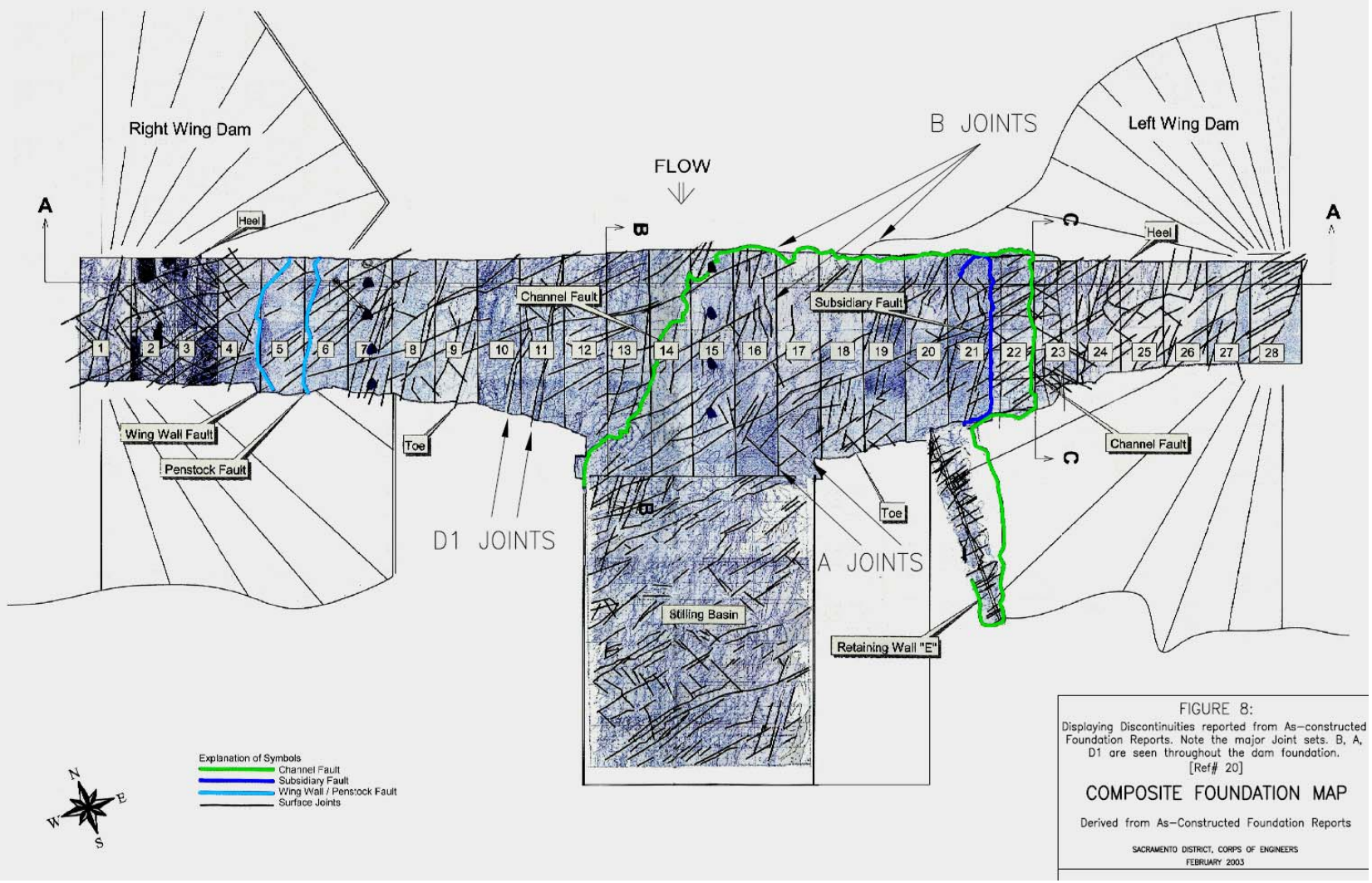
Issues Concerning Displacements

- Can we estimate displacements with a reasonable accuracy?
- How accuracy and reliability of displacement predictions can be improved?
- Are we ready to use displacement criterion for safety evaluation of concrete dams?

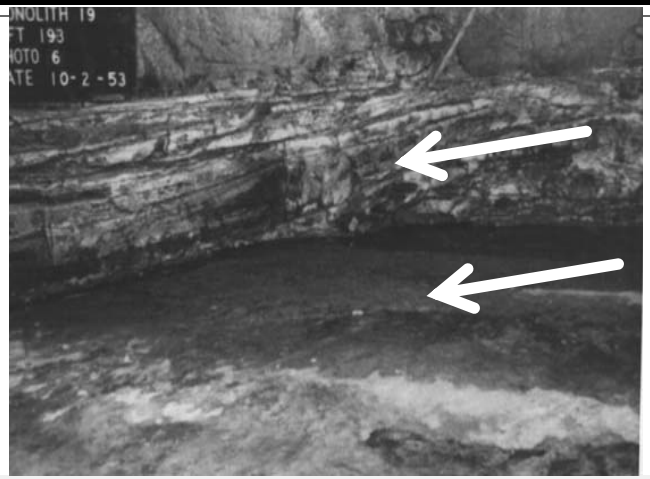
Folsom Dam, Folsom, CA

Construction 1952-56

Site and Construction Conditions

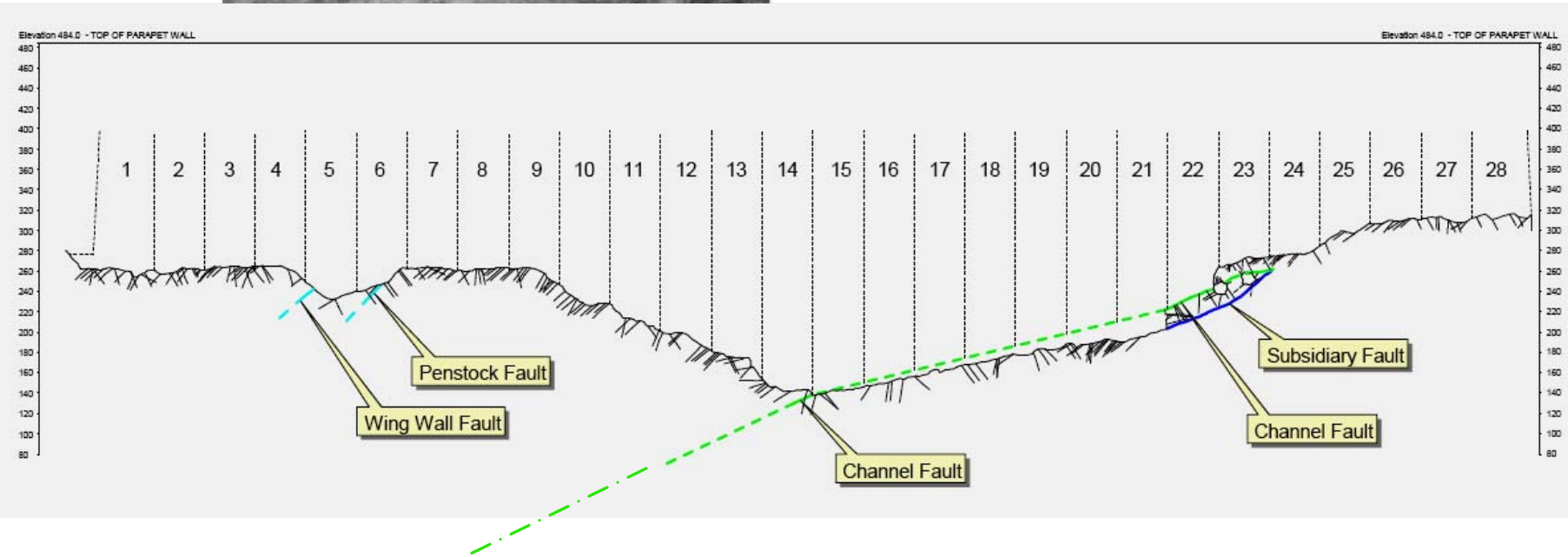


Geologic Section Across Dam Axis

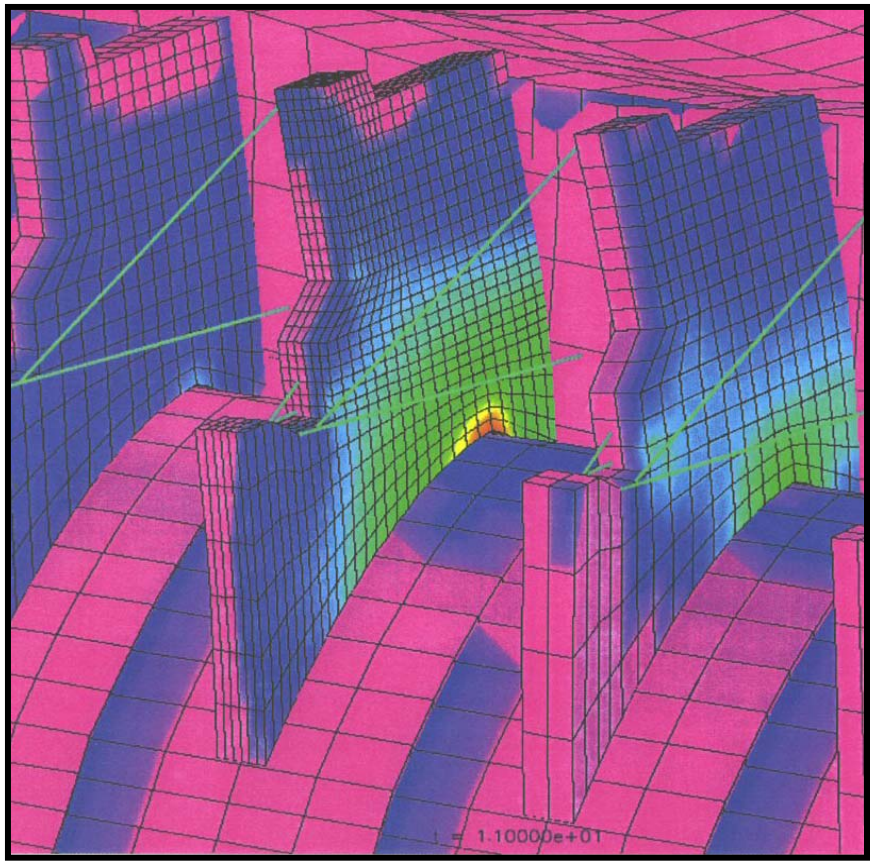


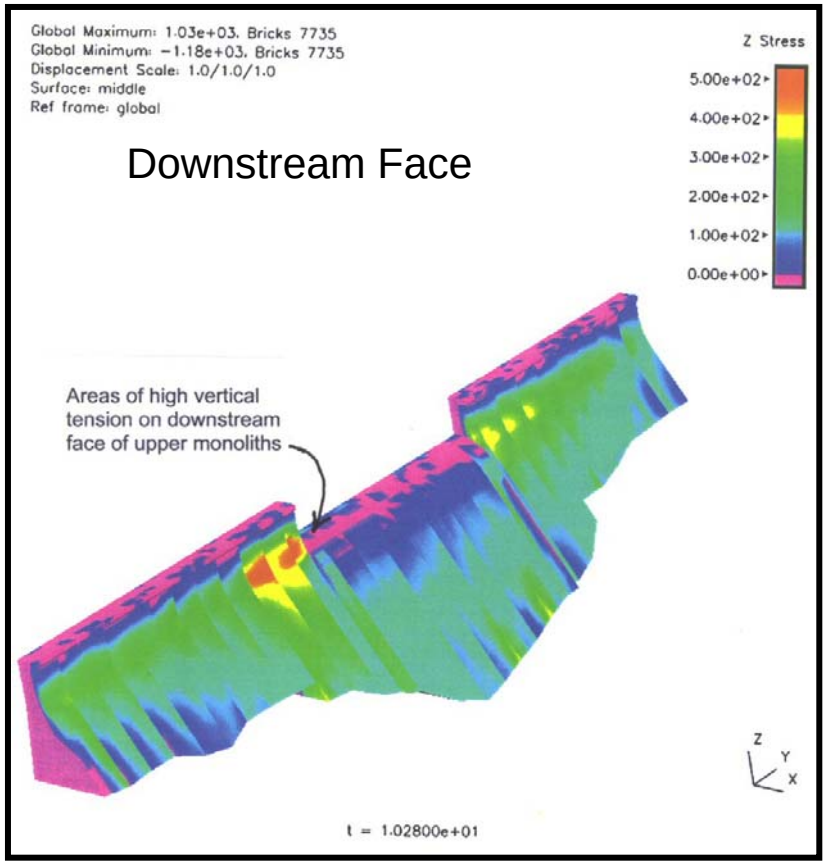
Channel Fault

Smooth Foot Wall



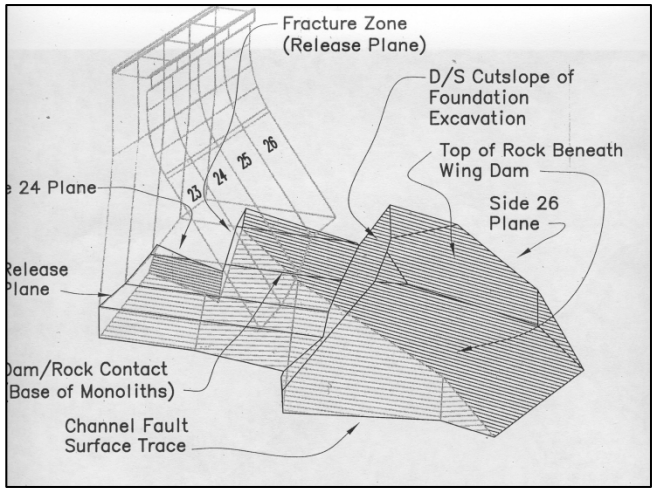
Initial Stress Analysis





Potential Modes of Failure
Uncontrolled release of water

- Sliding at foundation contact
- Sliding at foundation wedges
- Sliding on a lift line
- Failure of spillway gates
- Failure of spillway piers

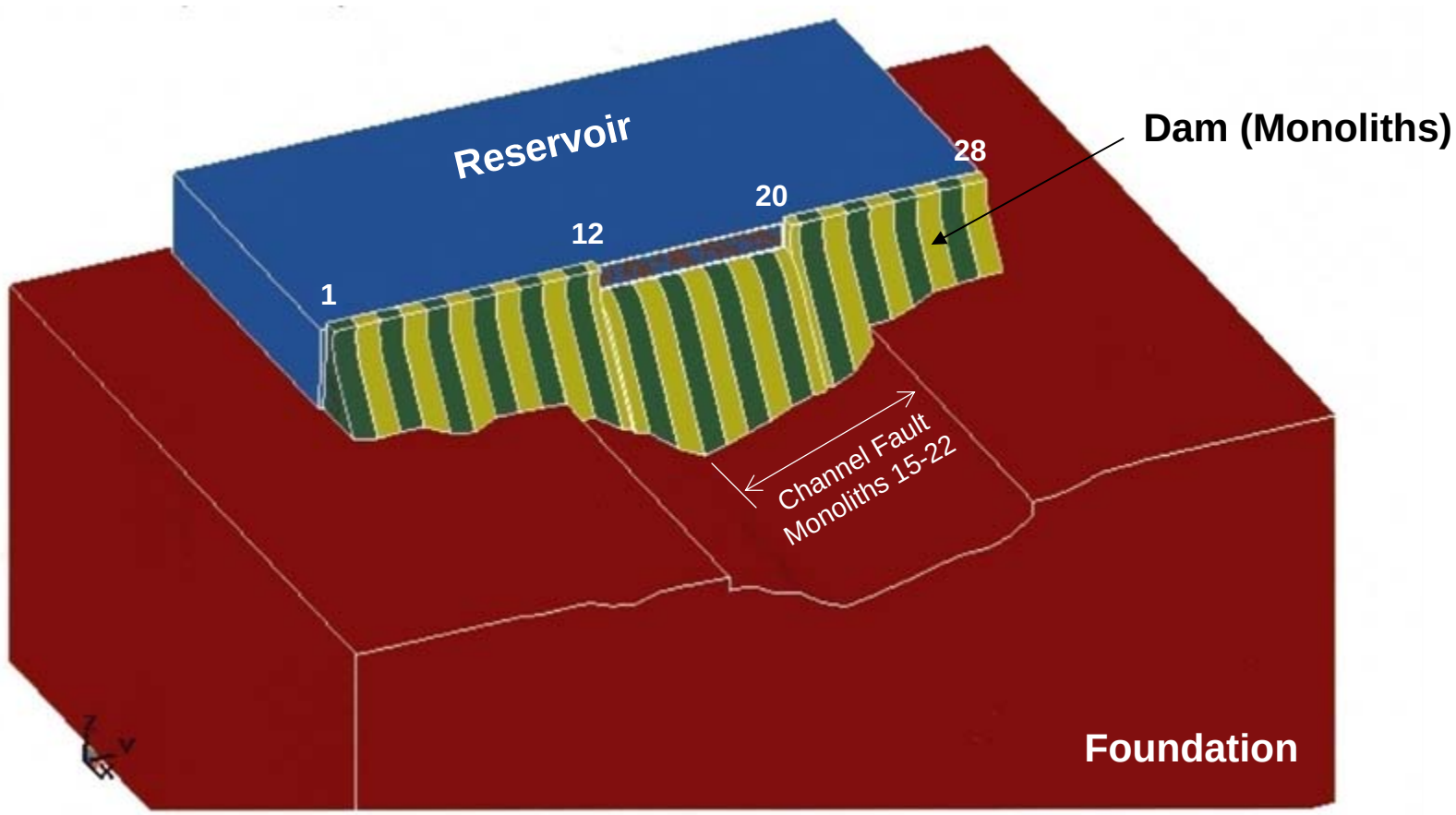


Modeling Issues
Critical parameters

- 3D nonlinear model
  - Full dam-water and dam-foundation interaction
  - Transmitting or non-reflecting B.C.'s
  - Capabilities for sliding and rotation
- Seismic input mechanism
- Damping
  - Configuration and stiffness dependency
- Shear strength properties of channel fault
- Uplift (post-earthquake condition)

Finite-element Model

Dam-water-foundation interaction

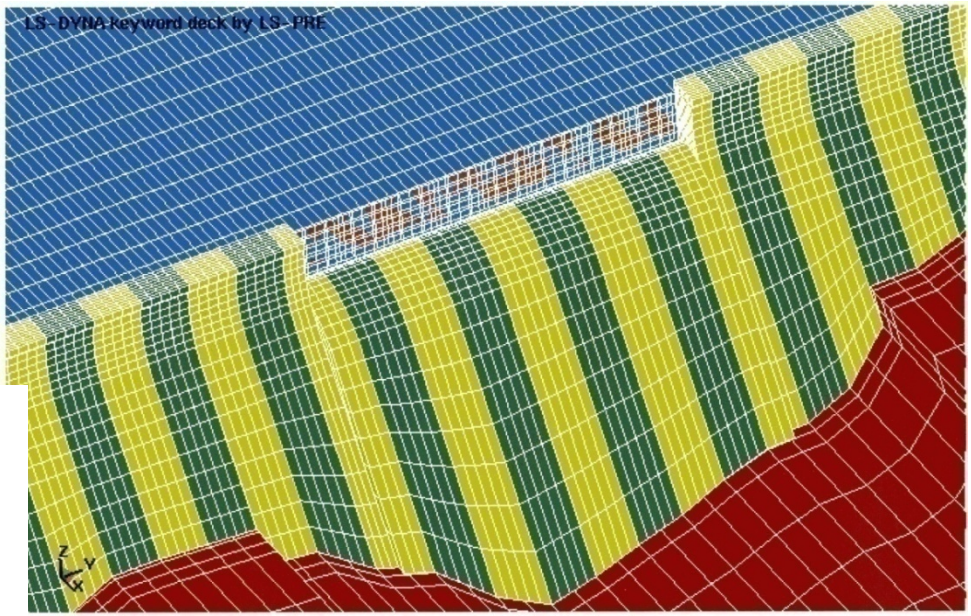


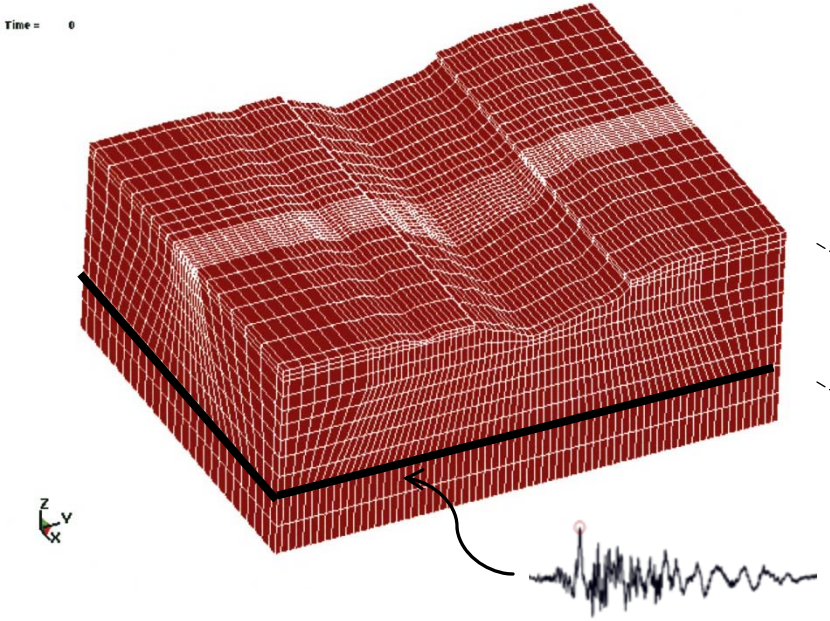
Earthquake Ground Motions

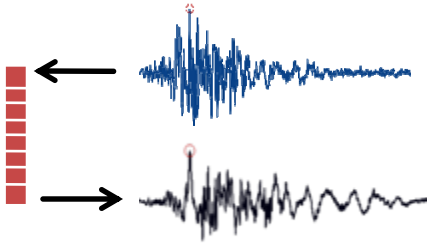
USACE	EQ. Records
OBE (500 –year UHS)	
MDE (10,000-year UHS)	1971 San Fernando (M6.6)
MCE (84th percentile deterministic)	1986 Chalfant (M6.2)

USBR	Exceedance Probability
San Fernando	1/5,500
Synthetic P5	1/36,000
1.5xMCE (Chalfant)	1/48,000
San Salvador	1/180,000
Extreme (un-factored P5)	1/410,000

FE Mesh
Application of Seismic Input

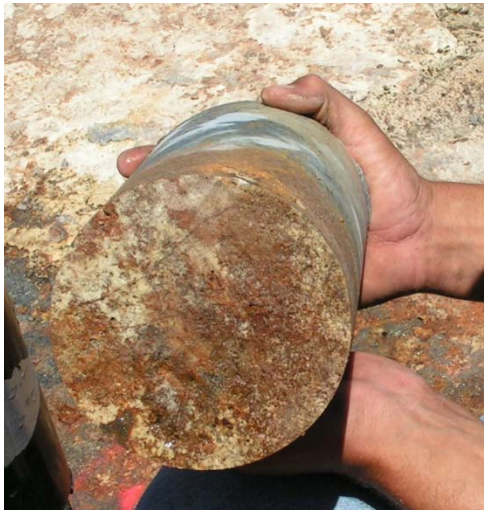






Shear Strength Parameters

- Direct shear tests on smooth outcrops of channel fault footwall to obtain the basic friction angle
- Direct shear testing of scale models to measure roughness or dilatancy angle (with and without side restraint)
- NQ borehole program to characterize concrete to rock bonding through testing, inspection of samples, and televiewer images of boreholes



***Non-bonded concrete-rock contact*;**

with *parallel open joint* in the rock below the contact

Preparation of the master mould for Mon 15 tests

Issues arising from shear strength measurements

- It may be simplistic to assume that the contribution of roughness to the shear strength of a non planar surface can be adequately represented by a single roughness angle.

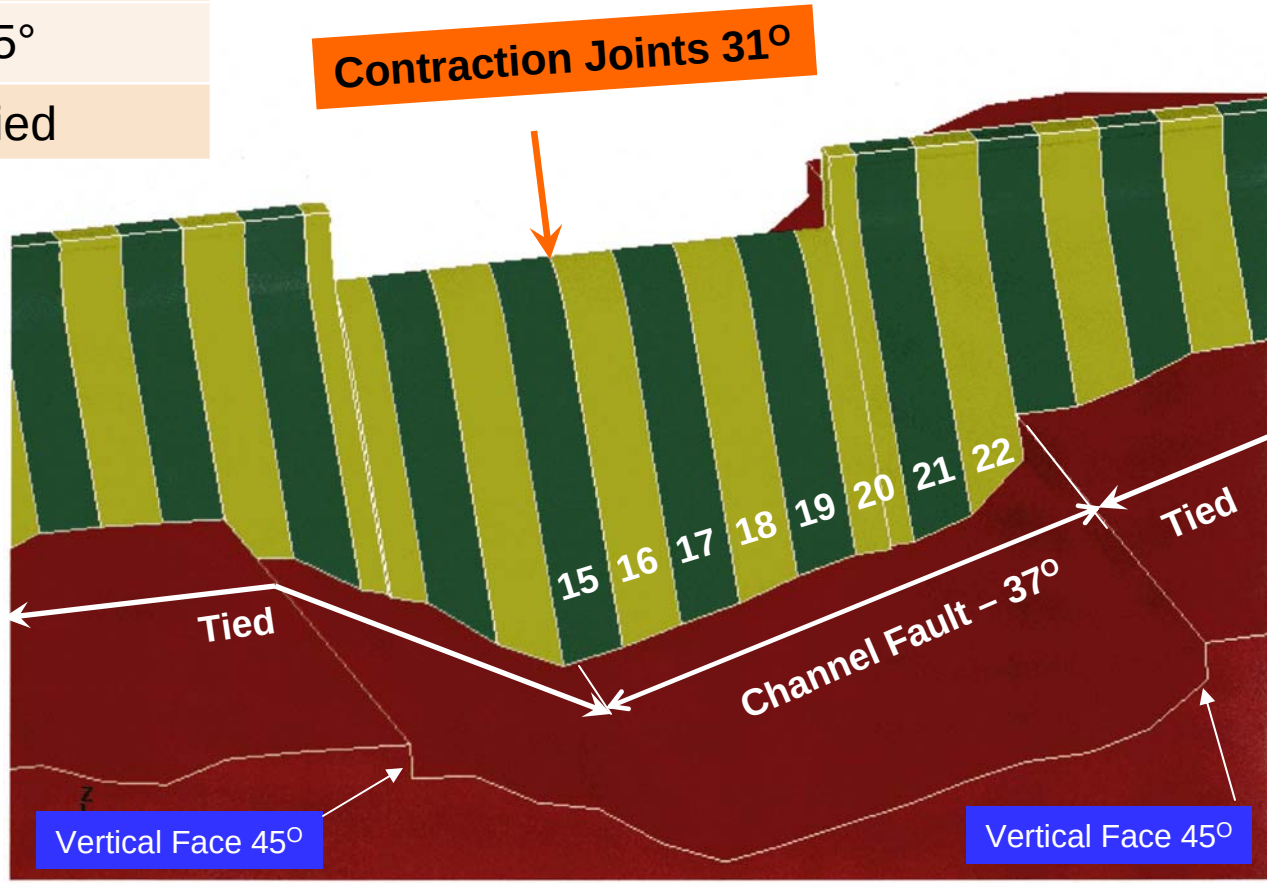
- Torsional behavior may play a role in what appears to be simply translational sliding on a rough surface. (We may not have much data on torsional friction at low shear displacements.)

- Constraints on motion associated with two-plane sliding (in the intersection mode) may increase the shear strength above that based on results of separate plane sliding tests for each face.

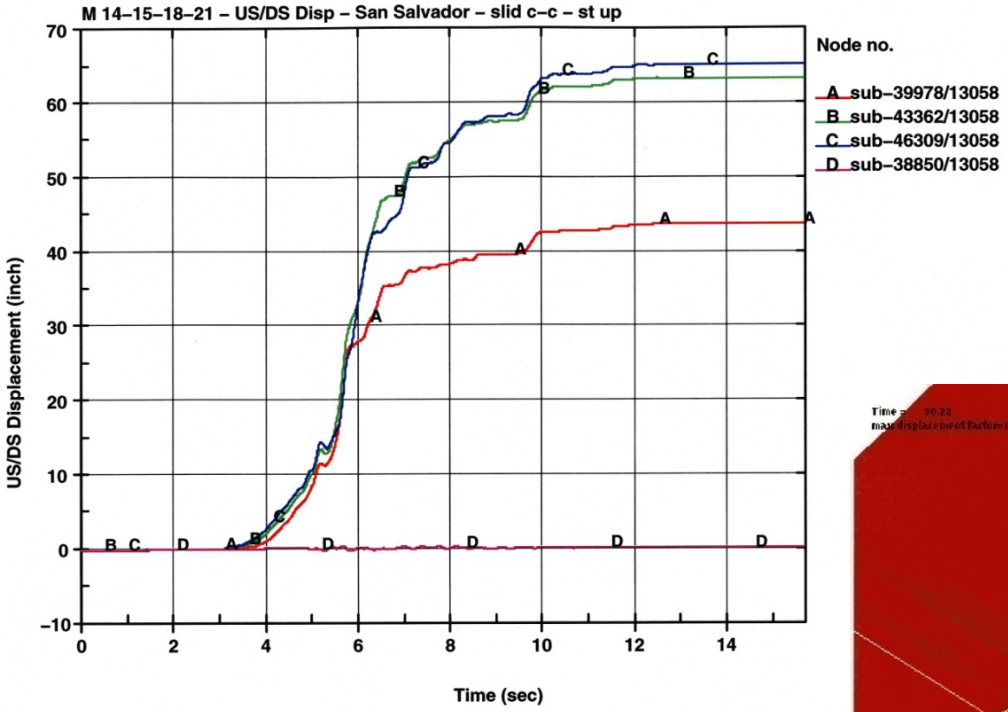
- **Subsequent research by Dom Galic (PhD – Berkeley 2008) confirmed much higher sliding friction values for constraint on both sides of the block, as when a single block is confined in its motion by both sides.**

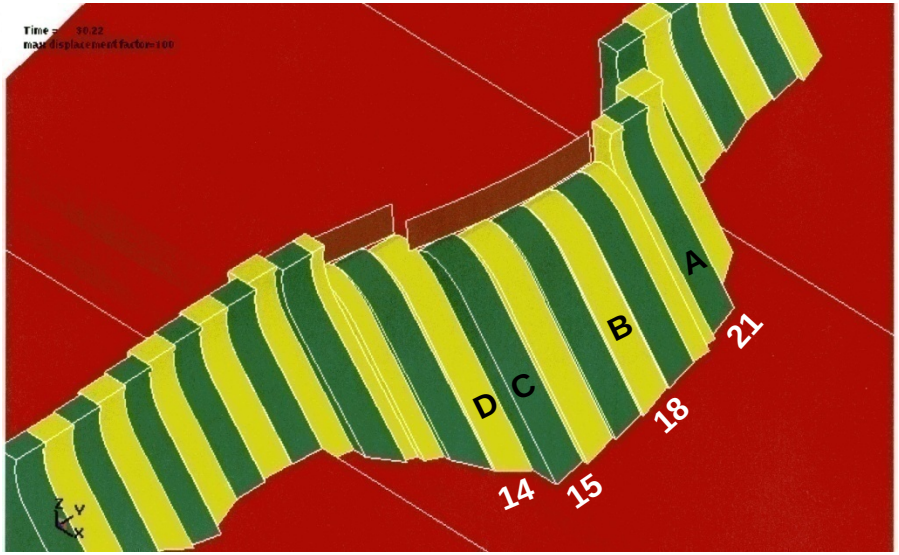
Friction Angles on Contact Surfaces

Contraction Joints	31°
Channel fault	37°
Vertical faces	45°
Outside Channel fault	Tied



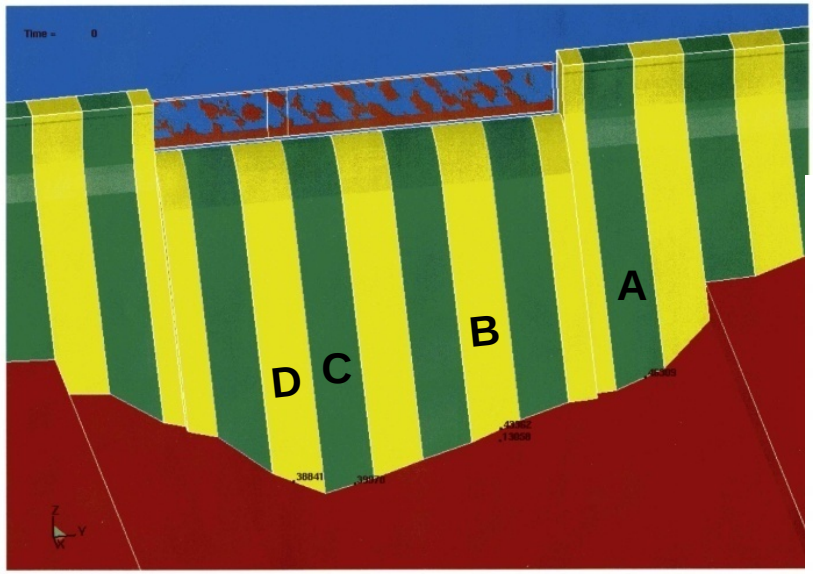
3D Dam Sliding Analysis
Downstream Sliding





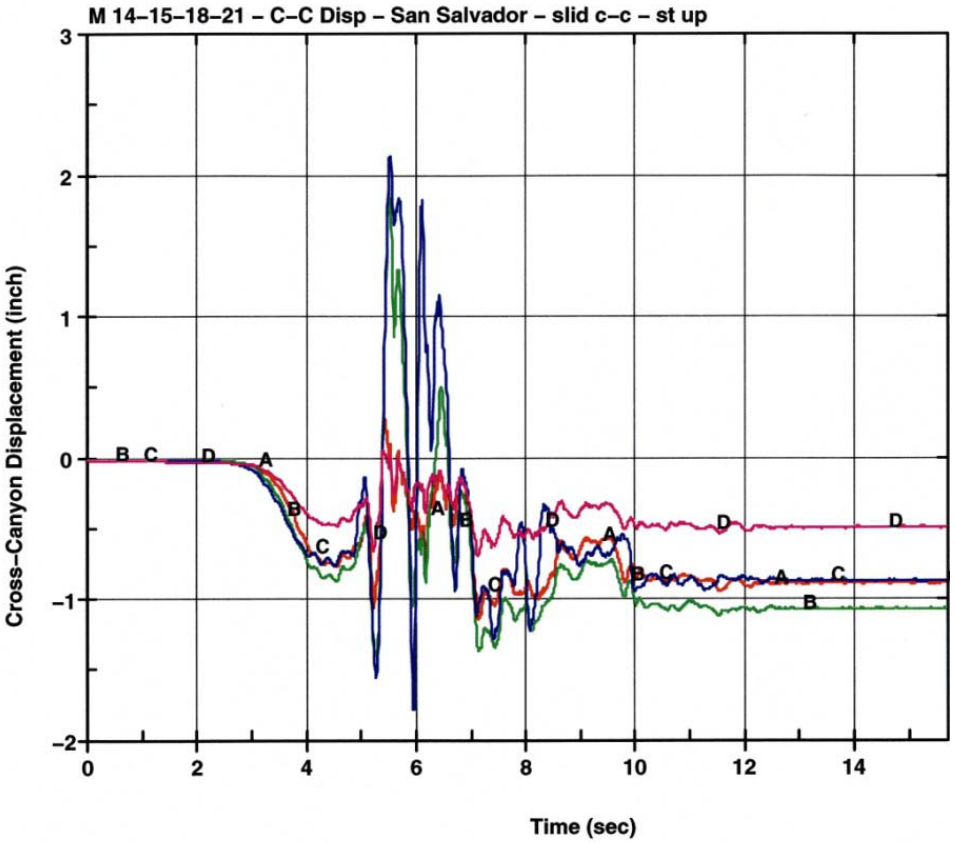
San Salvador Record (1/18000)
Water El. = 466 ft
Mass proportional damping =

3D Dam Sliding Analysis
Cross-canyon Sliding



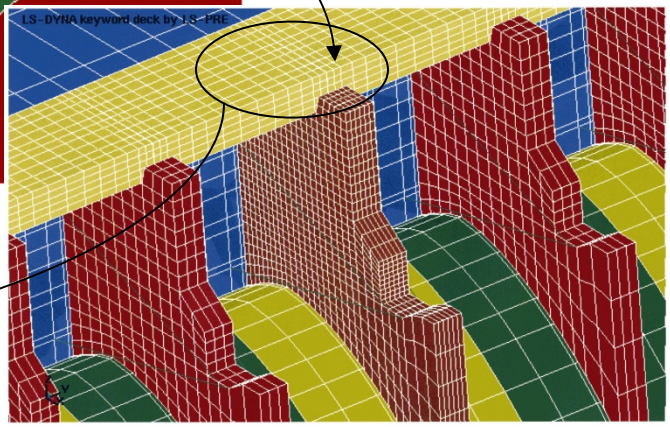
San Salvador Record (1/180000)
Water El. = 466 ft
Mass proportional damping =

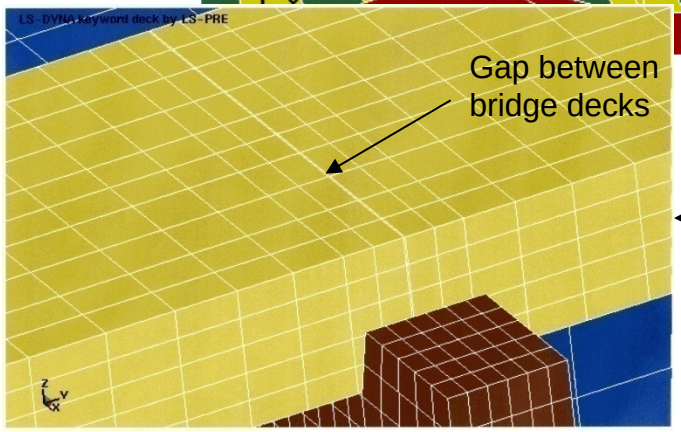
Cross Canyon Sliding



Pier Analysis

P5 Record (1/36,000)
Water El. = 466 ft
Mass proportional damping coeff = 1.40

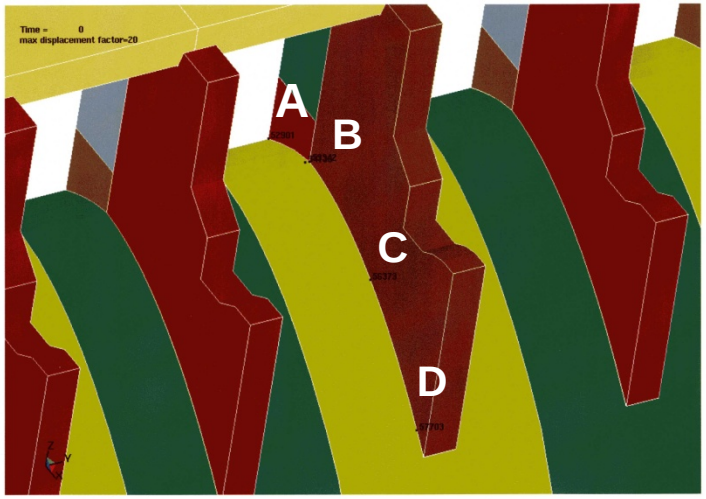


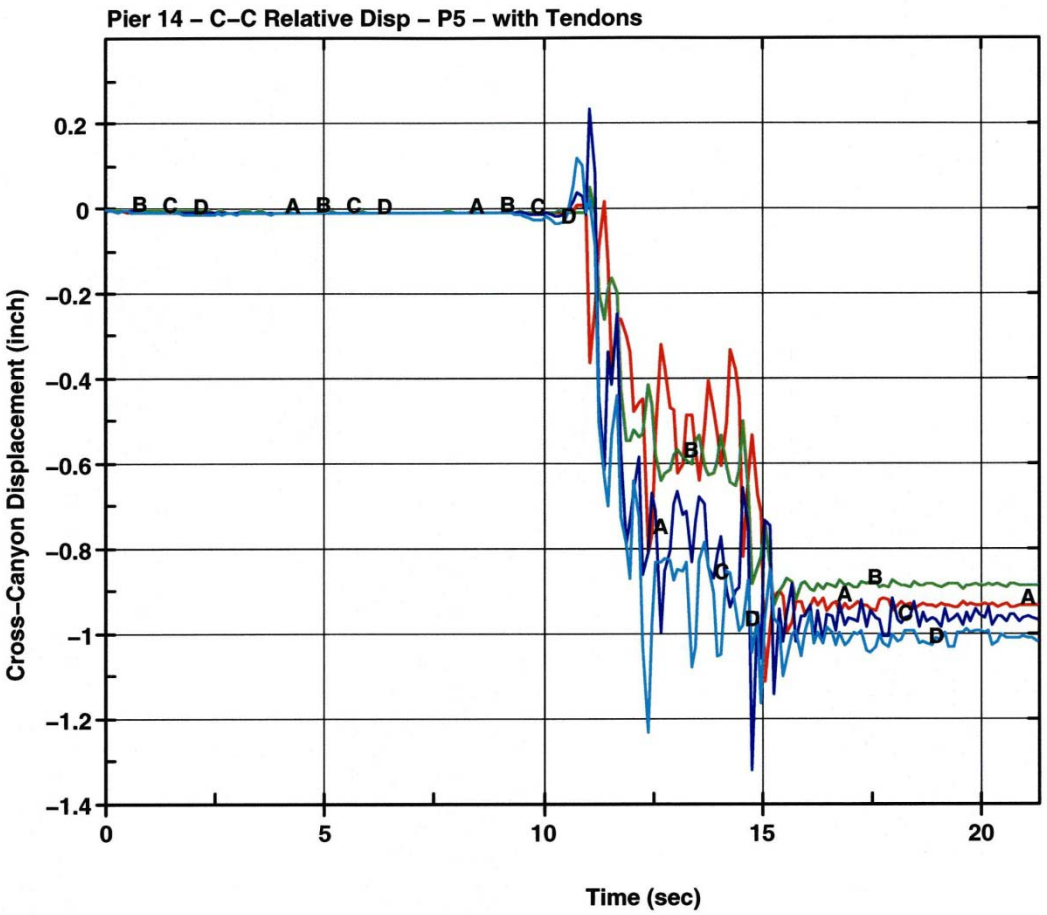


Modeled with 1/8th and 1/3rd inch gaps

Cross-canyon Sliding of Pier 14

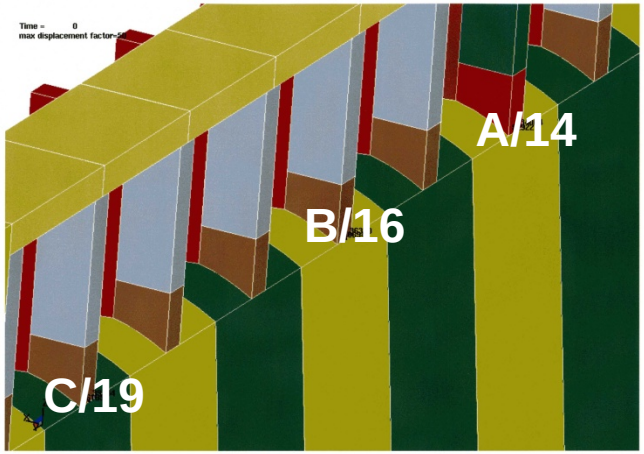
With tendons and struts

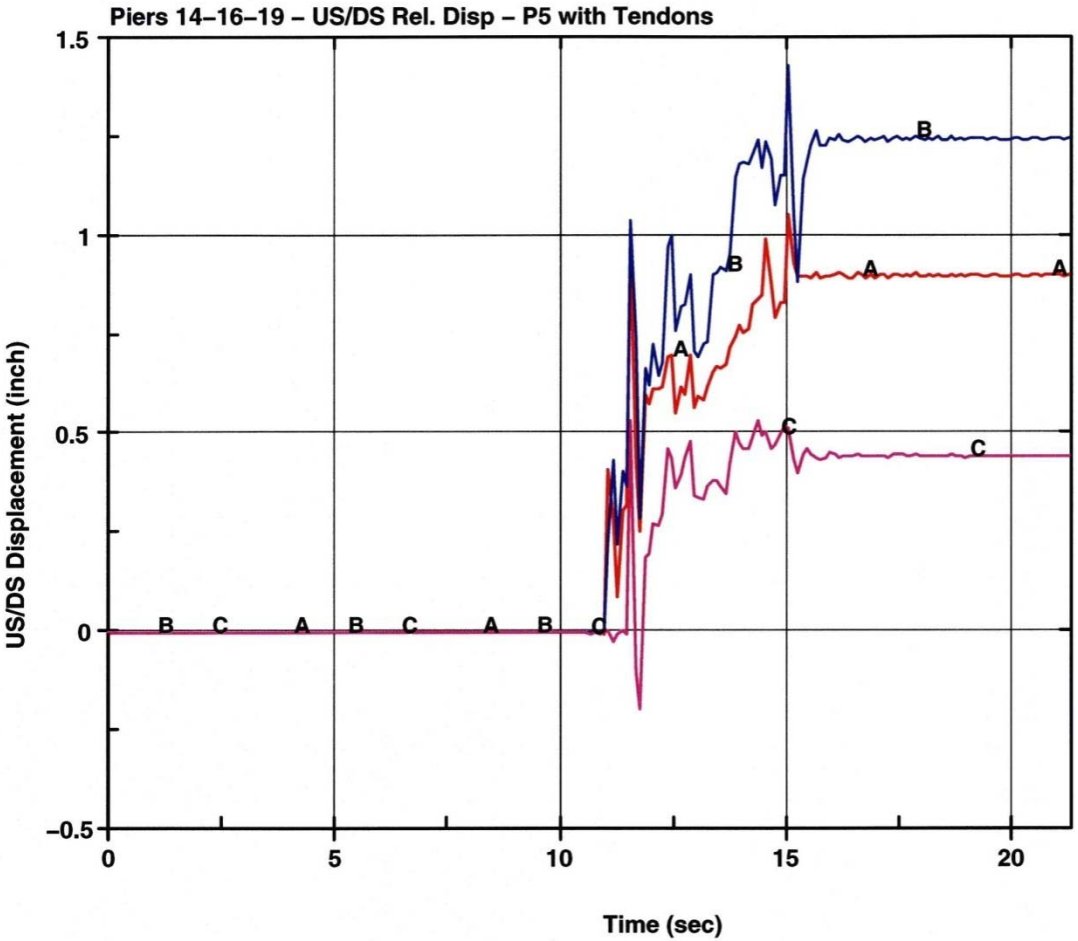




US/DS Sliding of Piers

With tendons and struts

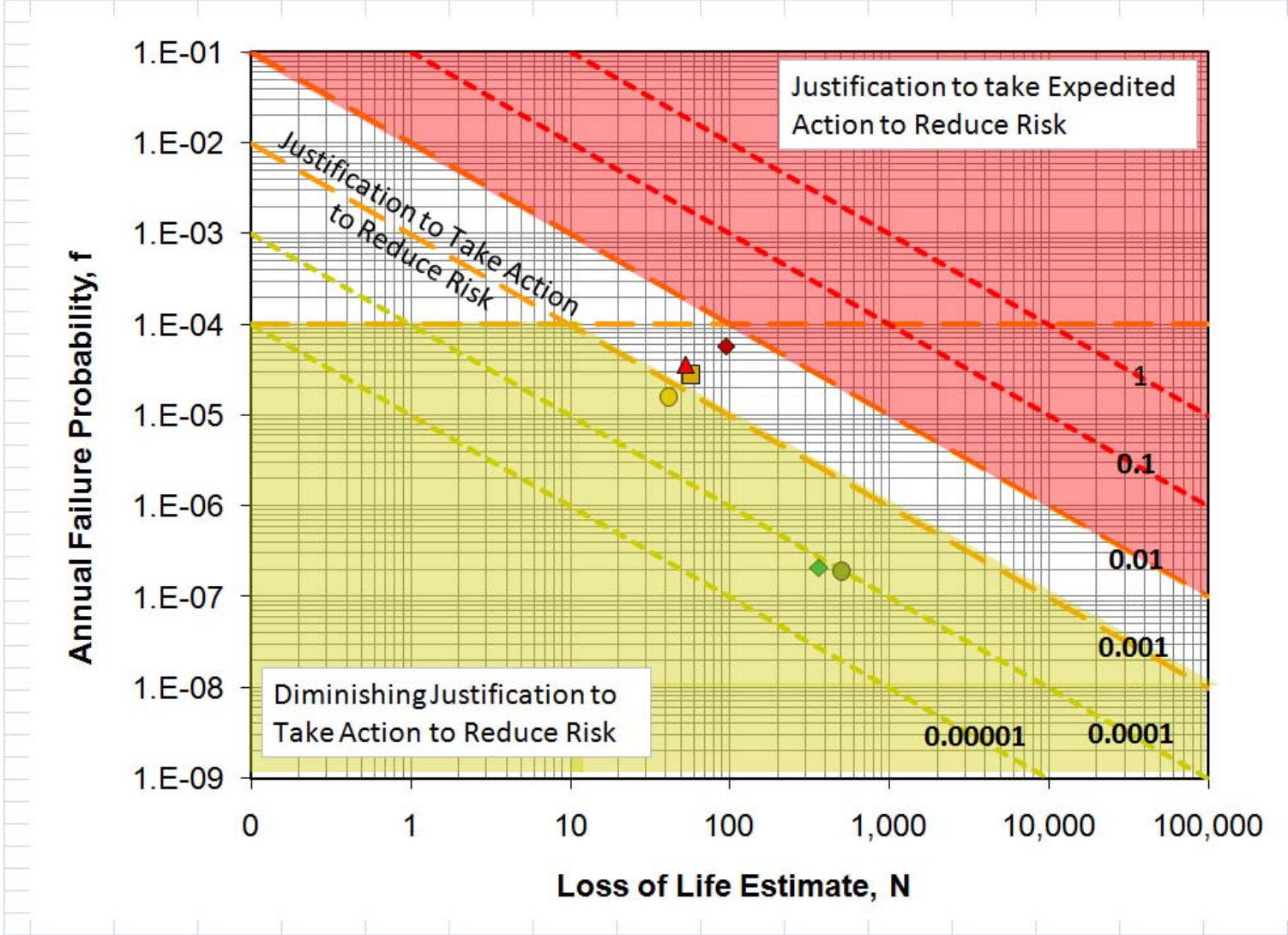




Concrete Dam Baseline Risk

Failure Mode	Total expected risk
Sliding on a lift line Near spillway and end monoliths	**9.56E-05**
Sliding on foundation wedge Wedge # 6 on right abutment	**7.56E-05**
Sliding at foundation contact	**6.60E-04**
Failure of spillway gates	**1.57E-03**
Failure of upstream pier	**1.91E-03**
Shear failure at trunnion anchor	**5.45E-03**

Reclamation Risk Assessment

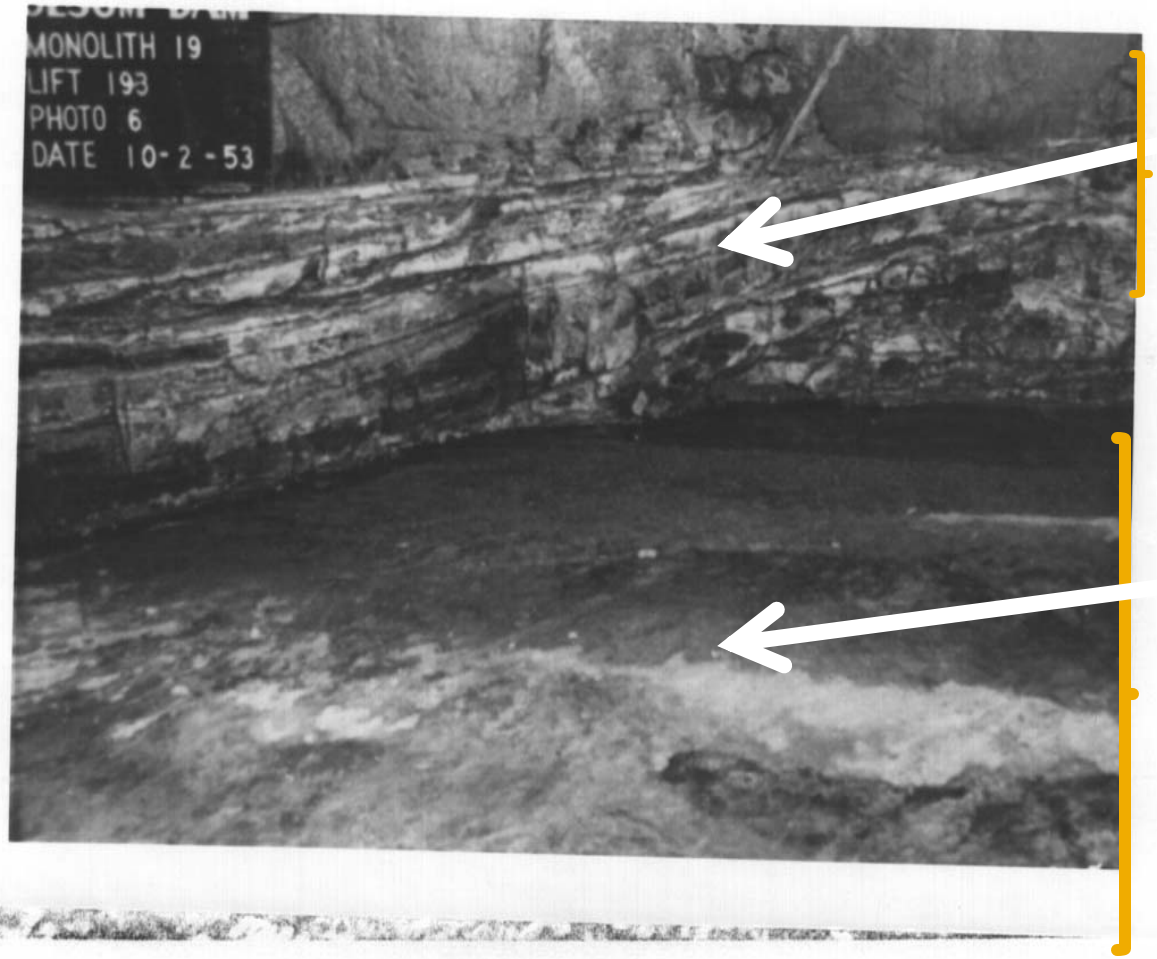


Closing Remarks

- **No movements should be allowed under sustained static loads. In other words the static factor of safety should remain greater than one before and after earthquake ground shaking.**
- **Estimation of displacements with reasonable accuracy depends on treatment of uncertainties associated with computer modeling, seismic input, shear strength properties, and the use of proper damping.**
- **The accuracy and reliability of predicted displacements can be improved by careful modeling of the failure mechanisms, sensitivity analysis, and model testing. For example failure mechanisms may involve combined rotation and sliding and also a group of monoliths, as opposed to individual monoliths.**

Concluding Remarks Cont'd

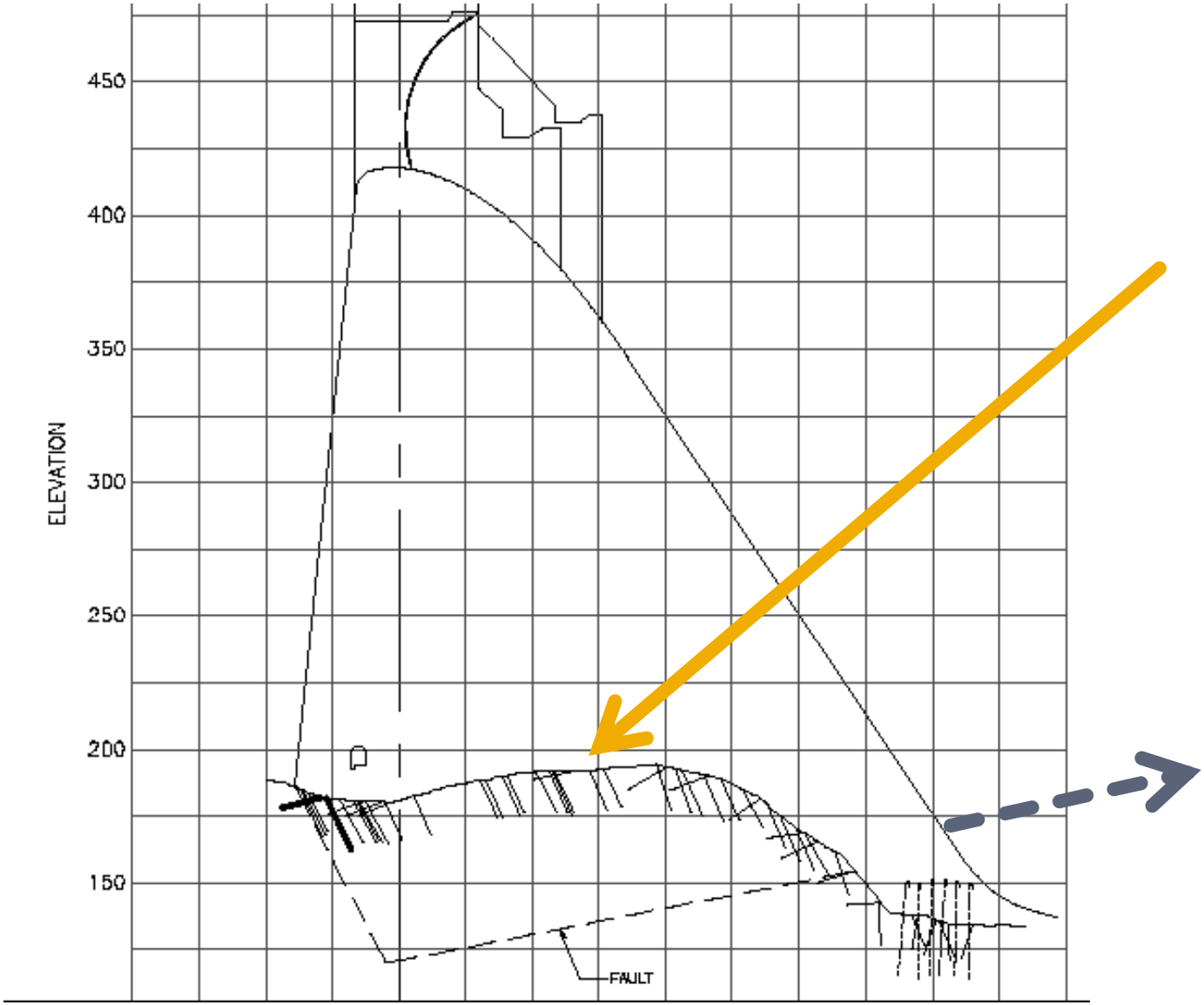
- **The acceptable level of displacements should be specified carefully and with a large margin of safety, if at all. Displacement limits are best quantified within the frame work of risk analysis and reliability methods.**
- **When displacements approach a failure limit, it is prudent to retrofit instead of relying on computation. Sometimes relatively large movements could be acceptable as long as water retention capability of the dam is not undermined. In other situations even a few inches may not be acceptable if it causes uncontrolled release of water.**



Channel fault

Smooth foot wall

Photo #36, Closeup of fault at heel of Monolith 19.
Board at Sta. 294+70; 9+63.



Monolith potentially sliding on smooth footwall of channel fault