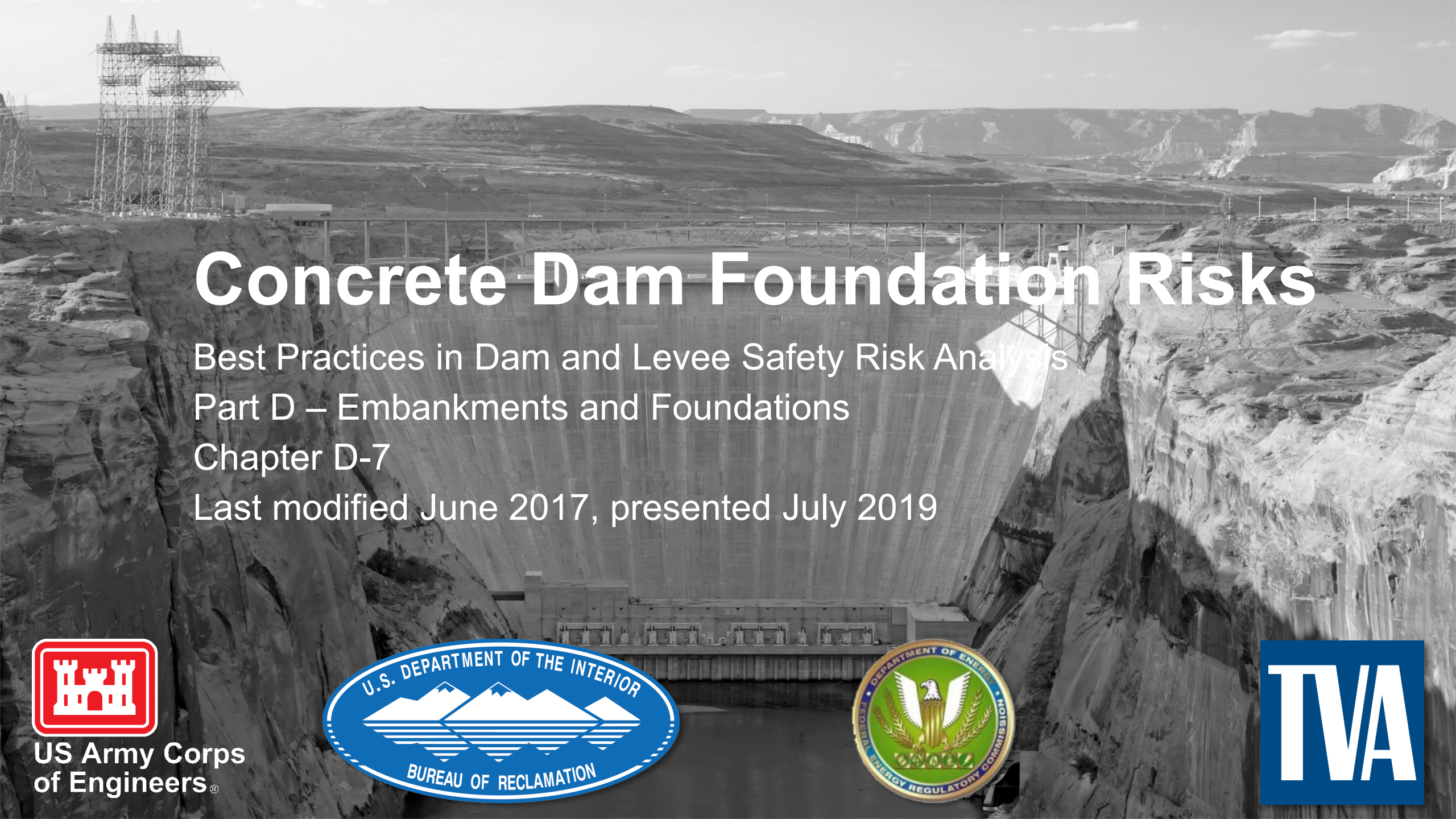

Concrete Dam Foundation Risks

Best Practices in Dam and Levee Safety Risk Analysis

Part D – Embankments and Foundations

Chapter D-7

Last modified June 2017, presented July 2019

US Army Corps of Engineers®

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DEPARTMENT OF ENERGY FEDERAL ENERGY REGULATORY COMMISSION

TVA

Outline

- Objectives and key concepts
- Historical perspective
- Case studies
- Foundation discontinuities and potential failure modes
- Discontinuity shear strength
- Foundation uplift pressures and forces
- Foundation modulus and loading considerations
- Multi-block systems
- Exercise (important to complete this)

Objectives

- Understand the mechanisms that affect concrete dam foundation failure
- Understand how to construct an event tree to represent concrete dam foundation failure (exercise)
- Understand how to estimate the probability of concrete dam breach due to foundation failure (exercise)

Key Concepts

- Foundation deficiencies are the number one cause of concrete dam failures
- The location, orientation, and strength (including scale effects) of discontinuities often control the stability of concrete dams on rock
- Kinematic analyses can be used to evaluate concrete dam foundation stability – often 3-D analyses are needed (even for gravity dams)
- The effects of uplift pressures and drainage must be considered
- Loading from the dam and dam-foundation interaction must be considered
- Internal erosion of soil foundations under concrete dams not covered here – see section on Internal Erosion

Concrete Dam Failures, after ICOLD 1995+

Failure Type	Concrete Dams
Overtopping	5 (9%)
Foundation*	29 (53%)
Uplift	4 (7%)
Materials	5 (9%)
Structural	6 (11%)
Spillway	5 (9%)
Seismic Deformation**	1 (2%)
Total	55

*Includes Camara Dam, 2004

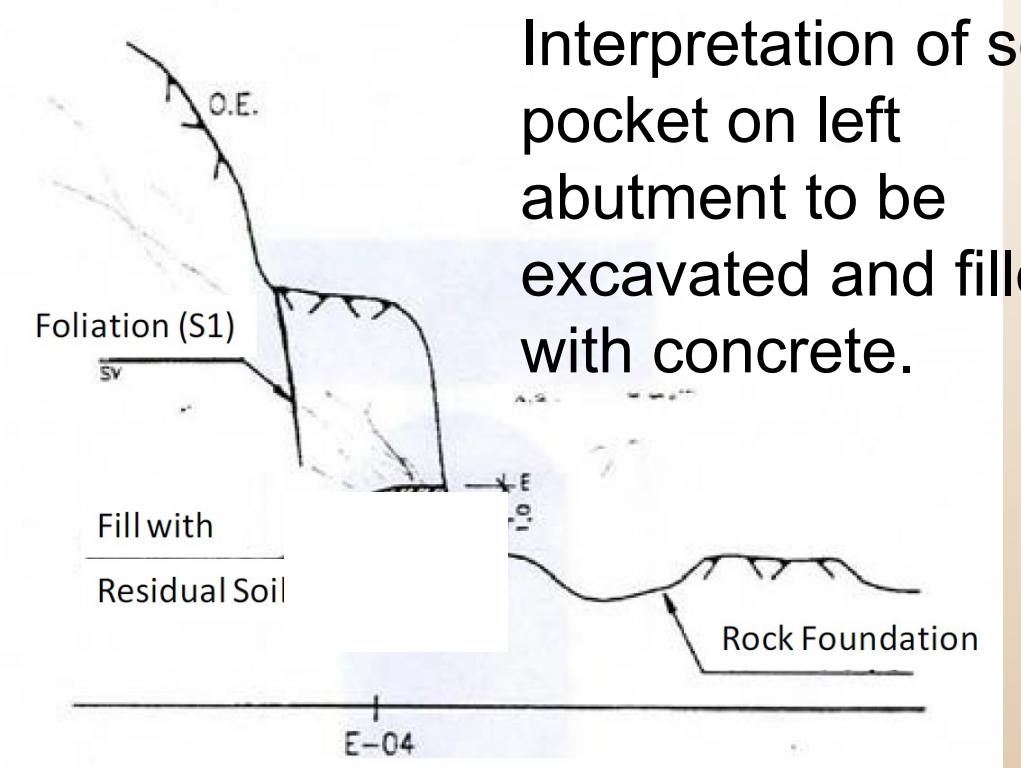
**Shi Kang Dam, 1999 Chi Taiwan E.Q.

Case Studies

Camara Dam, Brazil

- Originally designed as an embankment dam
- Switched to 160-ft-high RCC gravity dam after majority of explorations were completed
- Additional explorations for RCC dam were not adequate
- Gallery through dam for grout and drainage curtain

Camara Dam, Brazil



Interpretation of soil pocket on left abutment to be excavated and filled with concrete.

Dam foundation gneissic migmatites with foliation dipping 30 to 35 degrees toward the right abutment.

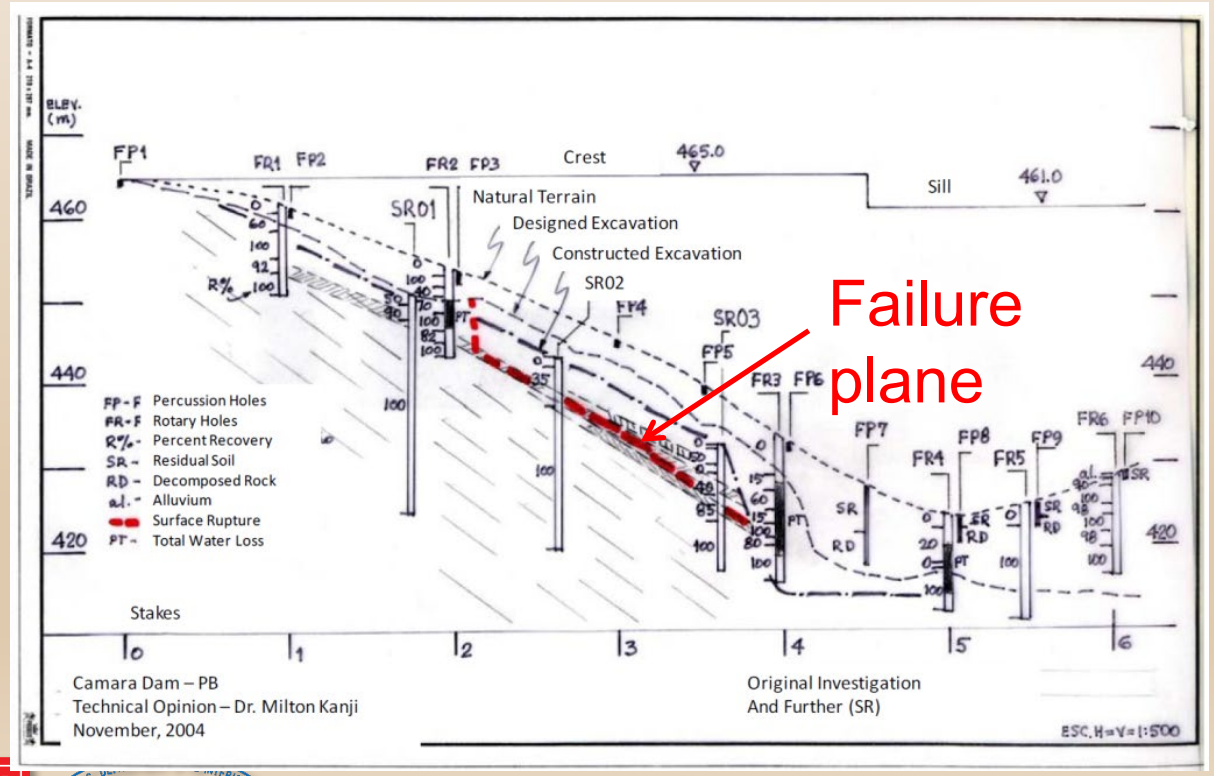
Camara Dam, Brazil

- Reservoir filled to within 5 m of full pool quickly in early 2004 due to heavy rains
- Filling continued into June 2004
- Reports of material carried by drain flows, plugged drains, and wet spot d/s toe left abutment during this time period
- Dam failed June 17, 2004
- 5 deaths
- 800 homeless

Note that dam bridged over failure zone

Camara Dam, Brazil

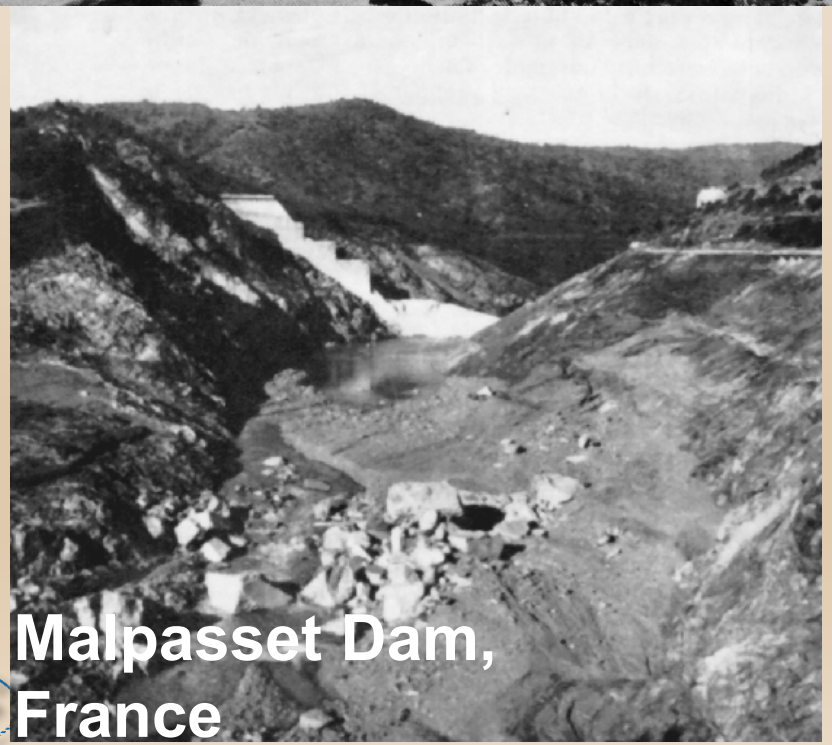
Arrow points to remnant of shear zone
Note unfractured footwall
Note direction of sliding toward channel

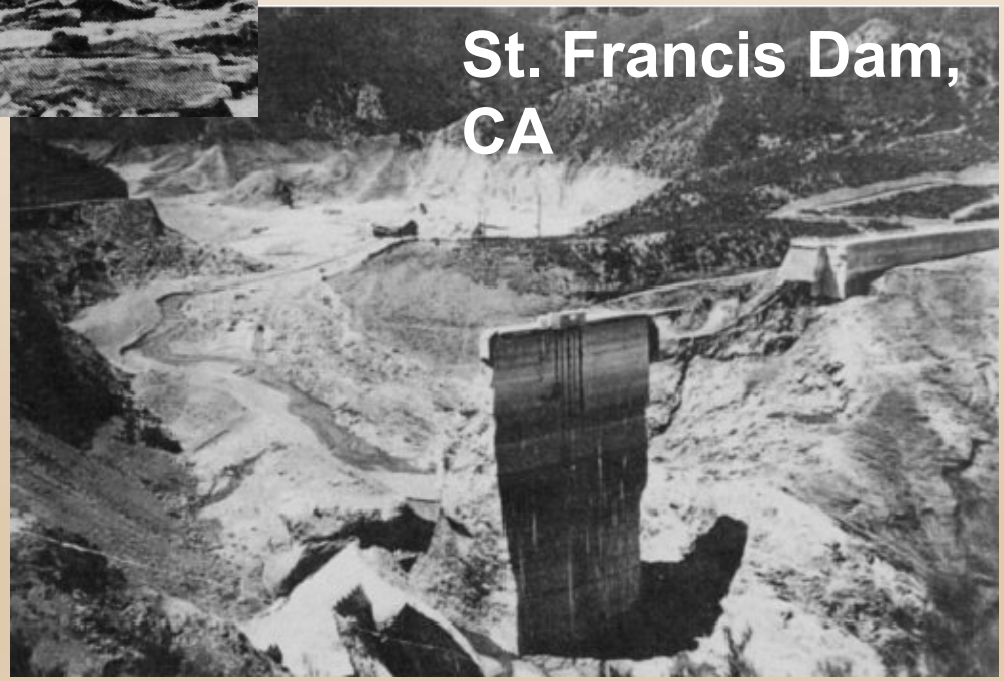


Profile developed post-failure

(1) Large uplift pressures in shear zone caused block to slide, or
(2) Erosion of shear left a gap into which dam collapsed

Other Notable Foundation Failures





Discontinuities and Potential Failure Modes

Foundation Stability Analysis

Identify potential sliding failure modes

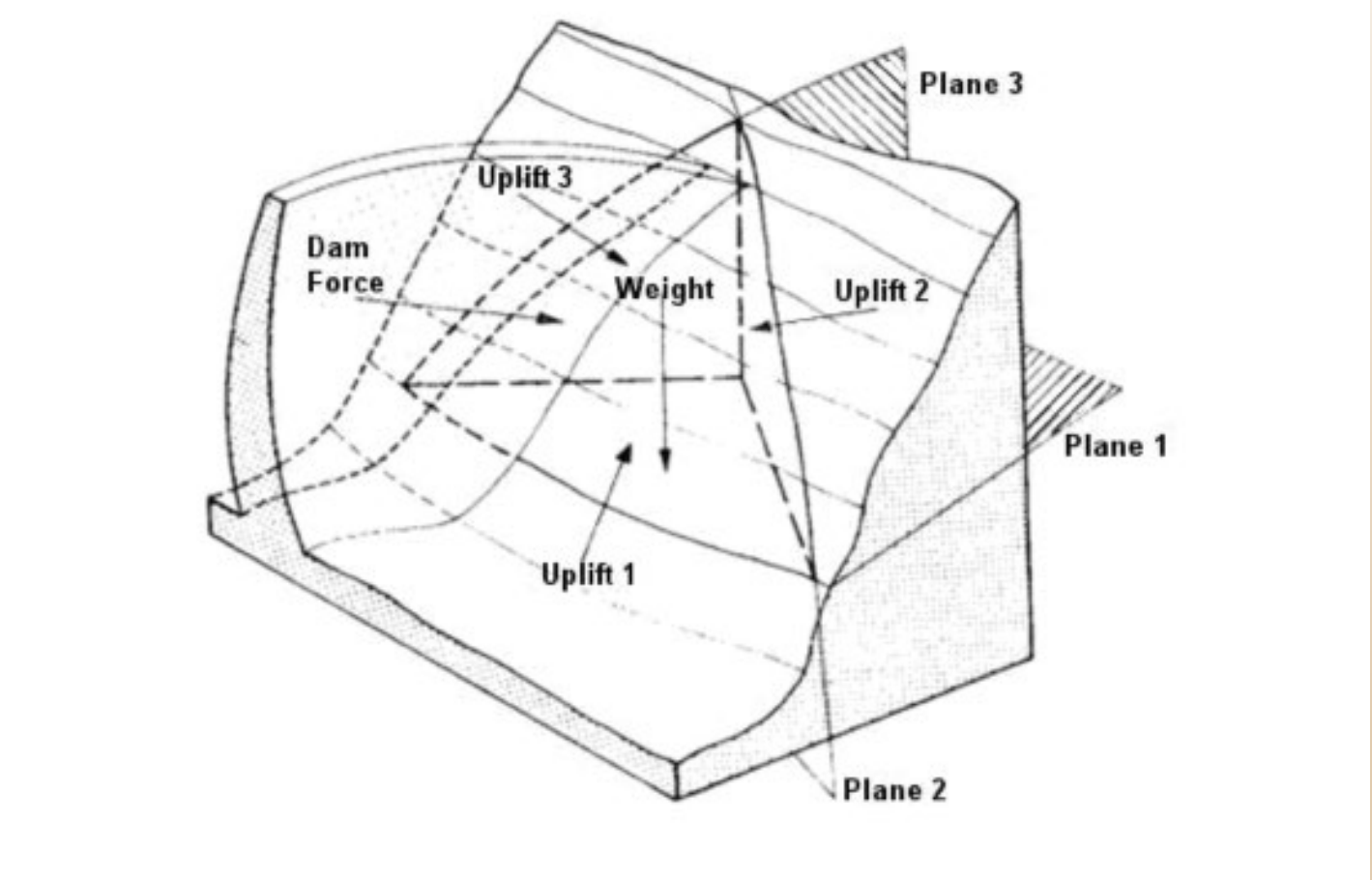
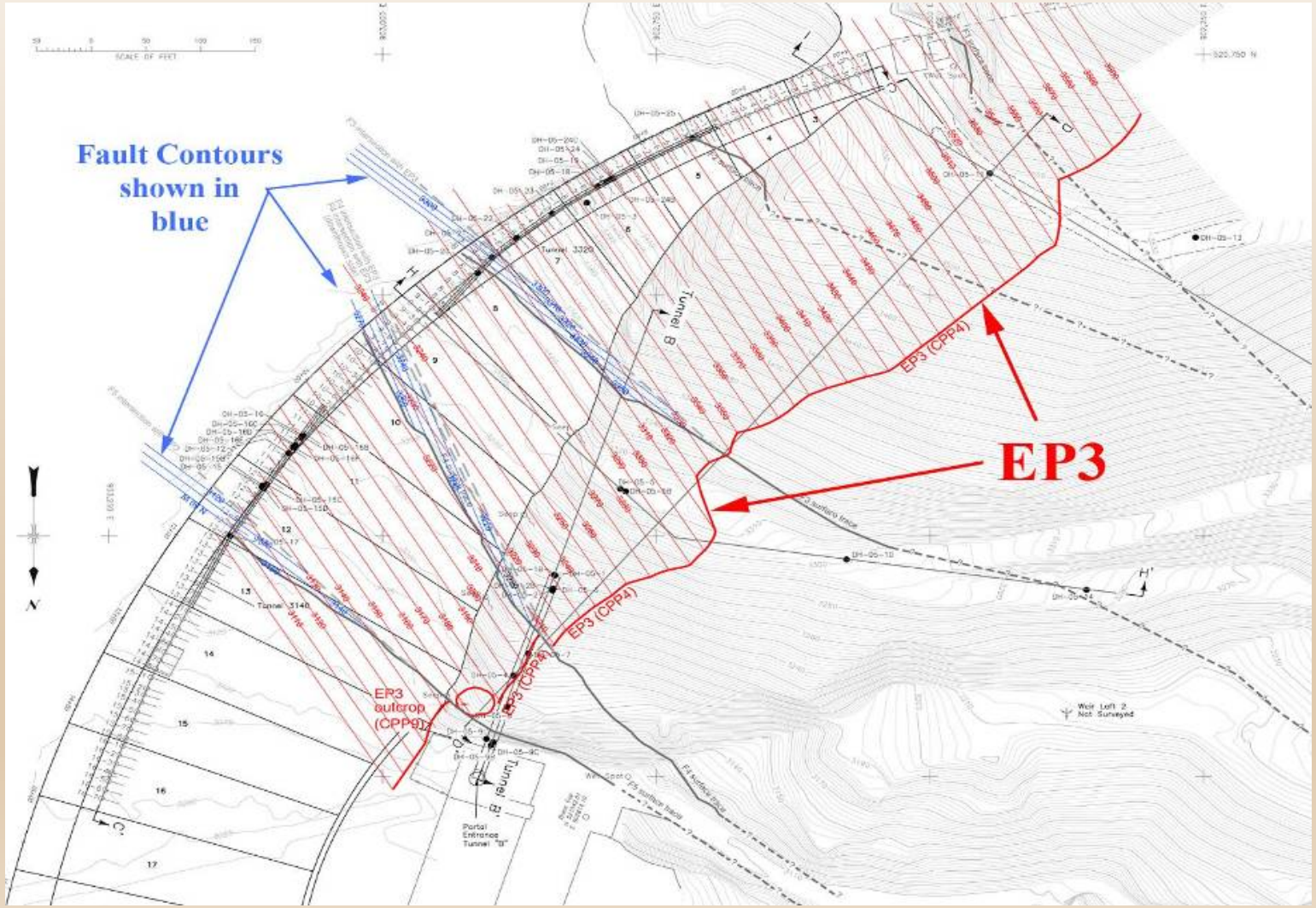
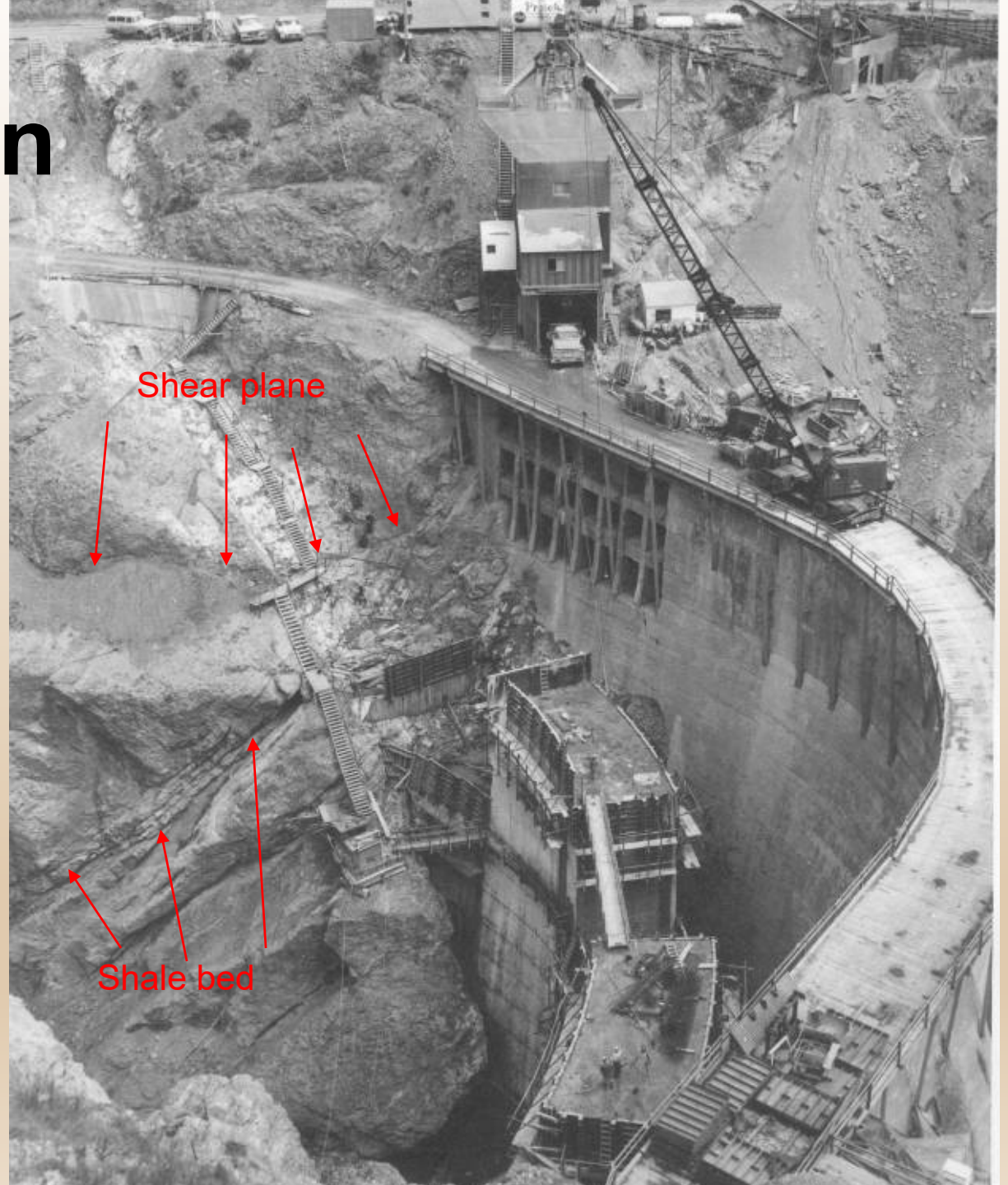


Figure 16. Rock Block within the Foundation of an Arch Dam. Plane 1, Plane 2, and Plane 3 are Discontinuity Planes; Uplift 1, Uplift 2, and Uplift 3 are Water Forces; W is the Block Weight; and Dam Force is the Thrust from the Dam (adapted from Londe [22]).

Structural Contours for Major Bedding Plane Partings and Faults

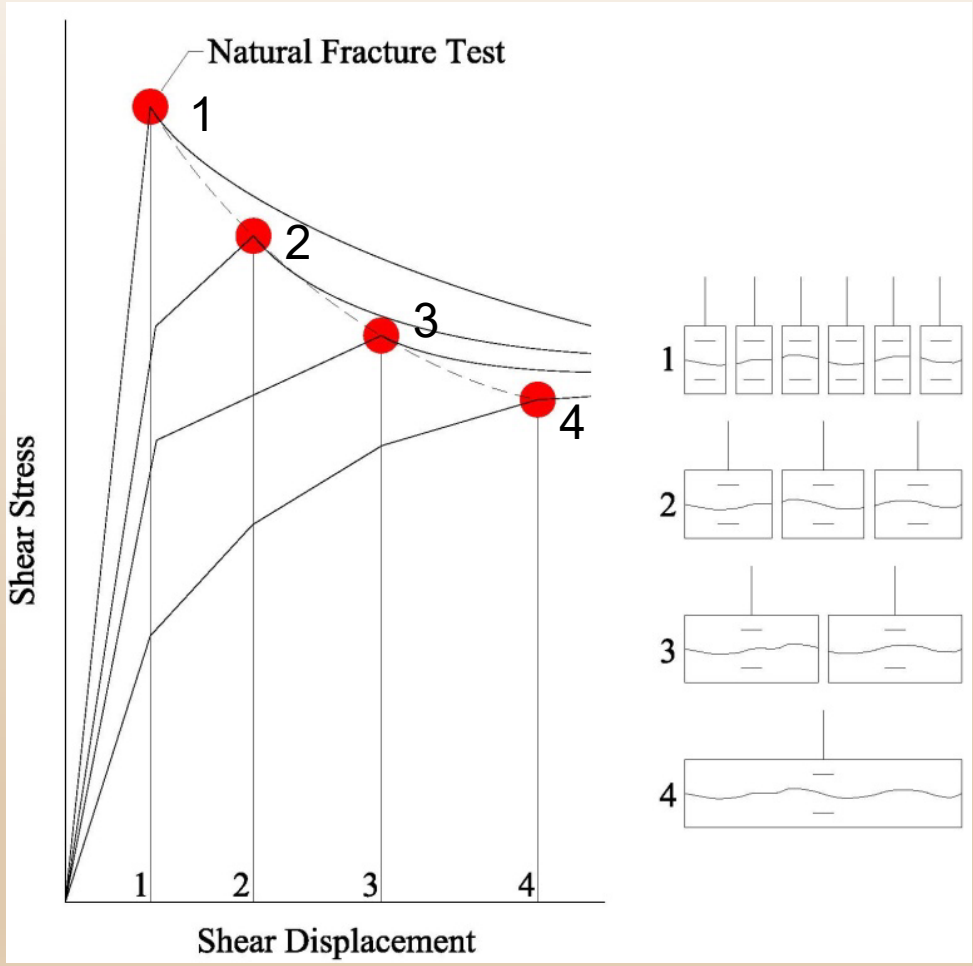


Construction Photos are Invaluable



Discontinuity Strength – Scale Effects

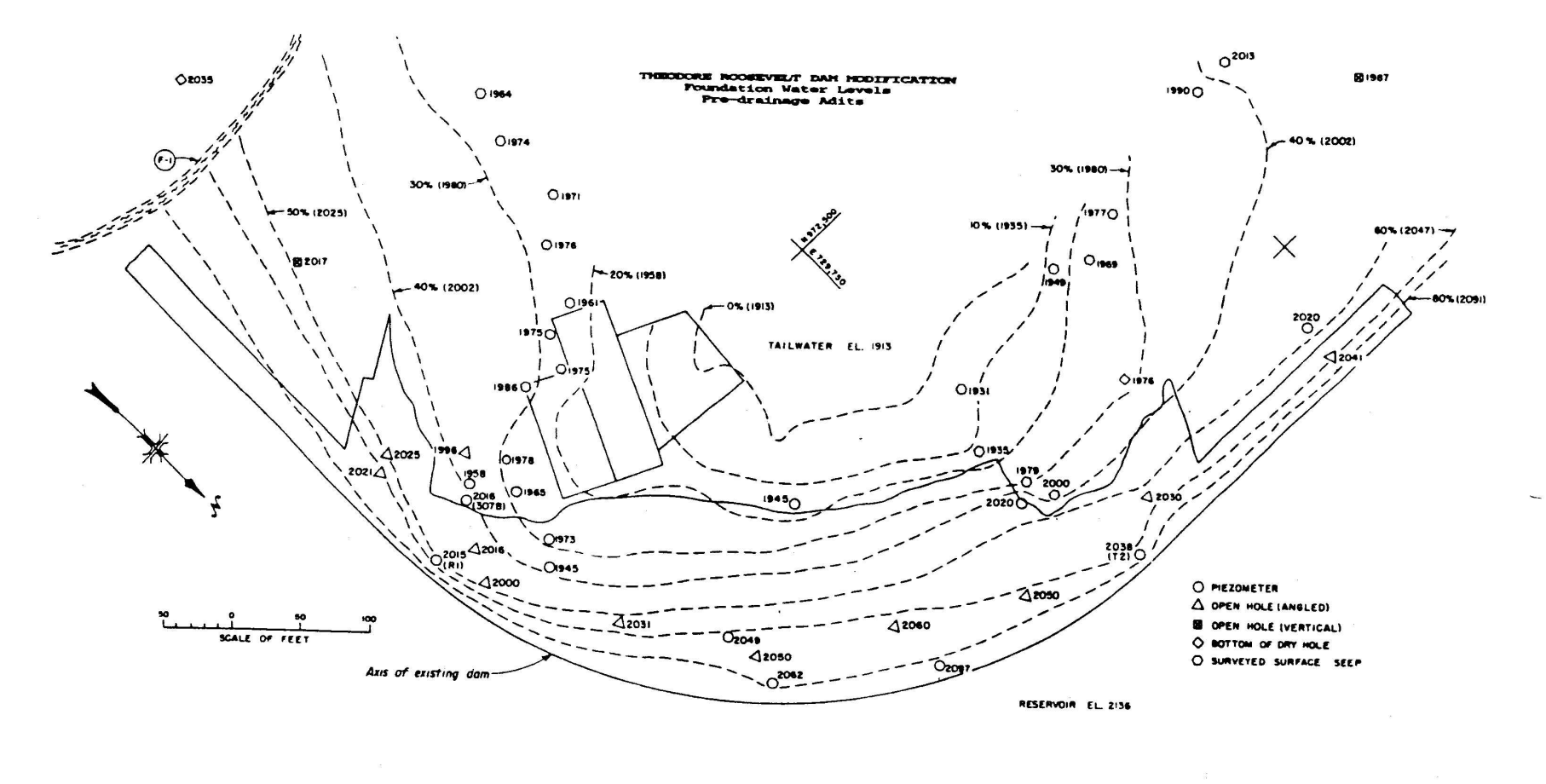
- Small scale rough samples overestimate strength
- Saw cuts typically under-estimate basic friction angle
- Test actual joints and subtract roughness (dilation angle) by measuring horizontal and vertical displacements) to obtain basic friction angle
- Add in large scale field roughness measured from outcrops
- See manual for details



Adapted from Bandis et al (1983)

Foundation Uplift Pressures

Foundation Water Pressures



$$DHR = \frac{Piezometric\ El - Tailwater\ El}{Reservoir\ El - Tailwater\ El}$$

Used to estimate @ other RWS Elevations

Effects of Foundation Drains

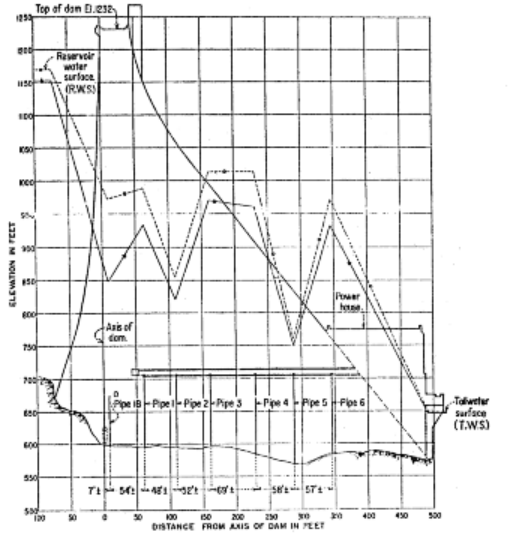


Figure C3. Uplift Measurements at Hoover Dam.
Note: 1 ft = 0.3048 m.

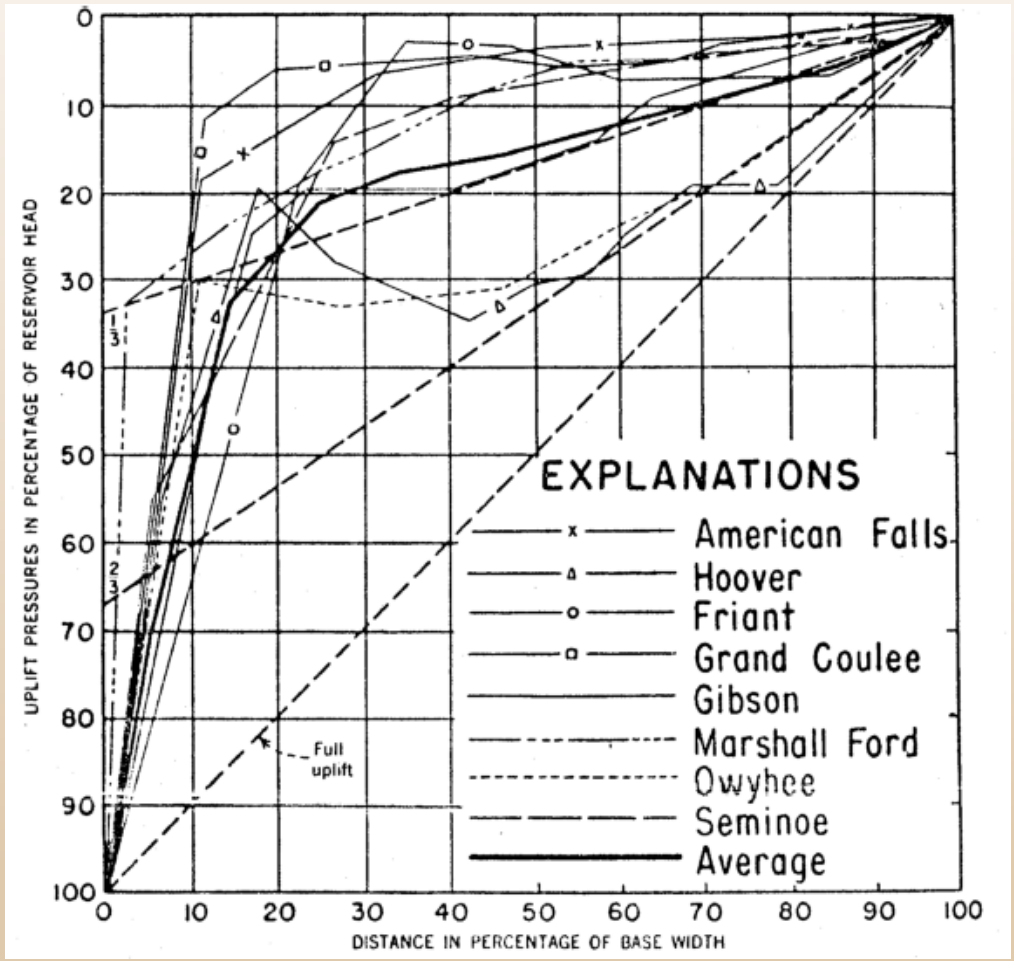
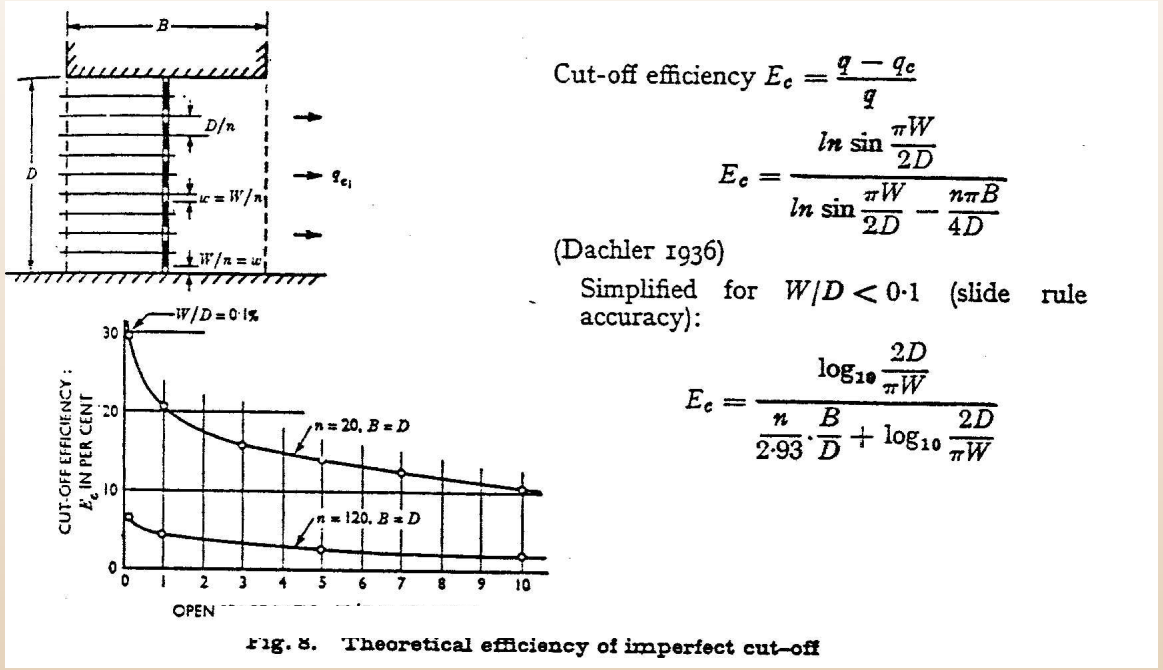


Figure C2. Uplift Measurements Recorded at Reclamation Concrete Dams

Drain depth (into fdn.) should be about 40% of hydraulic height, drains must be cleaned and maintained.

Grout Effectiveness



Cut-off efficiency $E_c = \frac{q - q_c}{q}$

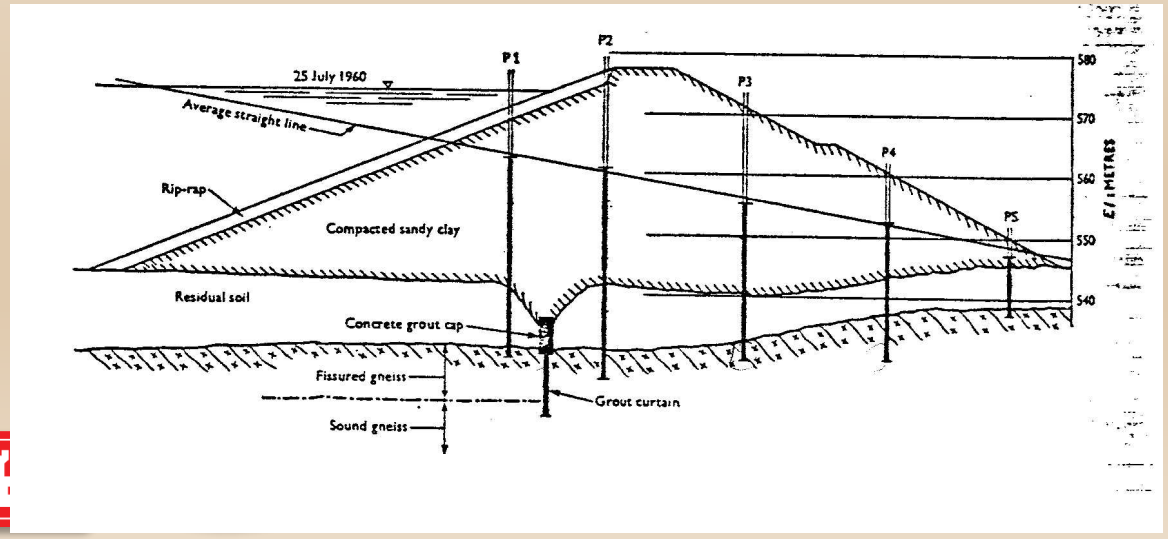
$$E_c = \frac{ln \sin \frac{\pi W}{2D}}{ln \sin \frac{\pi W}{2D} - \frac{n\pi B}{4D}}$$

(Dachler 1936)

Simplified for $W/D < 0{\cdot}1$ (slide rule accuracy):

$$E_c = \frac{\log_{10} \frac{2D}{\pi W}}{\frac{n}{2{\cdot}93} \cdot \frac{B}{D} + \log_{10} \frac{2D}{\pi W}}$$

Fig. 8. Theoretical efficiency of imperfect cut-off



Careful when grouting under reservoir head. Grout may travel downstream and set up, backing up increased pressures upstream under the dam.

If counting on grout curtain cutoff to reduce pressures, must verify with measurements

Arthur Casagrande, 1st Rankine Lecture

Water Forces on Block Planes

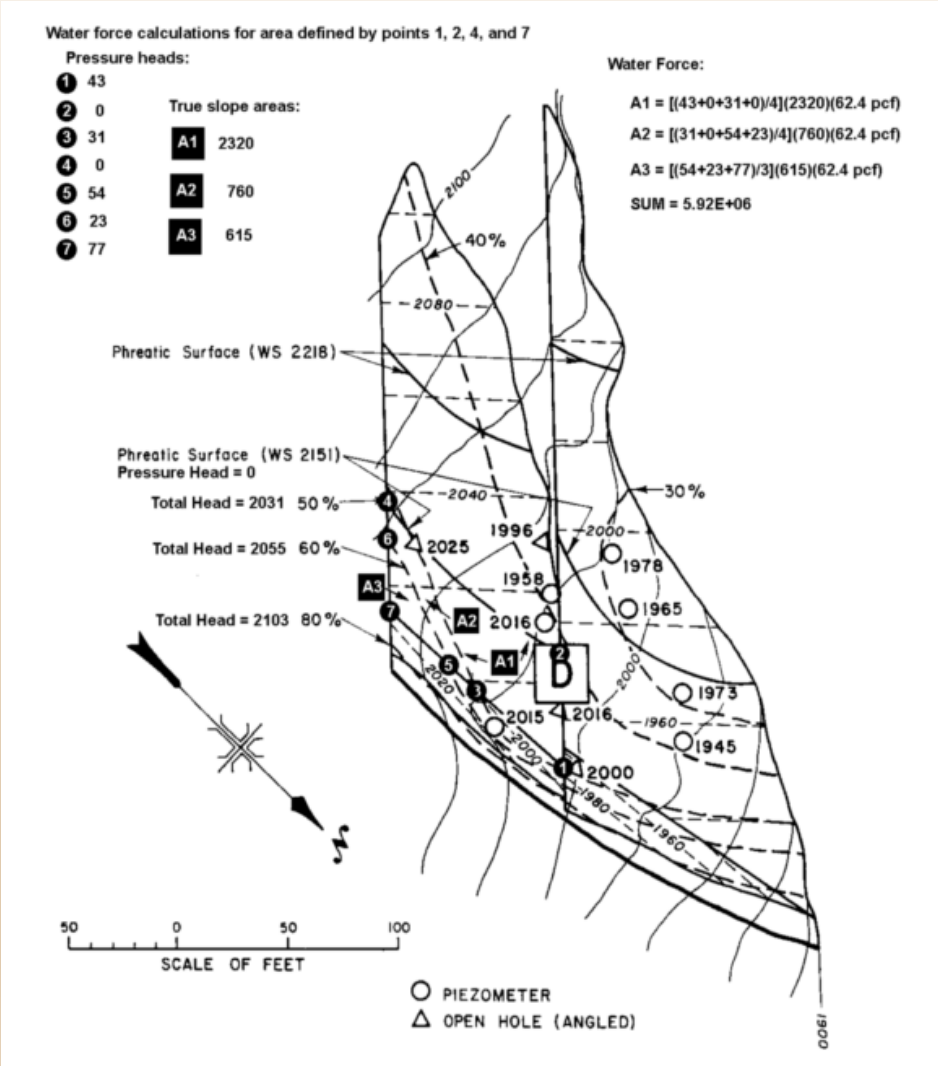


Figure 23. Example Water Force Calculation. Note: 1 ft = 0.3048 m, 1pcf = 16 kg/m³, 1 lb = 4.45 l

- Determine submerged area for each block plane
- Discretize each plane wetted area
- Calculate force for each area
- Sum to get total force on each plane

Dam Loading and Rock Mass Modulus Considerations

Dam Loads and Inertia Loads

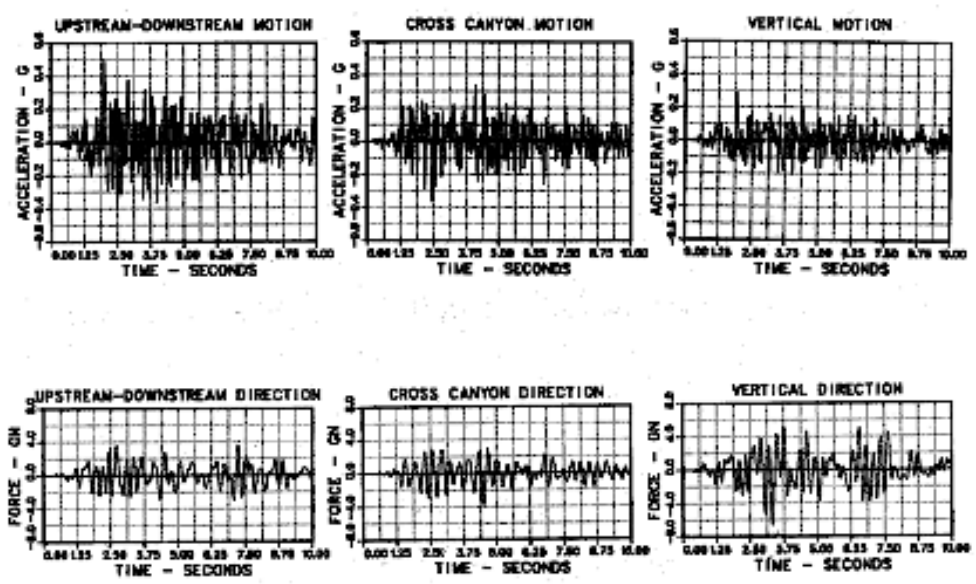


Figure 20. Time-Varying Ground Accelerations and Dynamic Dam Loads Acting on Foundation Block. Note: 1 GN = 2.25E+0 8 lb.

For uncoupled analyses

Include static loads

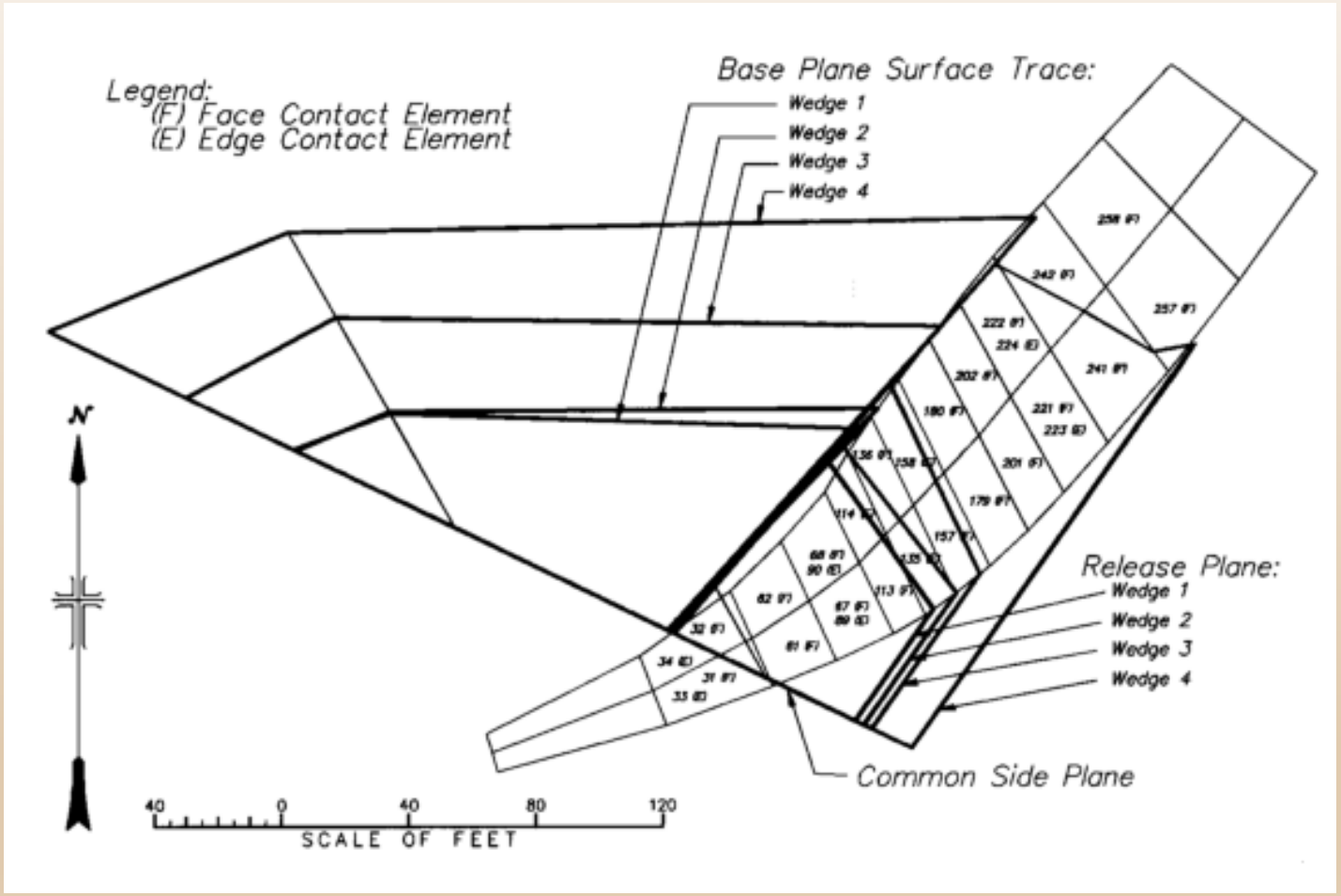


Figure 21. Finite Element Mesh Footprint Shown in Relationship to Foundation Blocks Identified at Morrow Point Dam. Note: 1 ft = 0.3048 m.

Foundation Rock Mass Modulus

- Affects load distribution, is critical to calculating dam loading
- Is not the intact laboratory modulus – affected by discontinuities
- Is probably not the geophysical modulus – strain too small
- Foundation modulus can be determined from empirical relationships, in-situ testing, or calibration to measured deformations or shake test frequencies
- In two cases where jacking tests were performed before and after grouting (Davis Dam and Auburn Dam) there was virtually no change in the rock mass modulus – no increase from grouting

Foundation Rock Mass Modulus (cont.)

- Too small of a foundation modulus can over-dampen the system for dynamic calculations (i.e. low value is not conservative) Calibration to shake tests useful.
- Typically, stiffer foundation modulus values are more conservative relative to structural response and loading as shown in table below
- But, should perform sensitivity studies to see what the difference is with respect to foundation load and stress distribution

Modulus Case	Factor of Safety		
	Block D Left Abutment	Block E Channel Area	Block F Right Abutment
Case 1 (Soft)	2.8	2.1	3.2
Case 2 (Stiff)	2.1	1.9	2.3

Multi-Block Systems

Multi-Block Foundation Systems

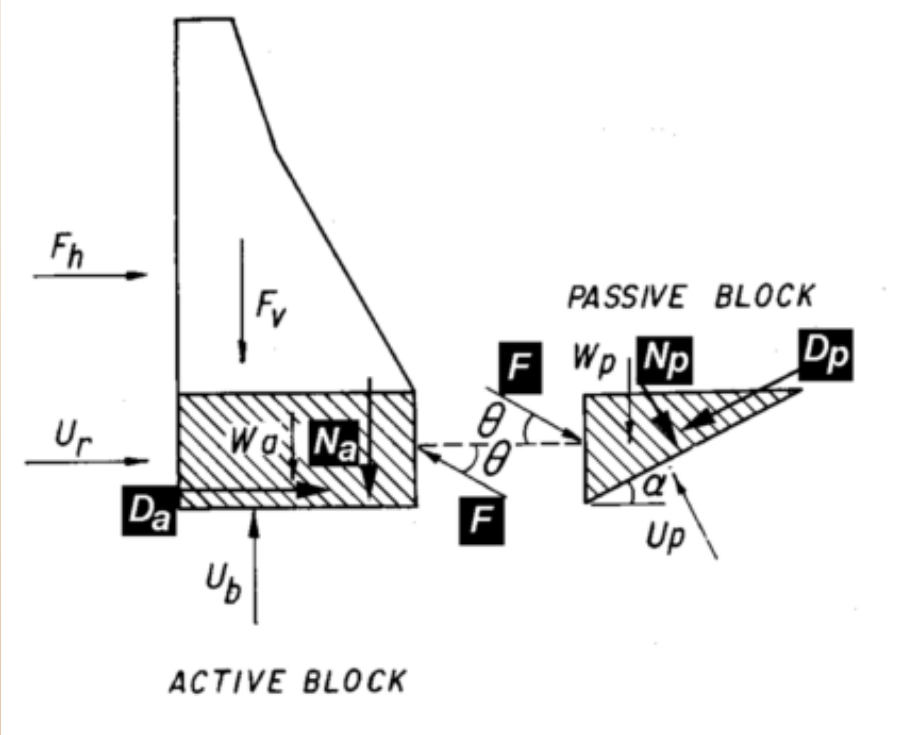
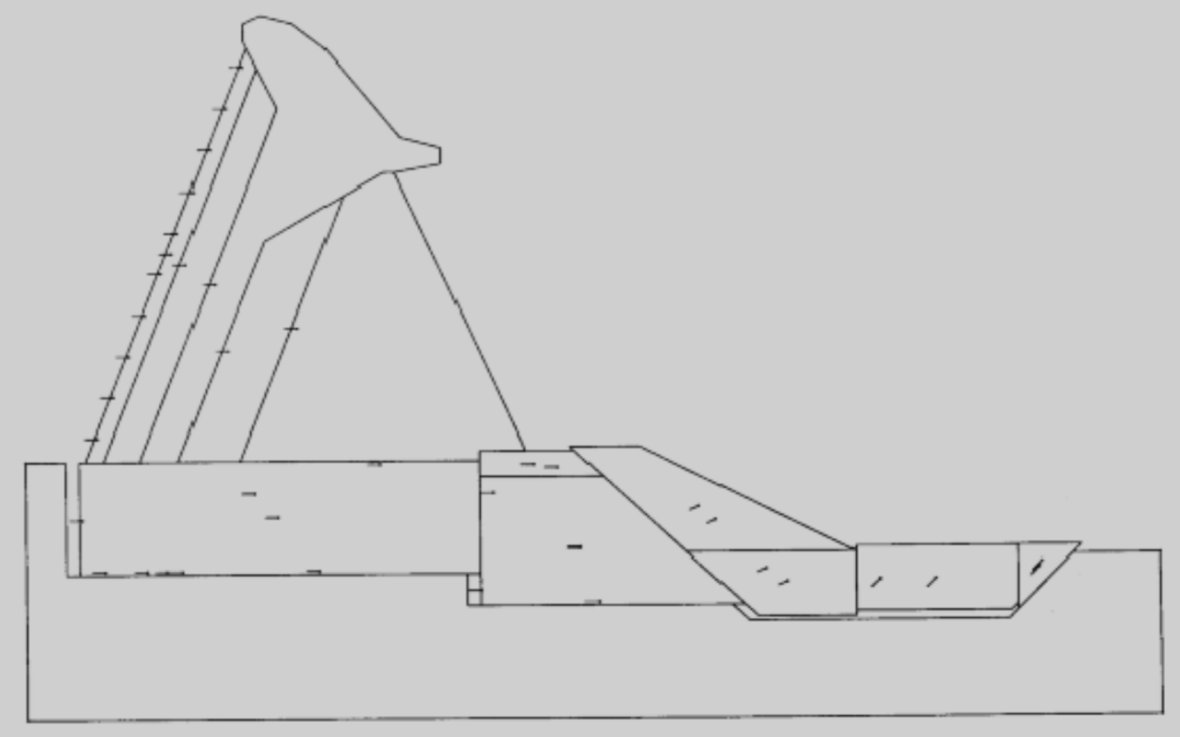


Figure E1. Forces Acting on Two Block System. Forces in Black Boxes Represent Summation of Forces Resolved into the Shown Directions

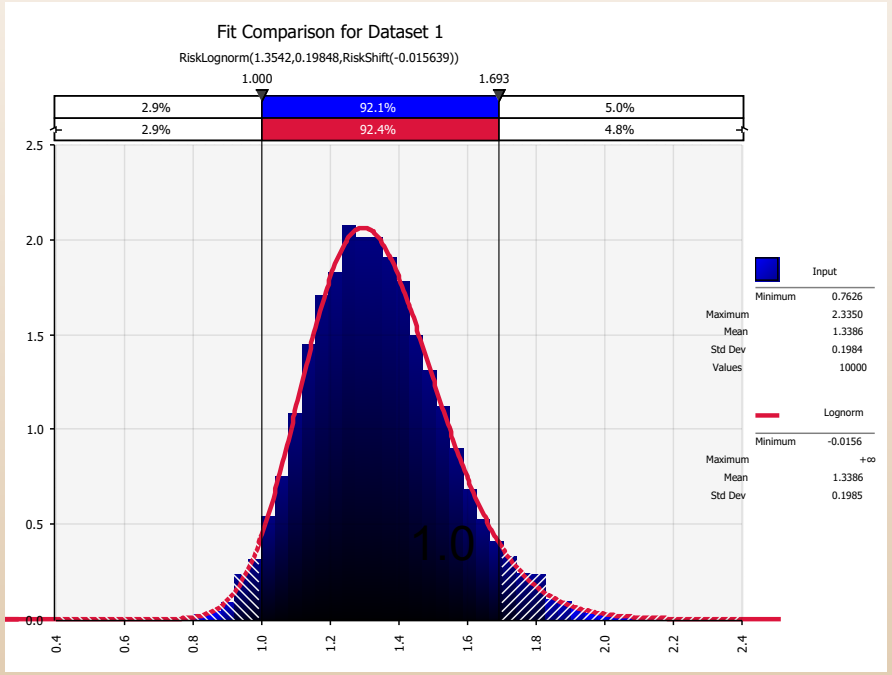
- Unless passive block is very thin, the rock material is weak or there is an adversely oriented discontinuity, shearing through passive rock mass is unlikely
- There must also be shearing along a near vertical feature between blocks
- Results are highly sensitive to assumed interblock force angle theta – approaches friction angle at limit of equilibrium

Distinct Element Analysis

- For multiblock analysis, distinct element or discontinuous deformation analysis (DDA) evaluations are more appropriate – account for interblock forces and their orientations



Sliding Factor of Safety



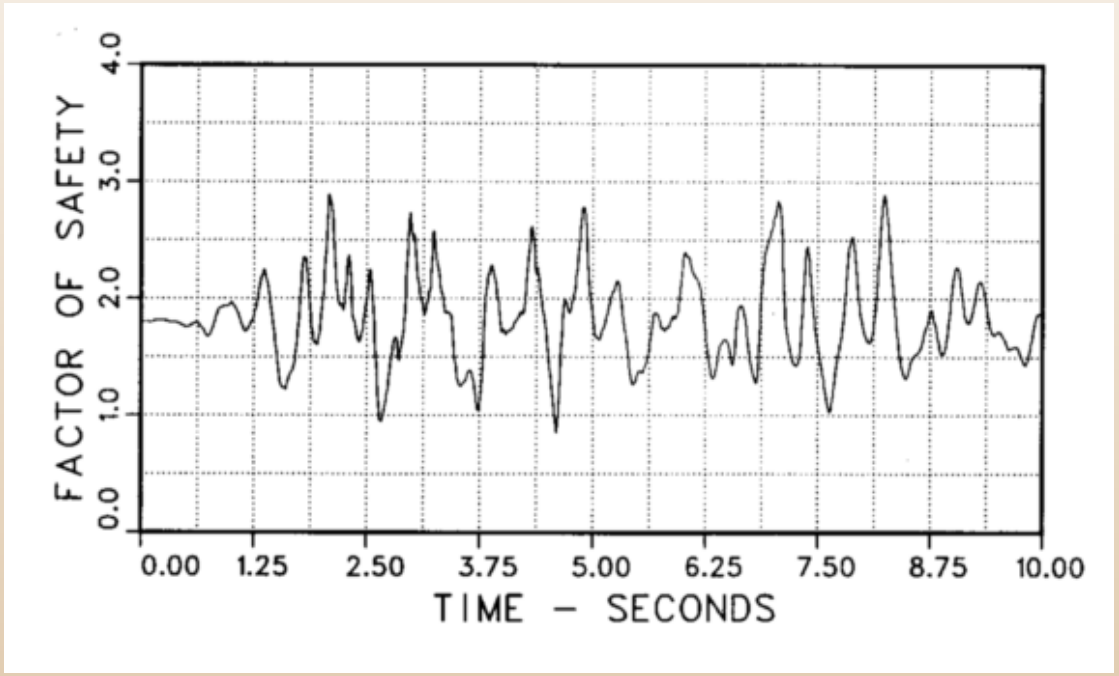


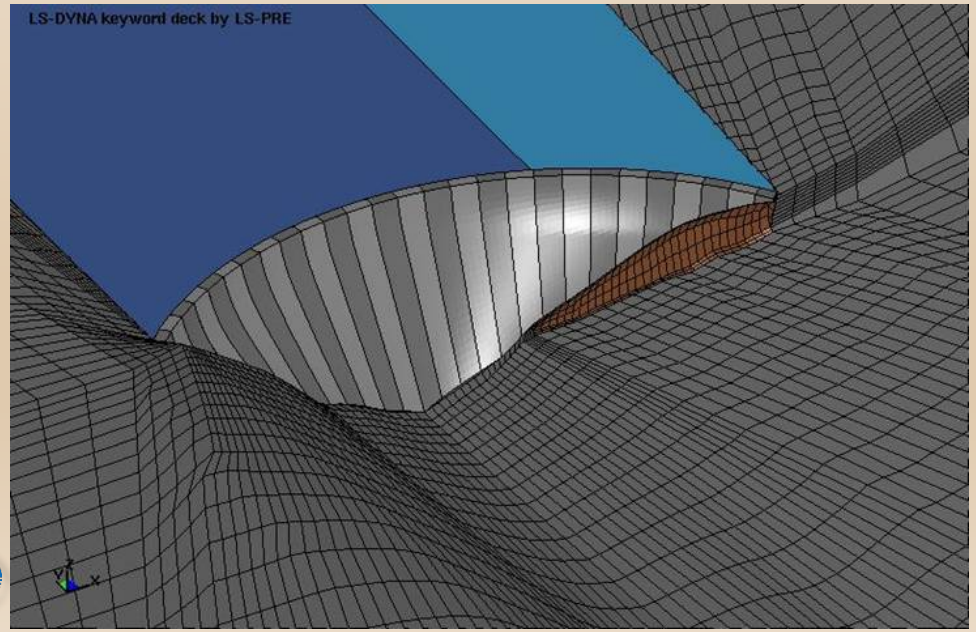
Figure 28. Factor of Safety as a Function of Time for Dynamic Analysis of Foundation Block

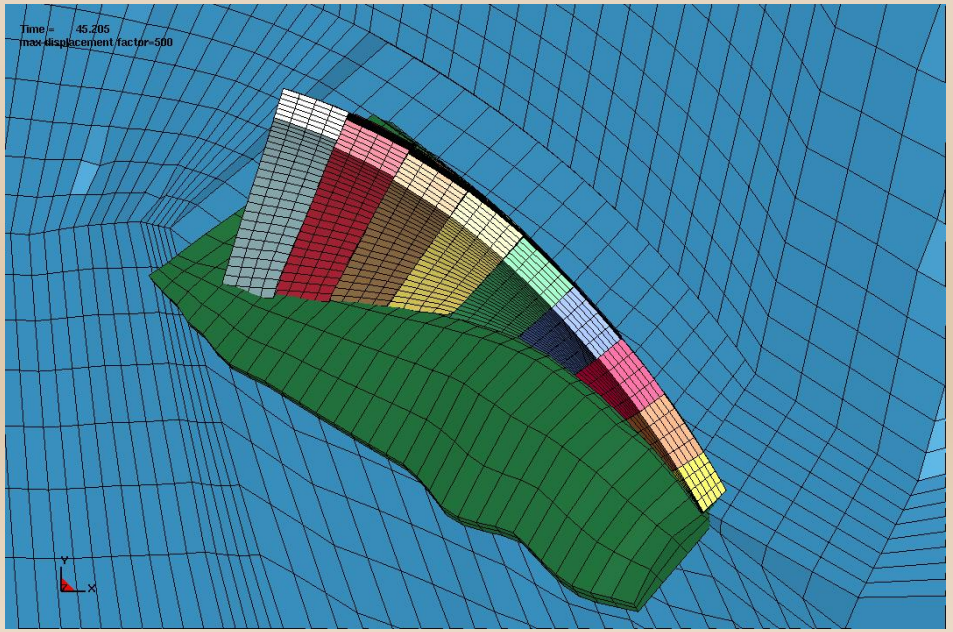
Results from probabilistic factor of safety calculations

"Newmark" displacements when factor of safety drops below 1.0. Large displacements would be unrealistically conservative

Nonlinear Coupled Analysis

- Typically only completed if an uncoupled analysis indicates large displacements and high risks are estimated
- Time consuming and expensive
- Requires thorough exercising and testing to validate the model is behaving properly and the results are reasonable





Takeaway Points

- Foundation deficiencies are the leading cause of concrete dam failures
- Careful evaluation of the 3-D geology and discontinuity geometry is needed to evaluate potential block formation and failure modes
- Analyses need to consider foundation modulus and dam loads, water uplift pressures, and scale-dependent shear strength, along with their variability and uncertainty
- Probabilistic and traditional deterministic stability analyses are needed in most cases
- The exercise that follows is key to understanding how to estimate these risks. An event tree will be developed, which can be used to evaluate potential corrective actions for high risk situations

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