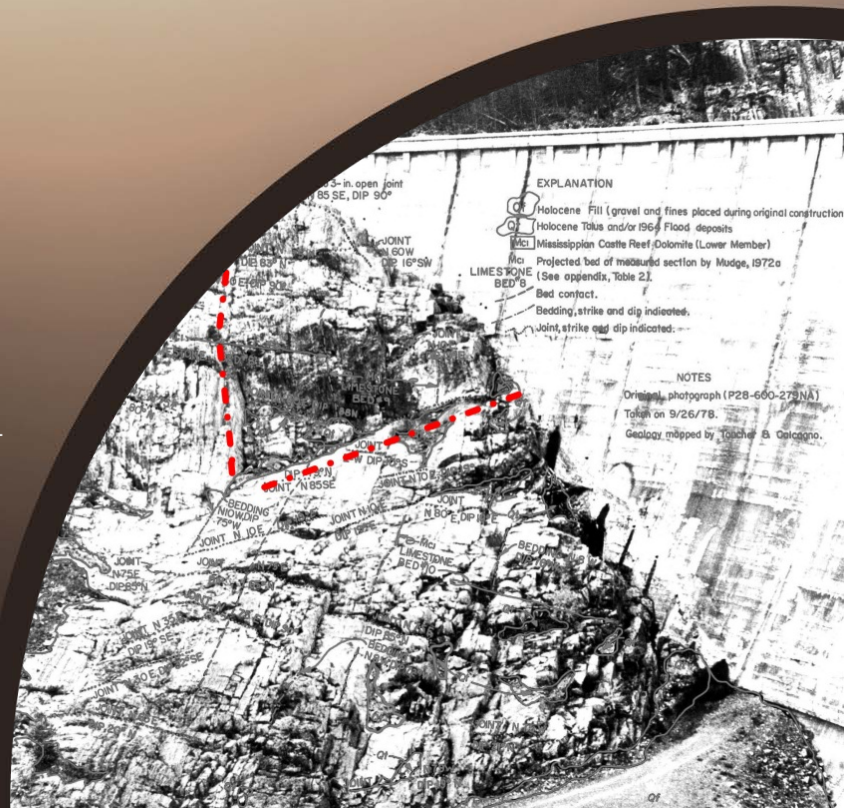
# Best Practices in Dam and Levee Safety Risk Analysis

## IV-5, Foundation Risks for Concrete Dams

11 May 2015




U.S. DEPARTMENT OF THE INTERIOR
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RECLAMATION
*Managing Water in the West*

US Army Corps of Engineers
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# Concrete Dam Failures, ICOLD 1995

| Failure Type | Concrete Dams |
|---|---|
| Overtopping | 5 (9%) |
| Foundation* | 29 (54%) |
| Uplift | 4 (8%) |
| Materials | 5 (9%) |
| Structural | 6 (11%) |
| Spillway | 5 (9%) |
| Total | 54 |

*Includes Camara Dam

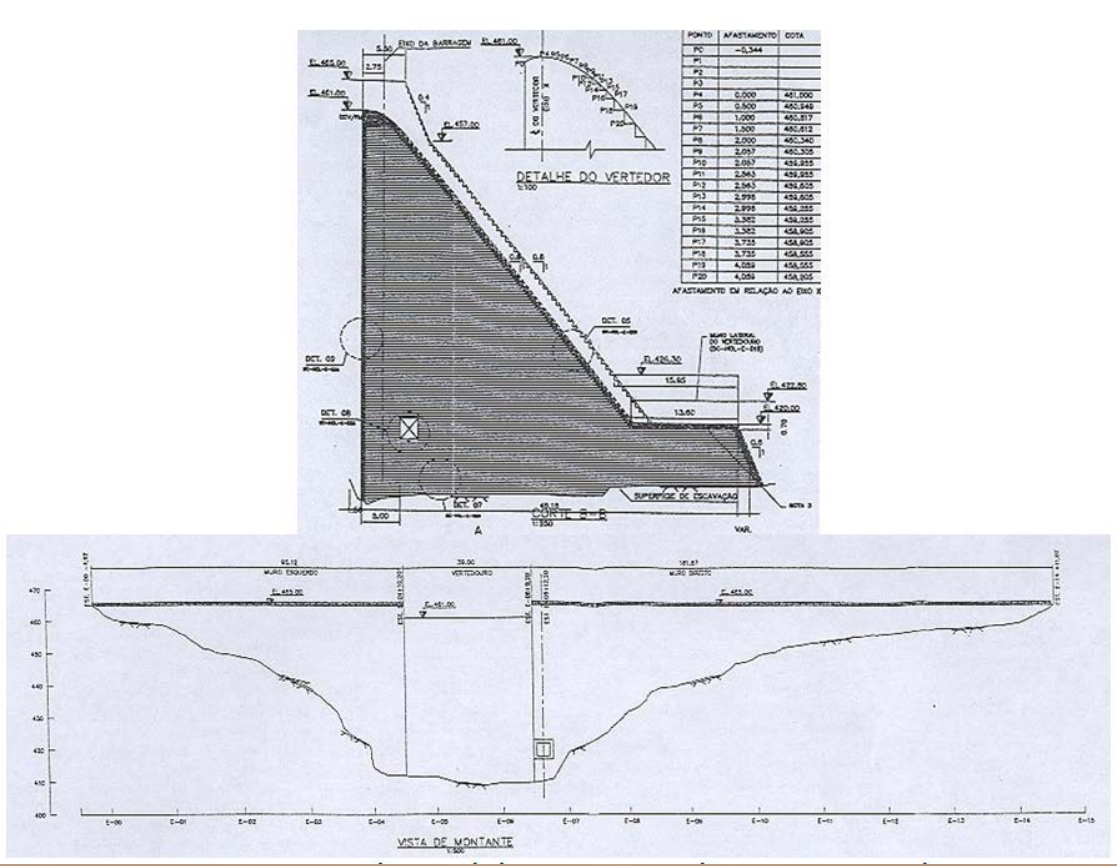
What's missing from this table?

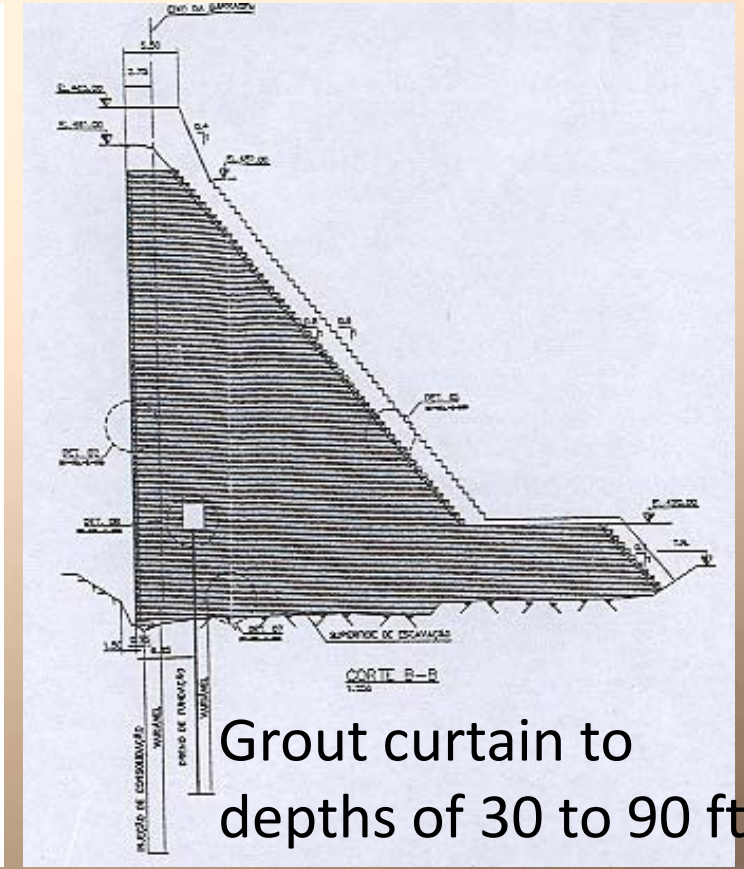
# Camara Dam, Brazil

- 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

Failed June 17, 2004

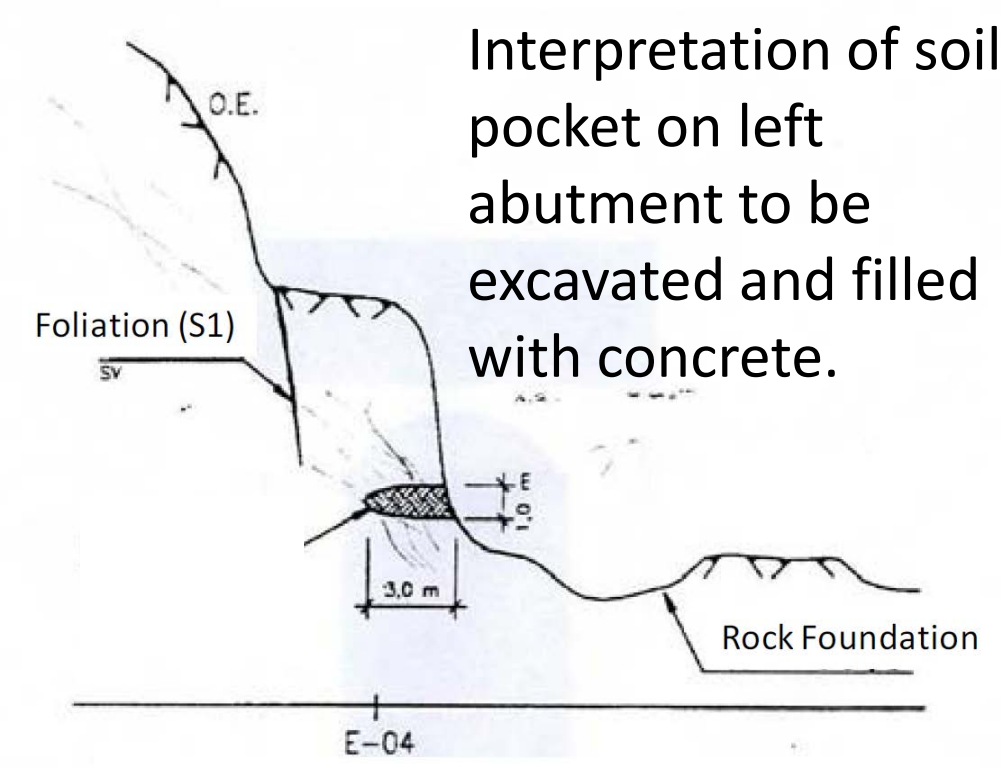
# Camara Dam, Brazil




Not shown, line of drain holes drilled downstream of grout curtain at 3.5m spacing to depths of 35 to 90 ft

# 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

Note that dam bridged over failure zone

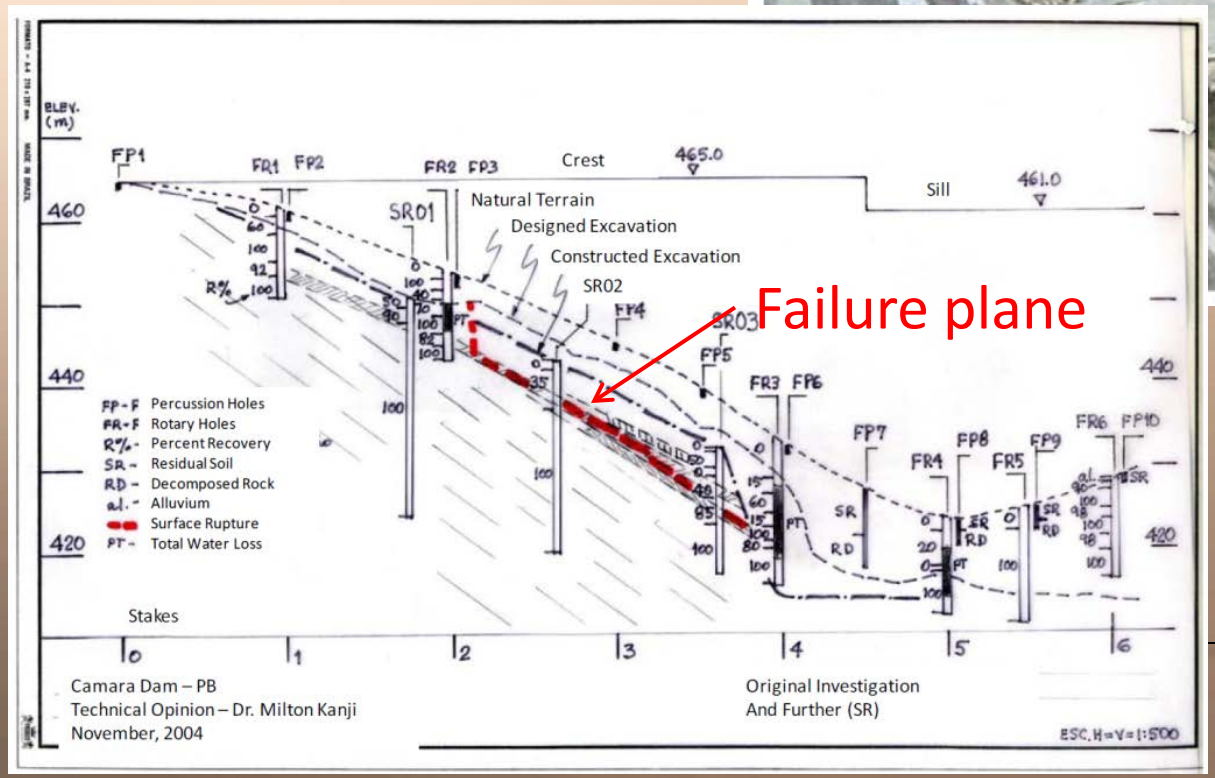
# Camara Dam, Brazil

Note small embedment and shear zone

Note possible disturbed rock blocks on lower left abutment during construction

# Camara Dam, Brazil

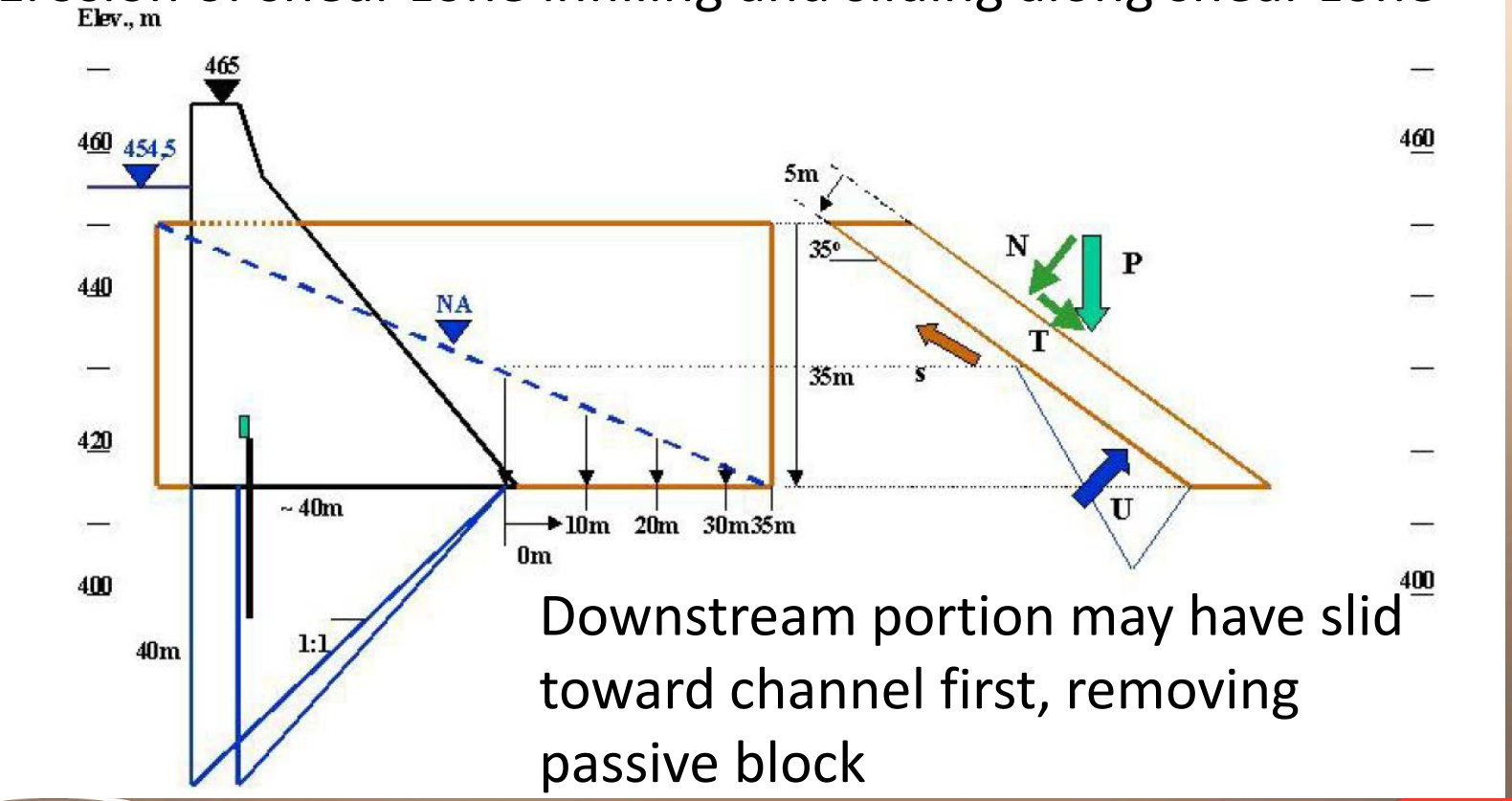
Arrow points to remnant of shear zone
Note unfractured footwall
Note direction of sliding toward channel




Profile developed post-failure

# Camara Dam, Brazil

- Flow along shear zone with limited drainage
- High uplift pressures extend downstream
- Erosion of shear zone infilling and sliding along shear zone

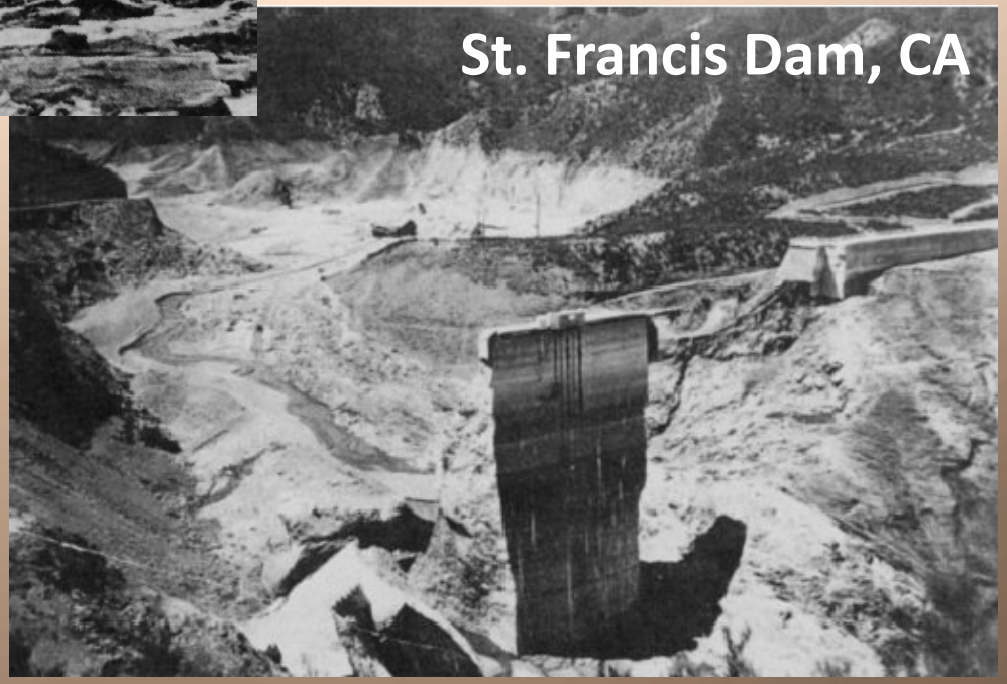



Downstream portion may have slid toward channel first, removing passive block

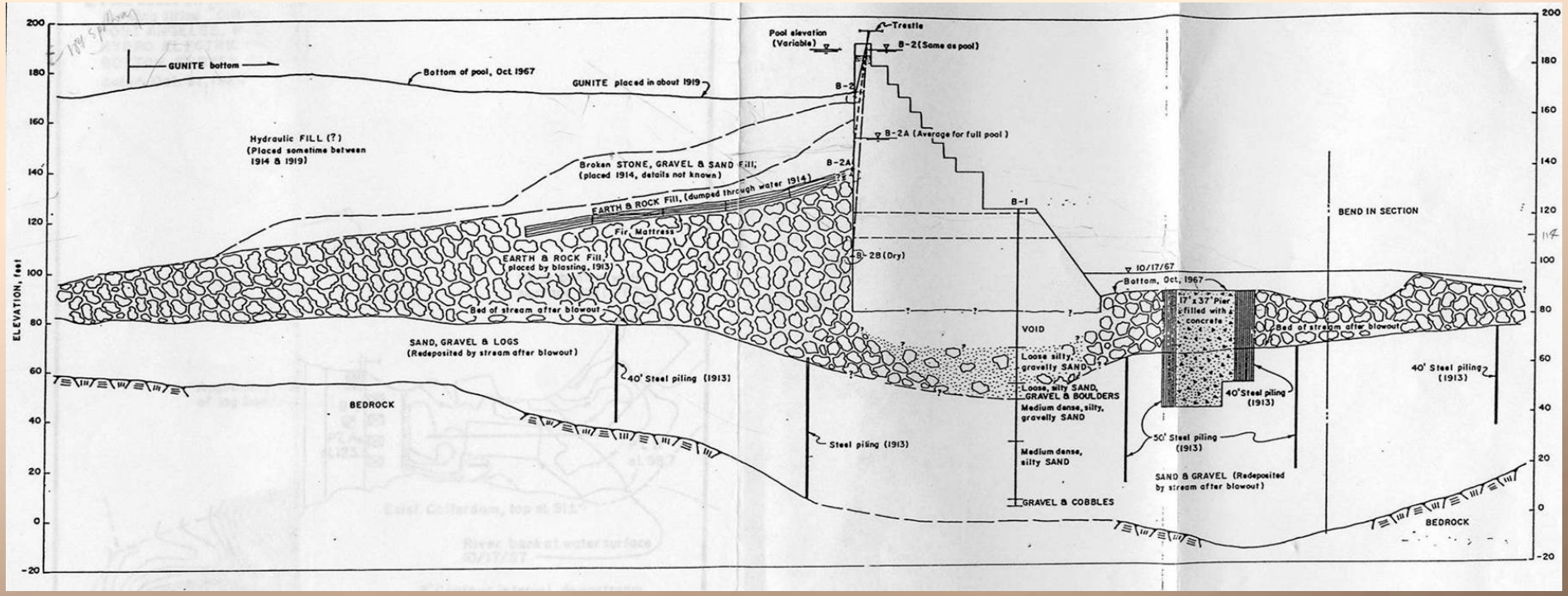
# Camara Dam, Brazil

- 5 deaths
- 800 homeless

# Other Notable Foundation Failures



# Elwha Dam, Washington




Note: Internal erosion of concrete dam foundations not covered here – see section on internal erosion

# Foundation Stability Analysis

Identify potential sliding failure modes

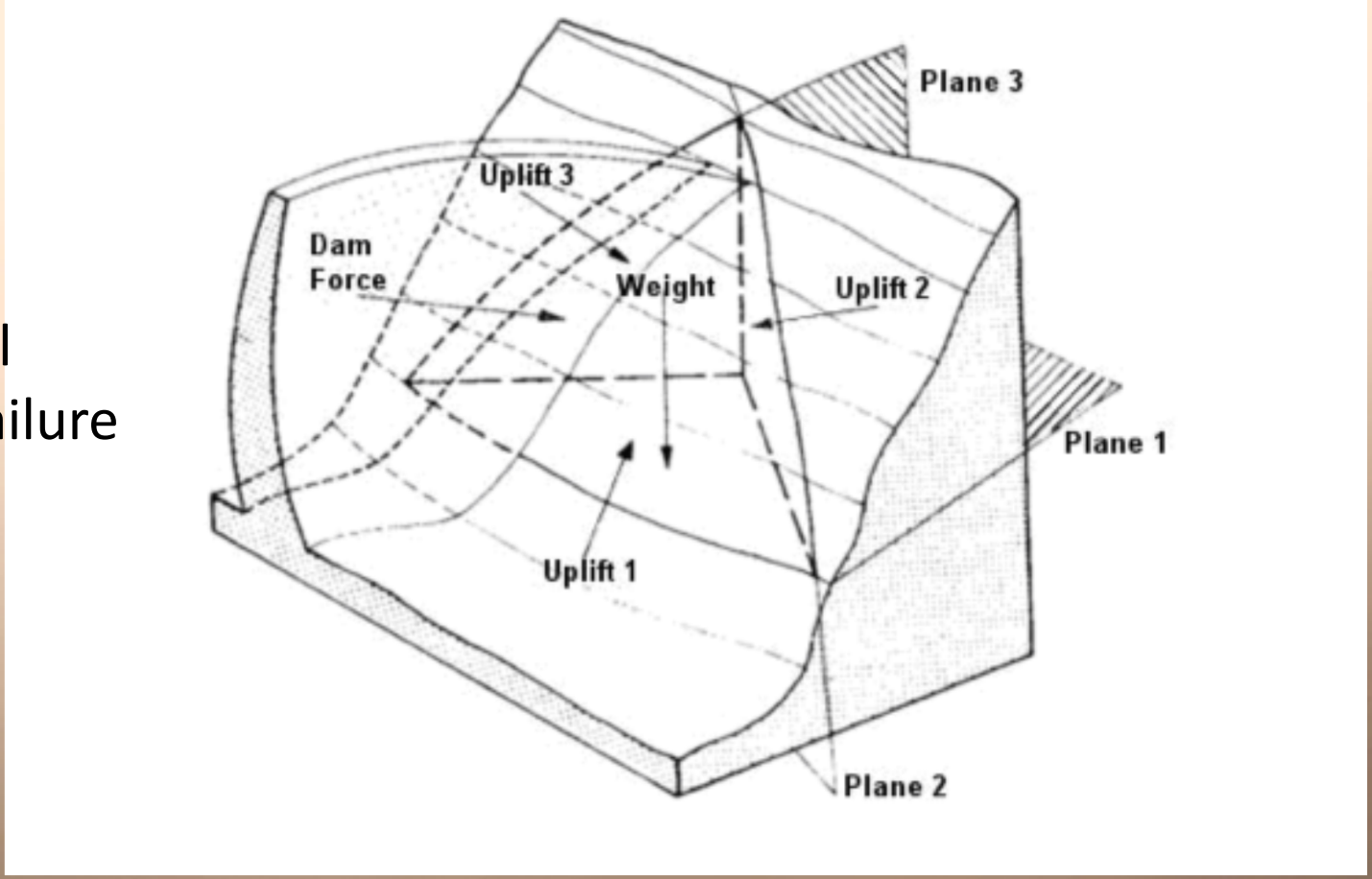



Figure 16. Rock Block within the Foundation of an Arch Dam. Plane 1, Plane 2, and Plane 3 are Discontinuity Planes; Uplift 1, Uplift 2, and Uplift 3 are Water Forces; W is the Block Weight; and Dam Force is the Thrust from the Dam (adapted from Londe [22]).

# Mapped Features

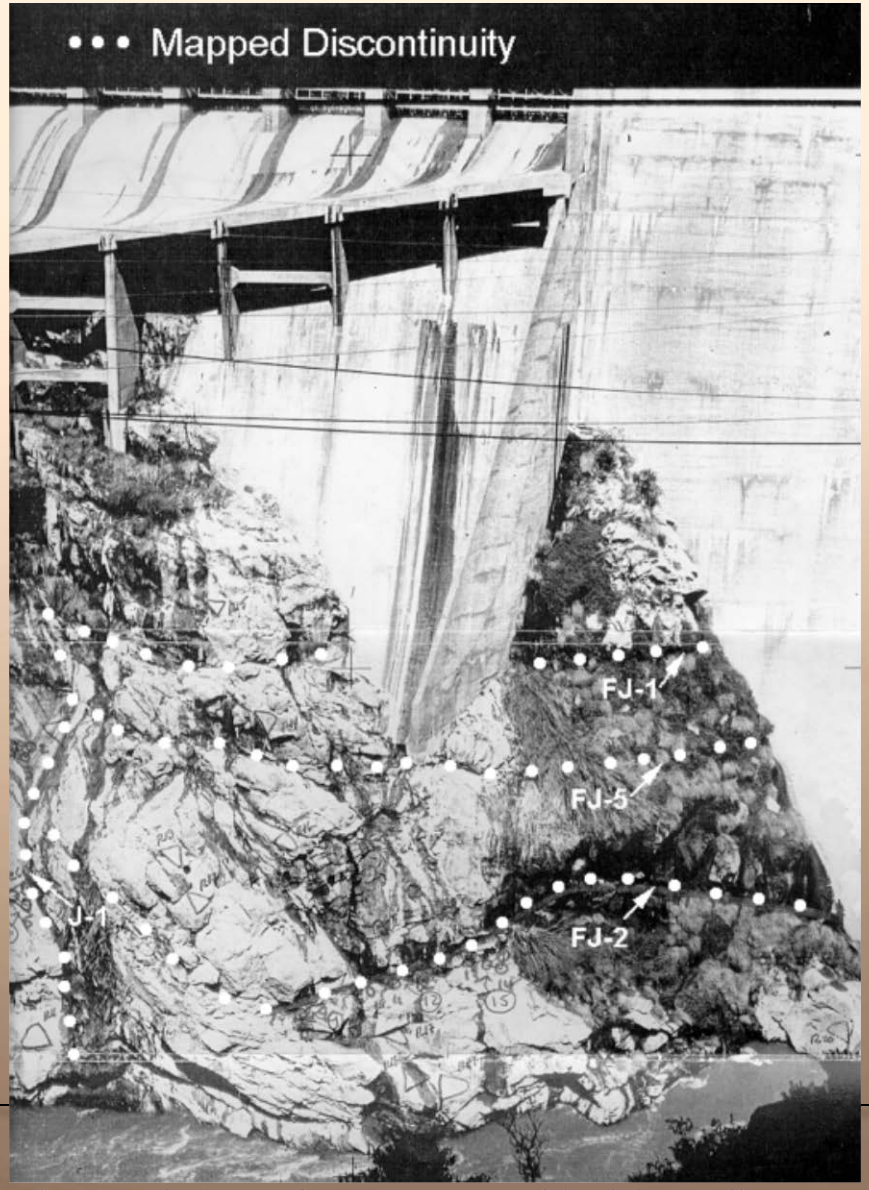
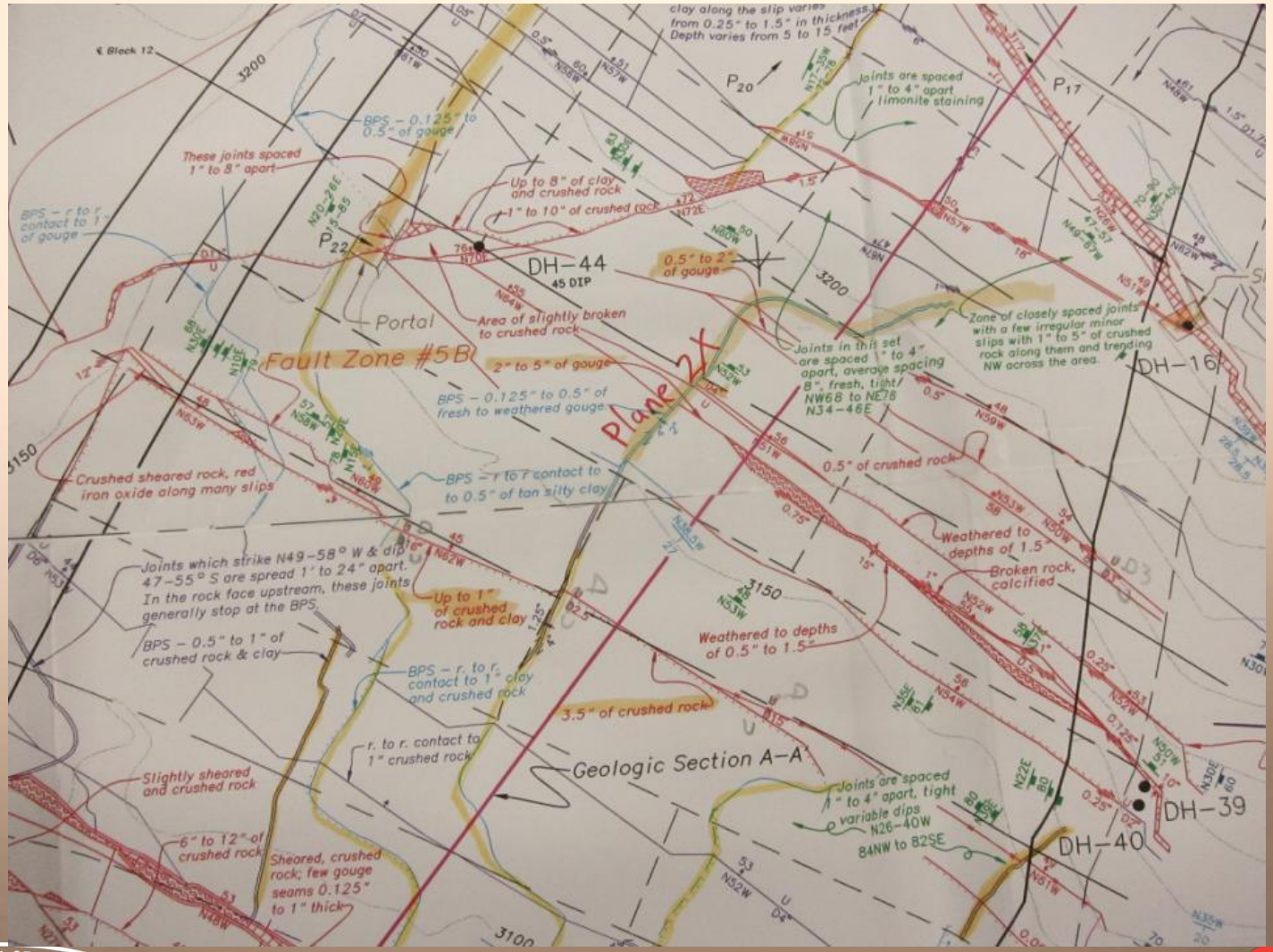
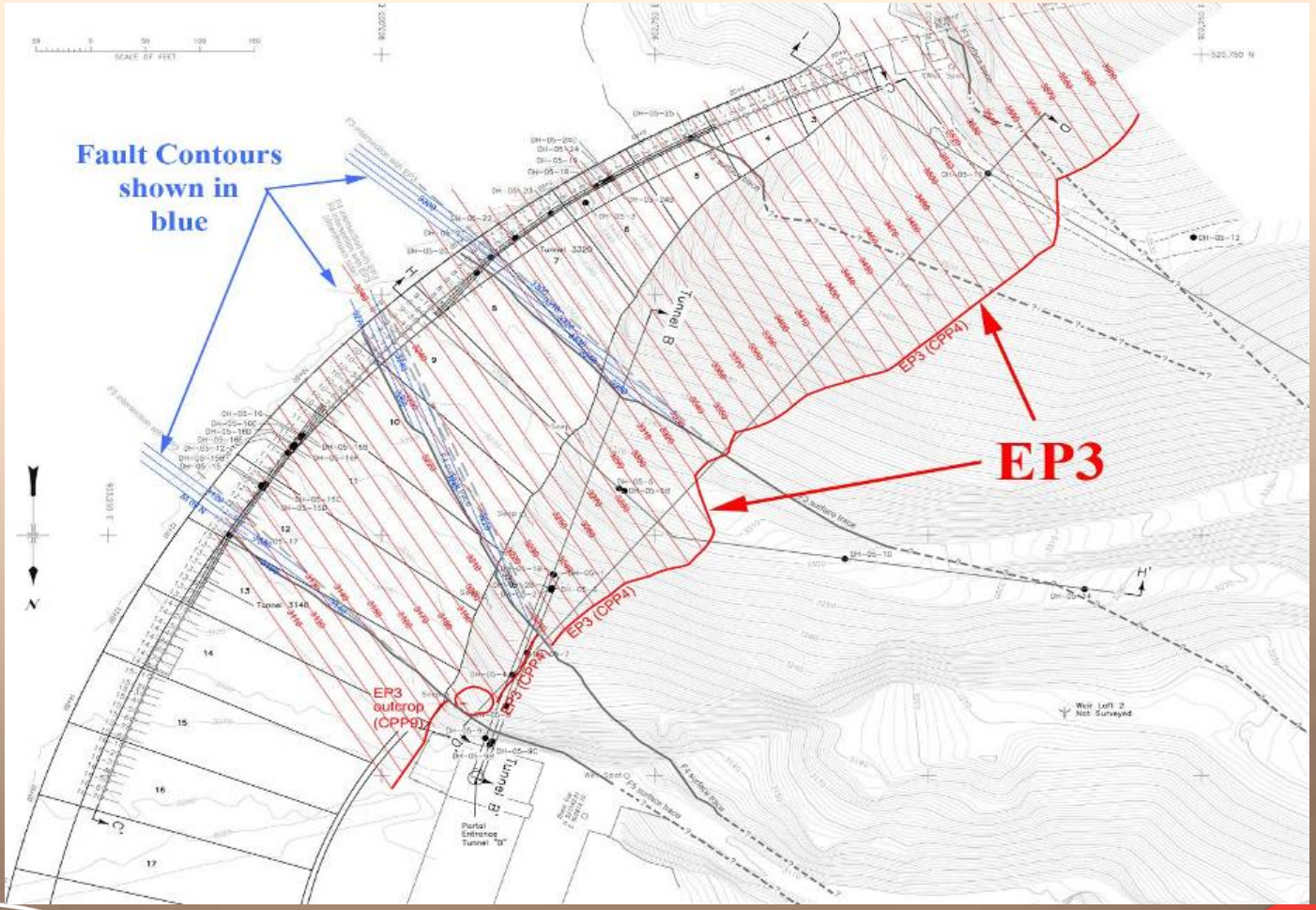


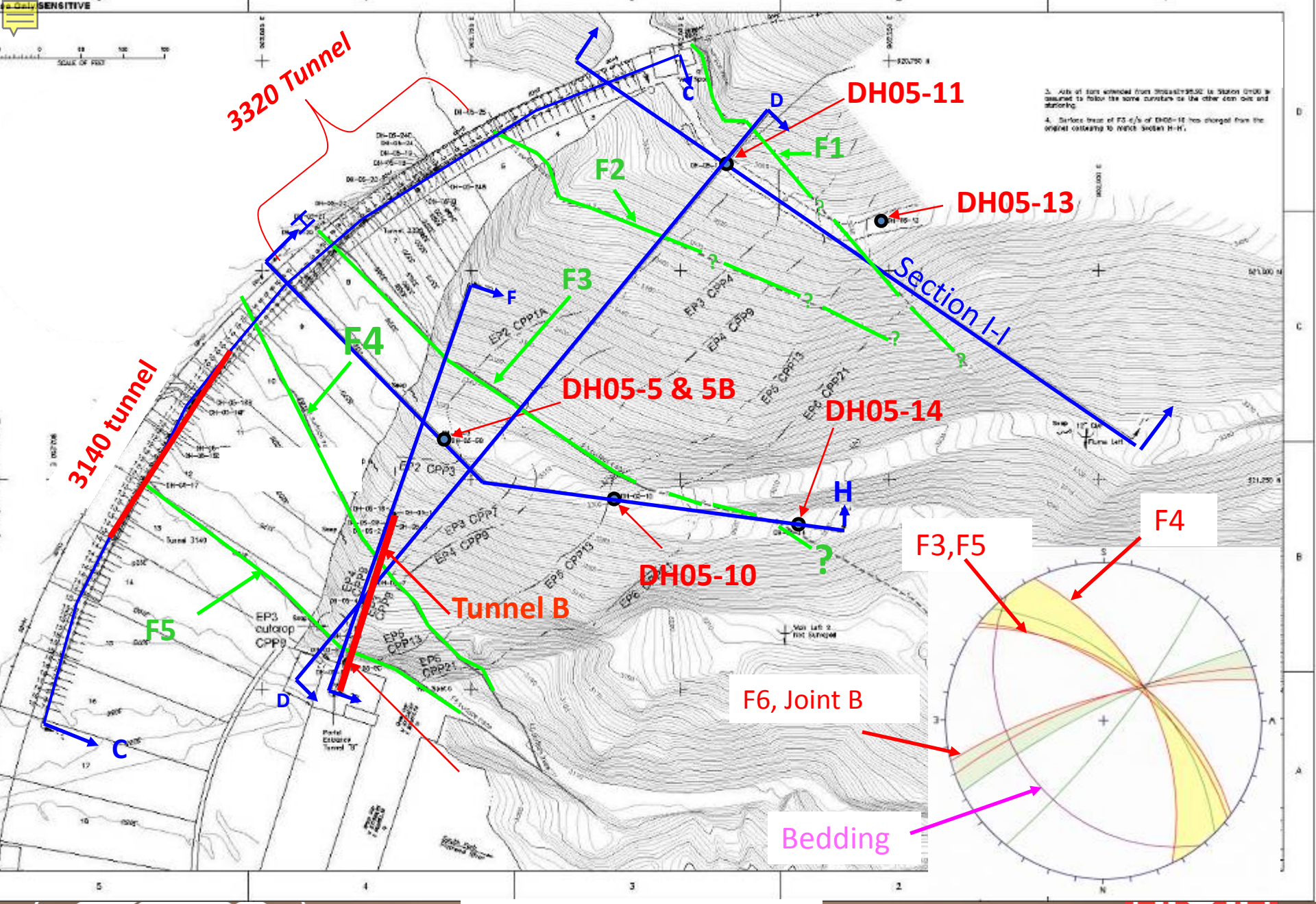

Figure 19. Right Abutment of Horse Mesa Dam. Foundation Blocks Formed by J-1 as a Side Plane and Either FJ-1, FJ-2, or FJ-5 as a Base Plane are Apparent.

# Review Existing Foundation Maps



# Structural Contours for Major Bedding Plane Partings and Faults






# Geologic Plan Map

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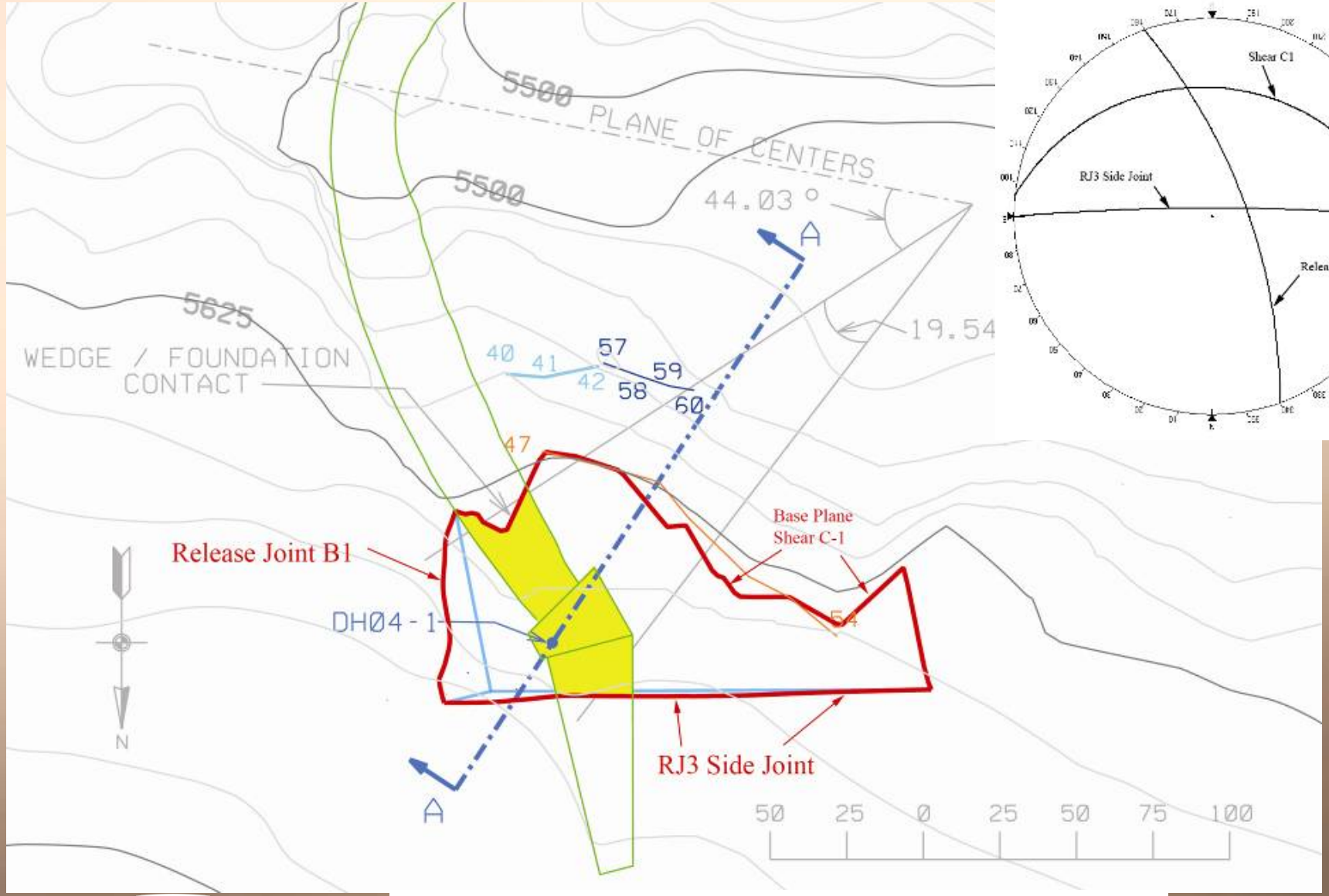
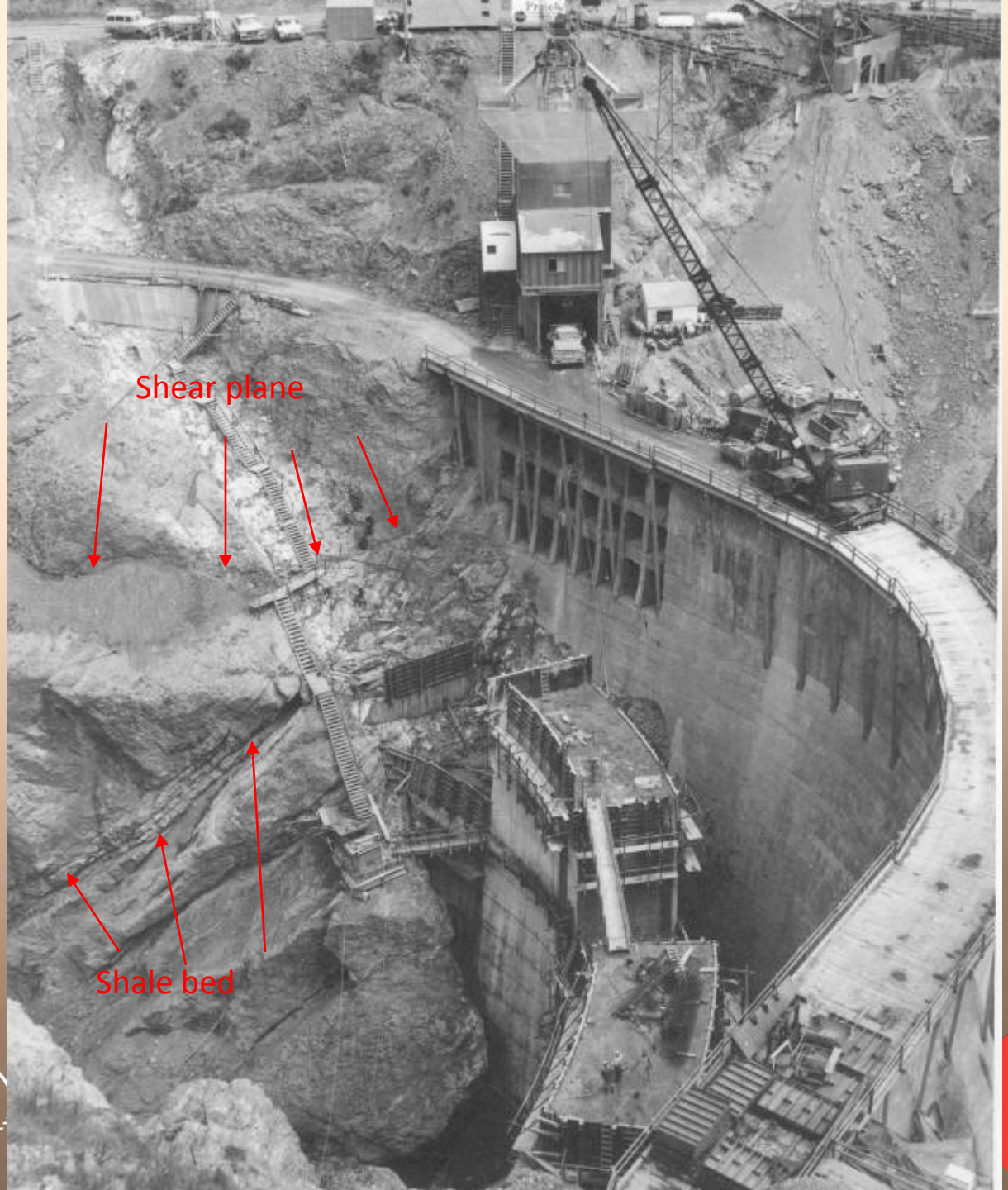
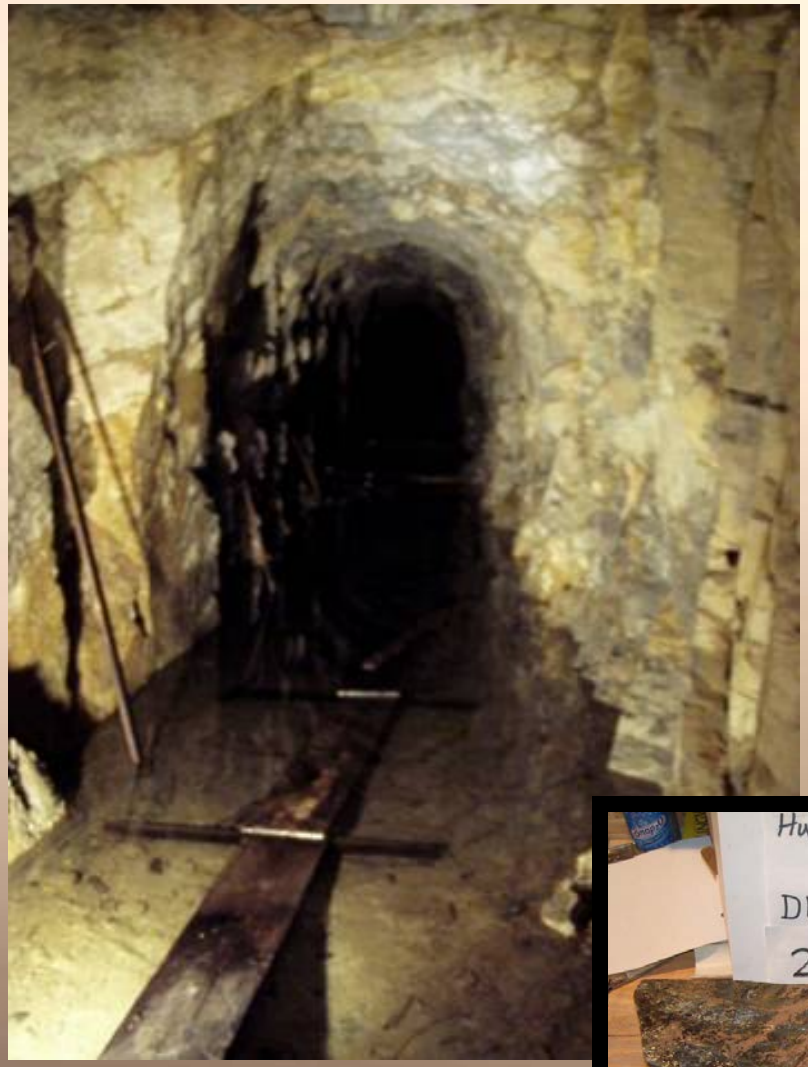



# Geologic Plan Map Showing Foundation Block

# Construction Photos


Shear plane
Shale bed

# TUNNEL B



# Jointing Must also be Considered

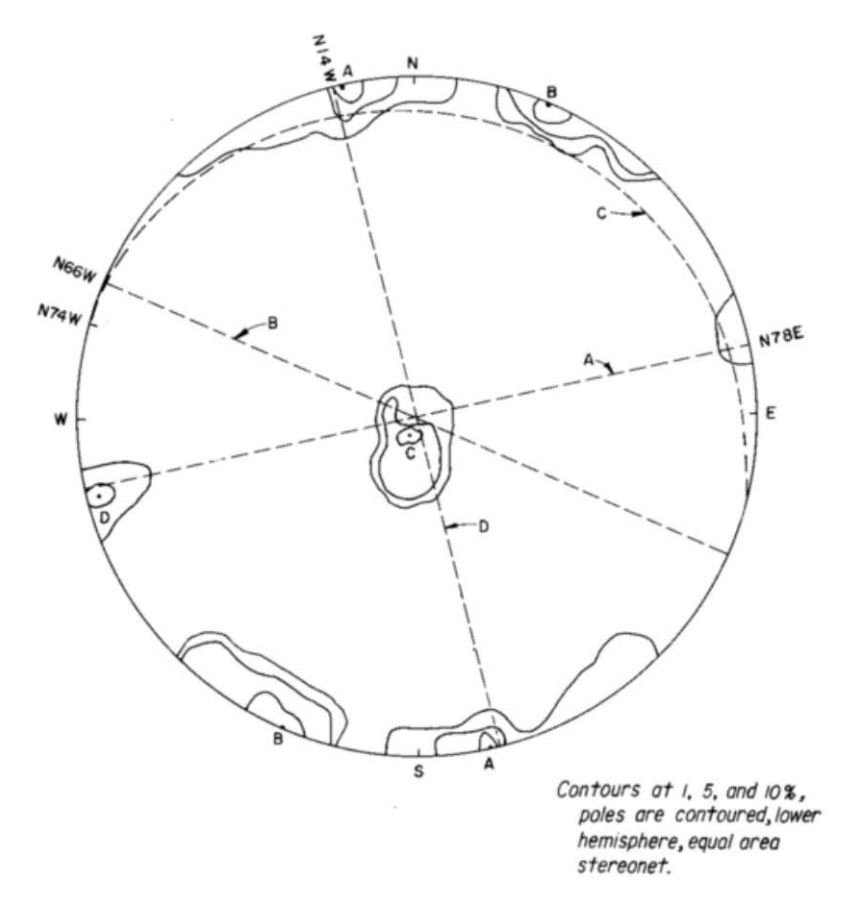



Figure 18. Joint Pole Contours on Stereographic Projection

Orientation, continuity, and other properties need to be considered

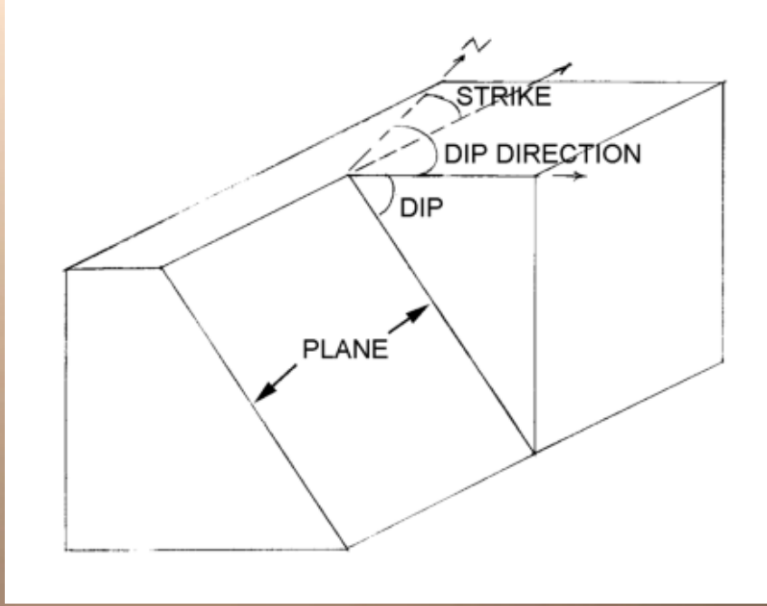
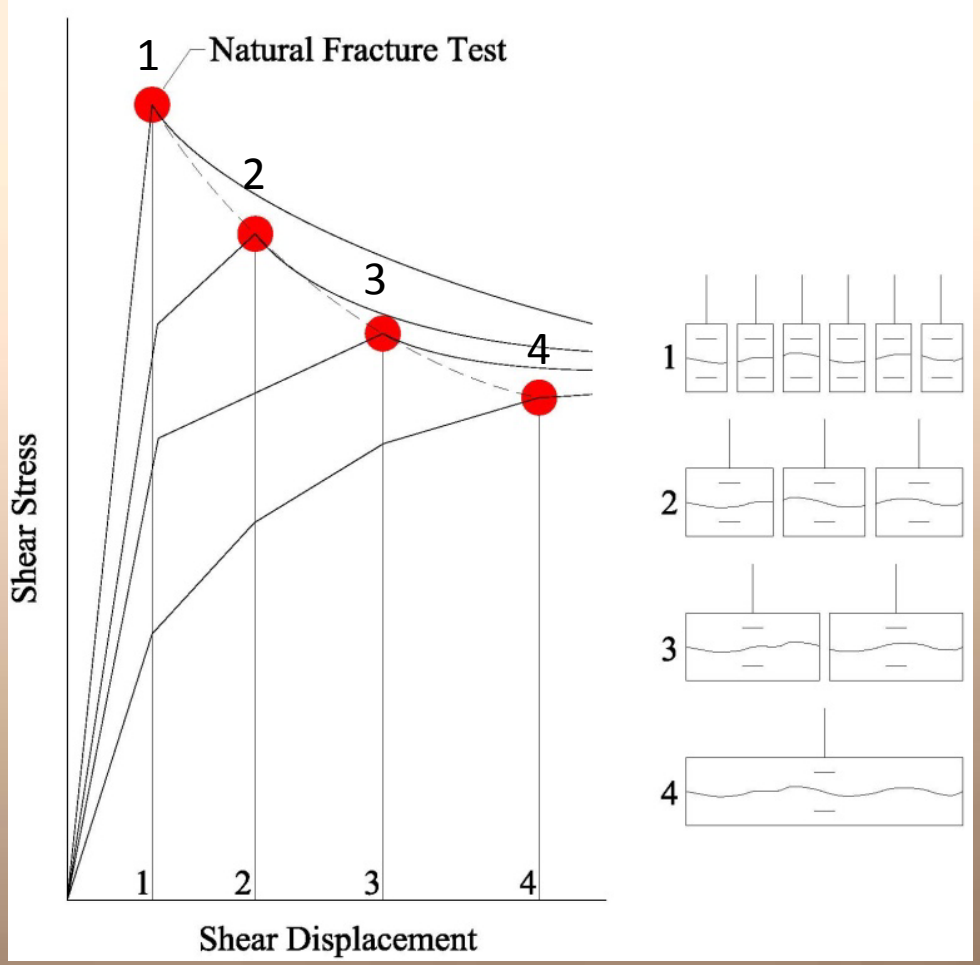



Figure 17. Definition of Strike, Dip, and Dip Direction

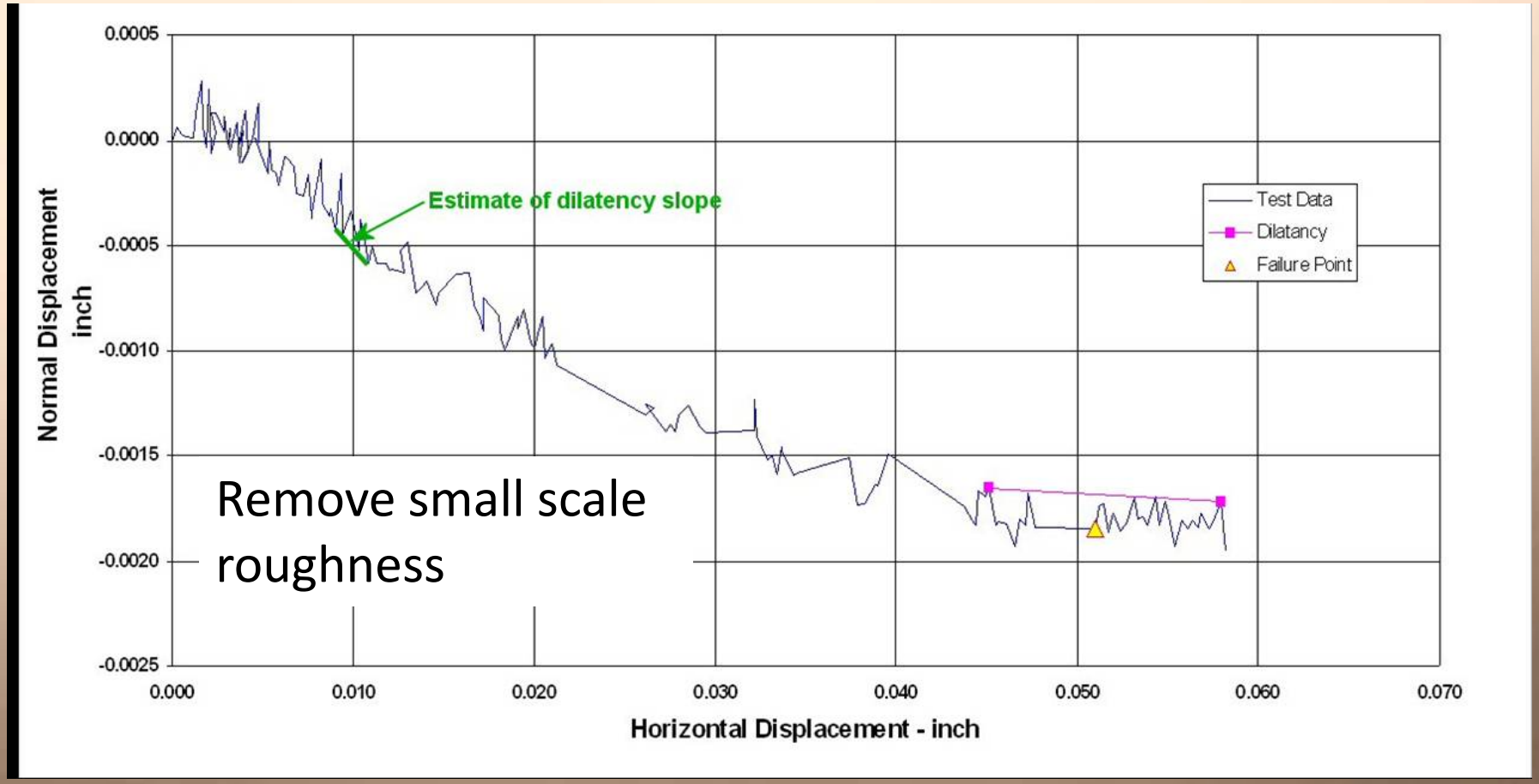
# Scale Effects




Adapted from Bandis et al (1983)

# Direct Shear Test

# Direct Shear Test

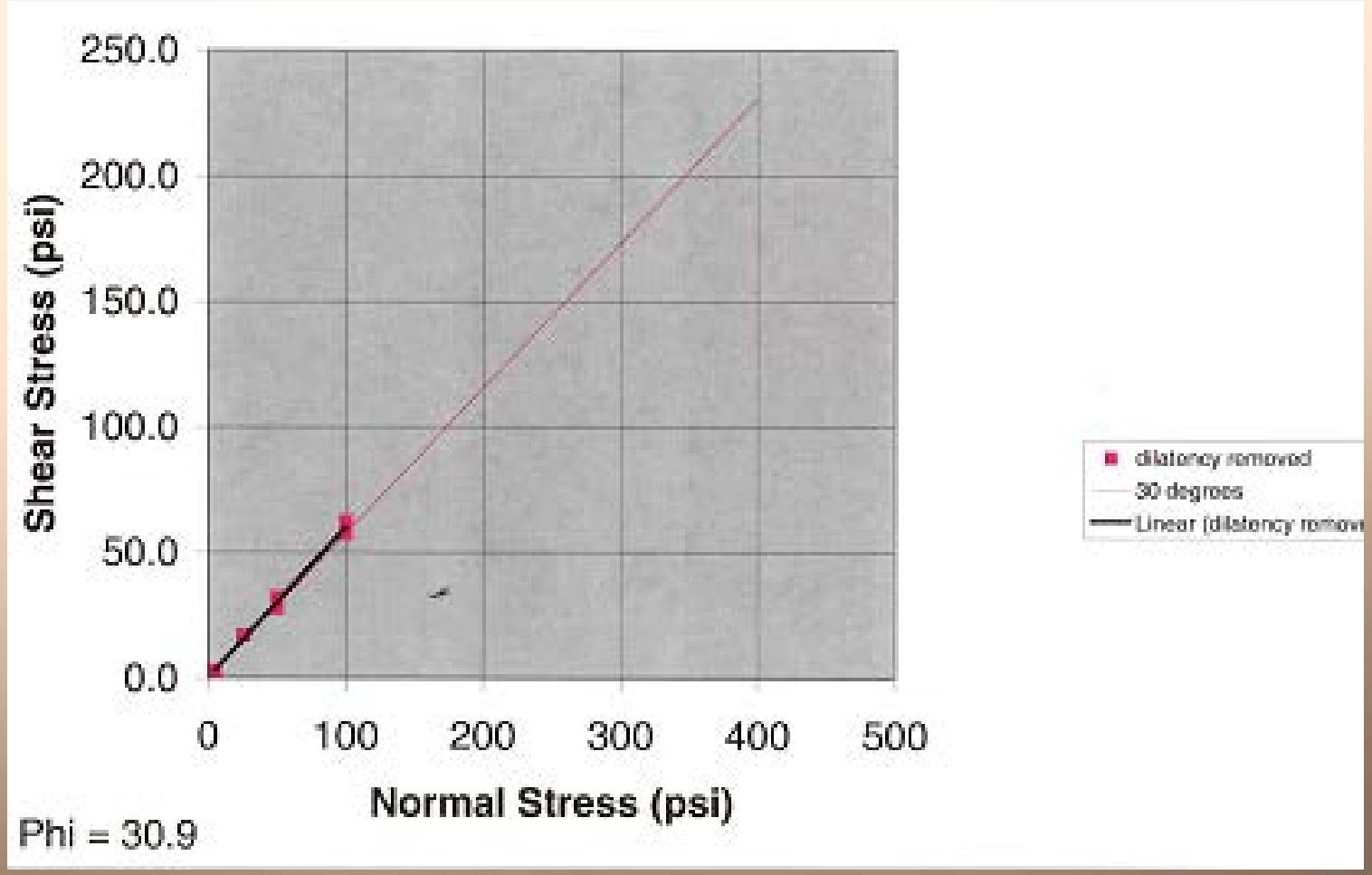


# Corrected Strength

$$\tau_{\phi+i} = \frac{\tan\phi + \tan i}{1 - \tan\phi * \tan i} * \sigma$$

**Solve for σ*tanφ (iteratively), increase strength for contracting plane, decrease for dilating plane**

# Results, Scatter Reduced

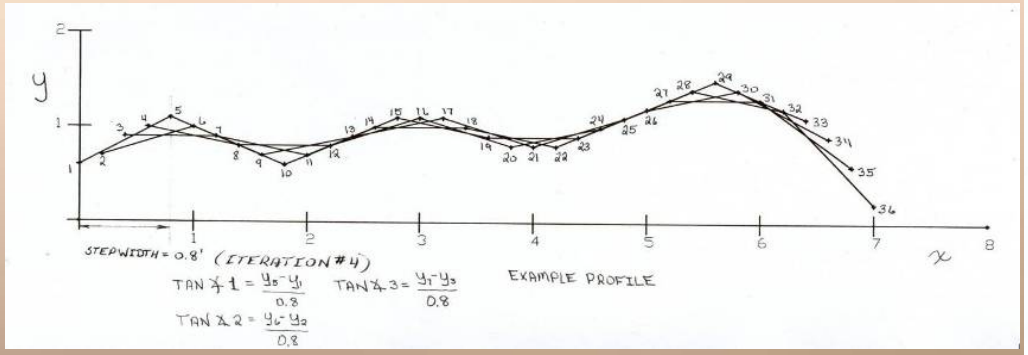


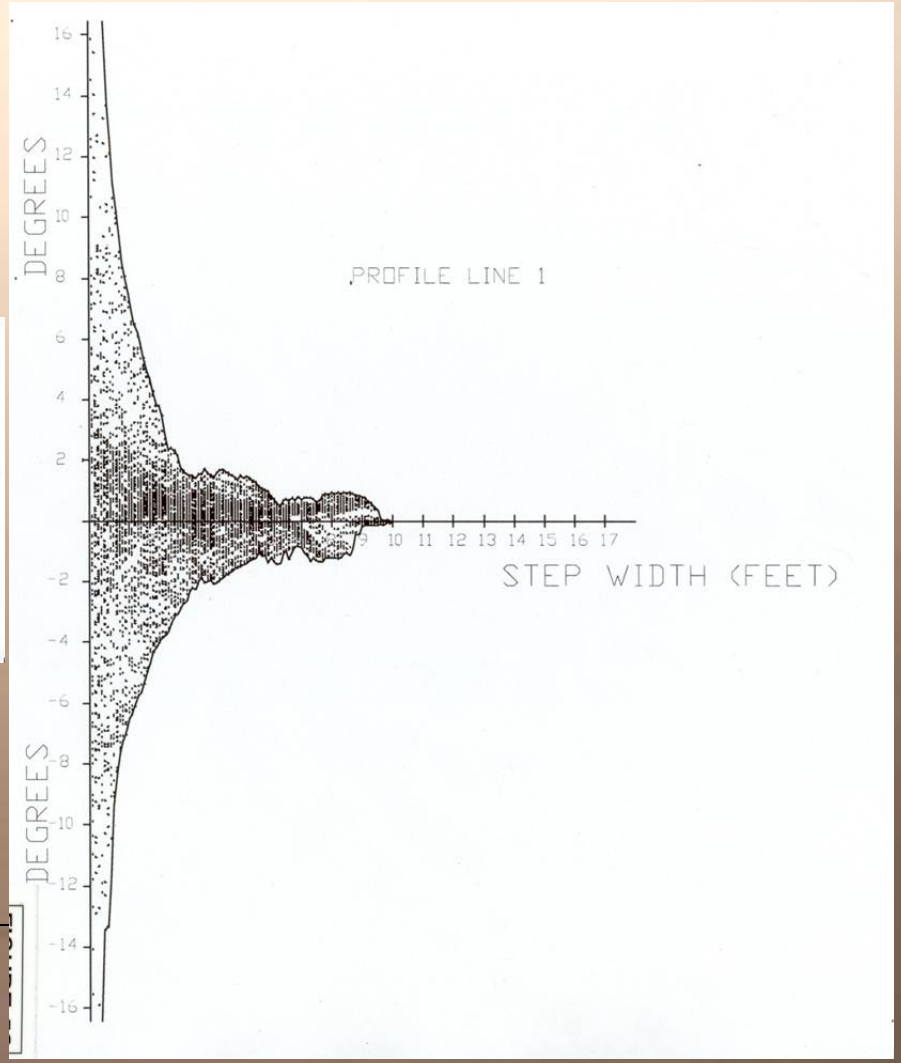

Careful of tests on saw cuts

# Large Scale Roughness

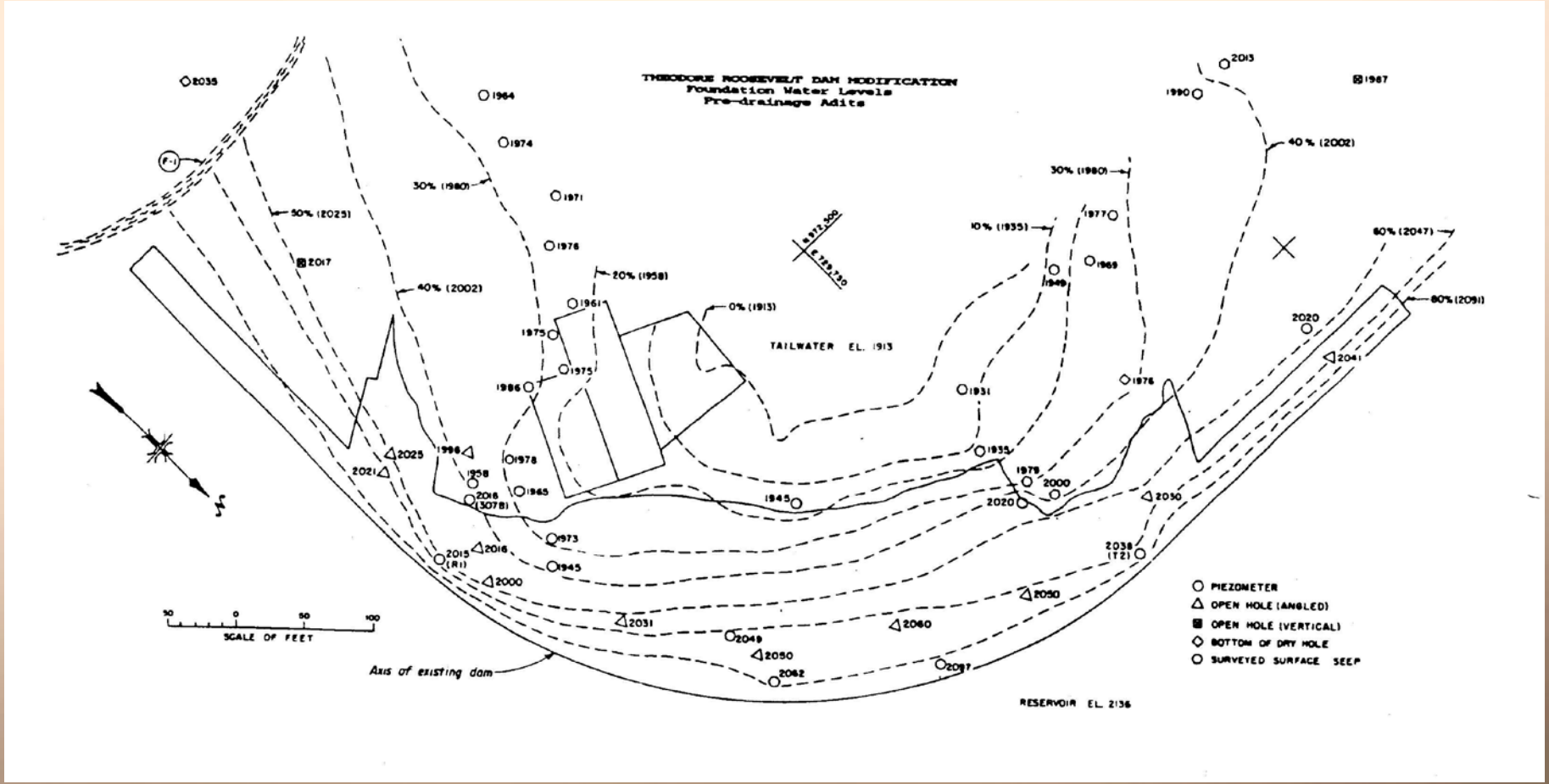
# Renger's Analysis

- Roughness angle = 5° at a step width of 1% of the sliding plane length



# Foundation Water Pressures




$$DHR = \frac{PiezometricEl - TailwaterEl}{ReservoirEl - TailwaterEl}$$

Used to estimate @ other RWS Elevations

# Effects of Foundation Drains

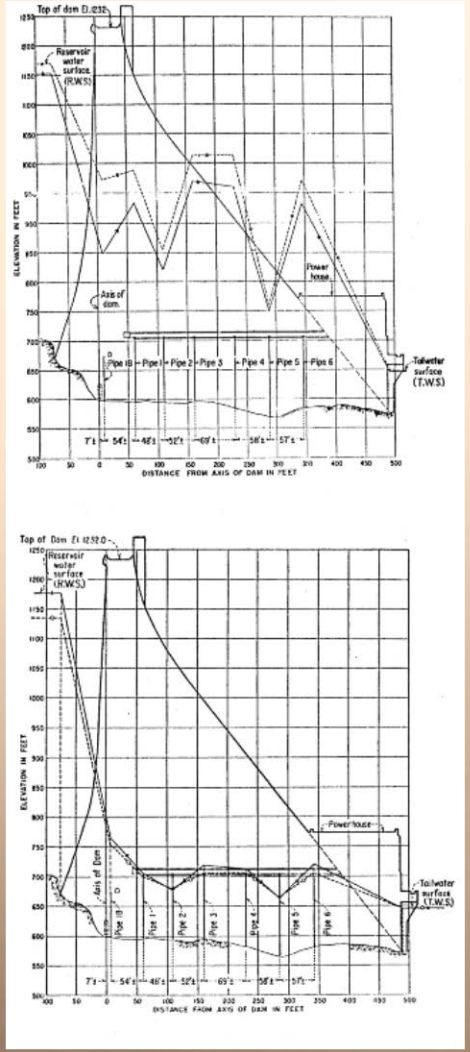



Figure C3. Uplift Measurements at Hoover Dam.
Note: 1 ft = 0.3048 m.

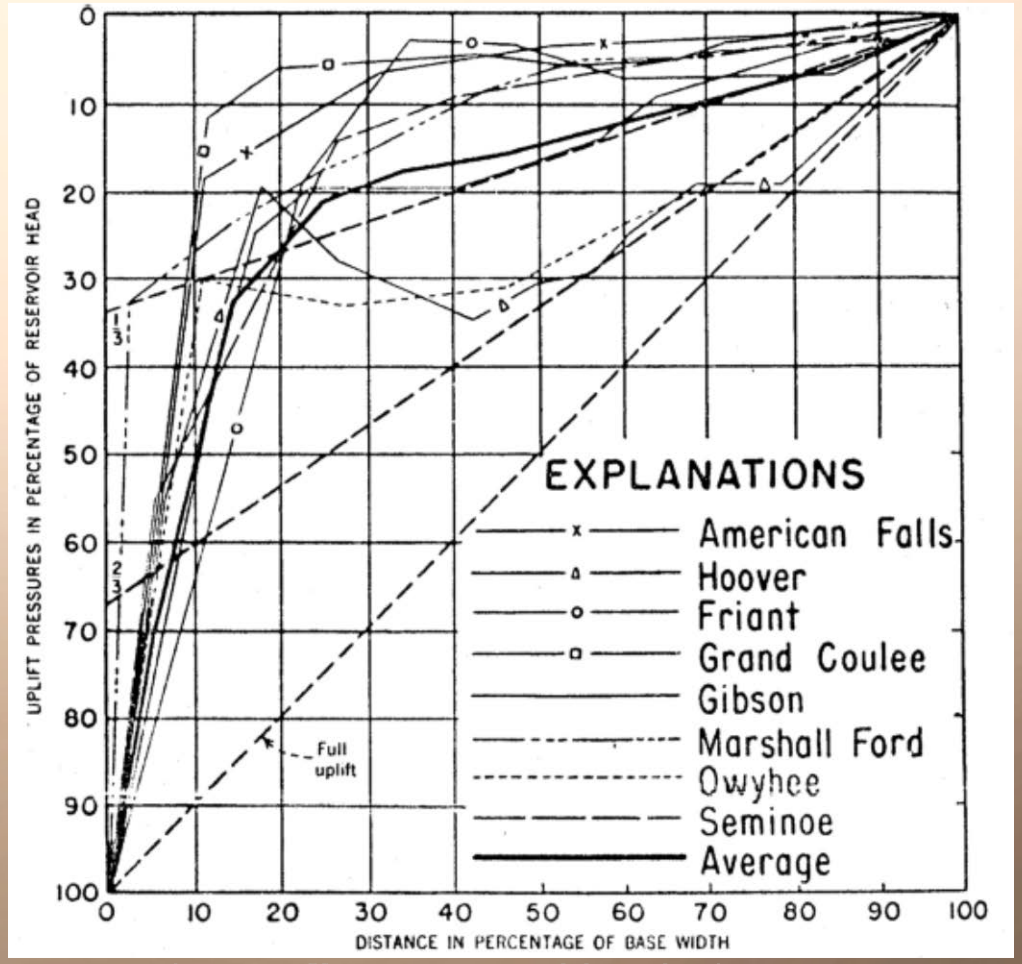
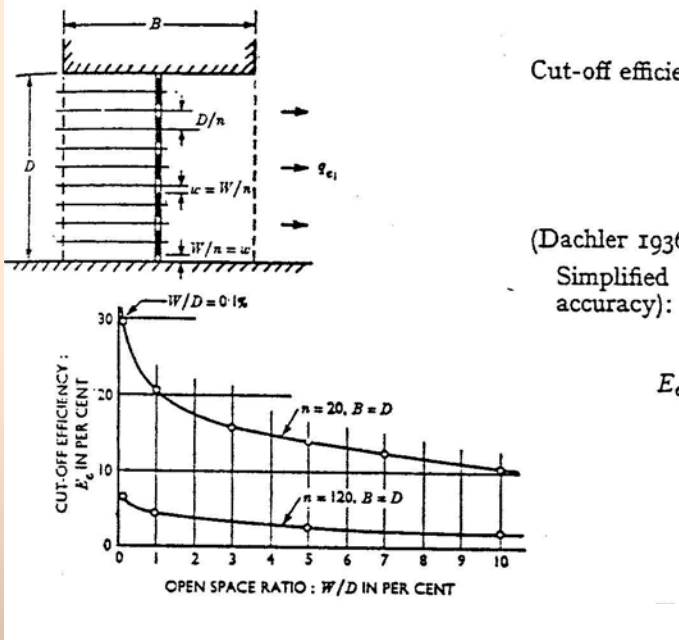



Figure C2. Uplift Measurements Recorded at Reclamation Concrete Dams

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

# Grout Curtain Effectiveness

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



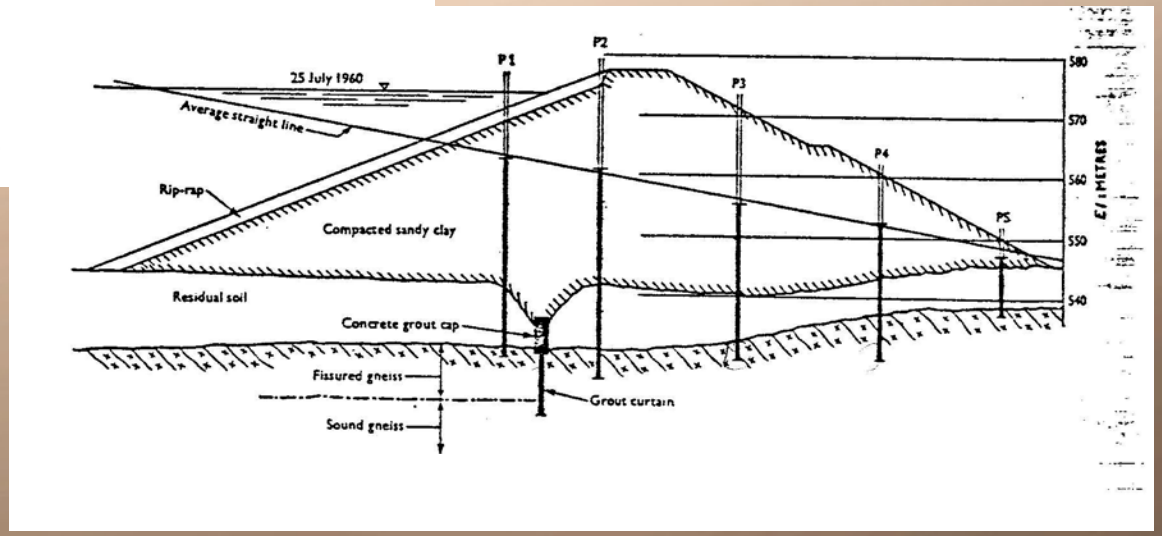

Cut-off efficiency $E_c = \frac{q - q_c}{q}$

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

(Dachler 1936)

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

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




If counting on grout curtain cutoff, must verify with measurements

Arthur Casagrande

1st Rankine Lecture

# Water Forces on Block Planes

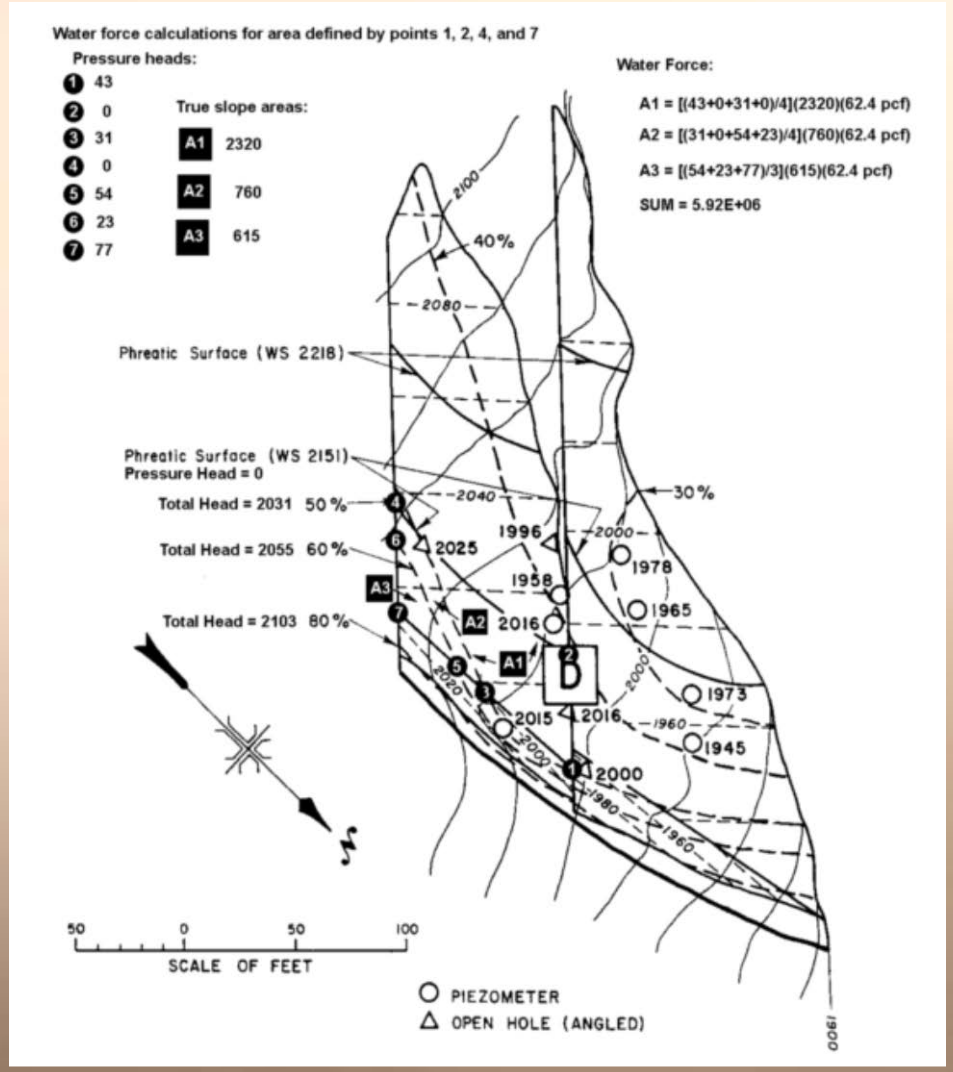



Figure 23. Example Water Force Calculation. Note: 1 ft = 0.3048 m, 1pcf = 16 kg/m³, 1 lb = 4.45 N

- 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 Loads and Inertia Loads

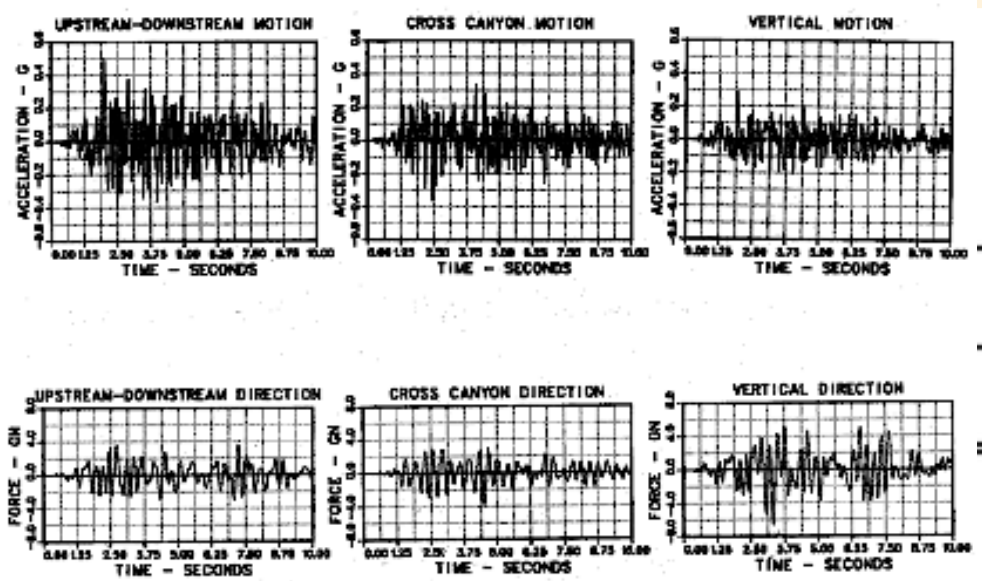



Figure 20. Time-Varying Ground Accelerations and Dynamic Dam Loads Acting on Foundation Block. Note: 1 GN = 2.25E+0 Kip.

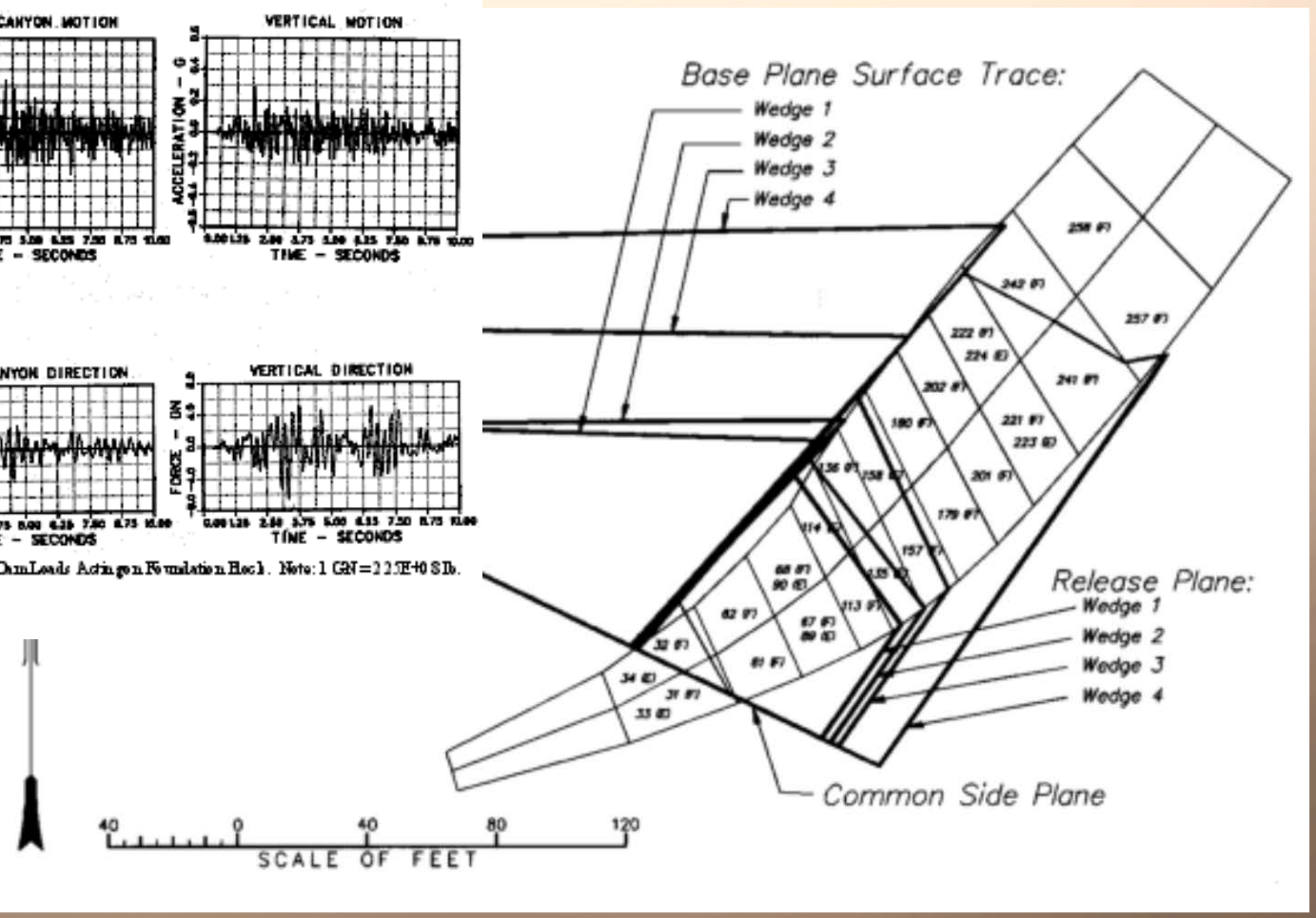



Figure 21. Finite Element Mesh Footprint Shown in Relationship to Foundation Blocks Identified at Morrow Point Dam. Note: 1 ft = 0.3048 m.

For uncoupled analyses

Include static loads

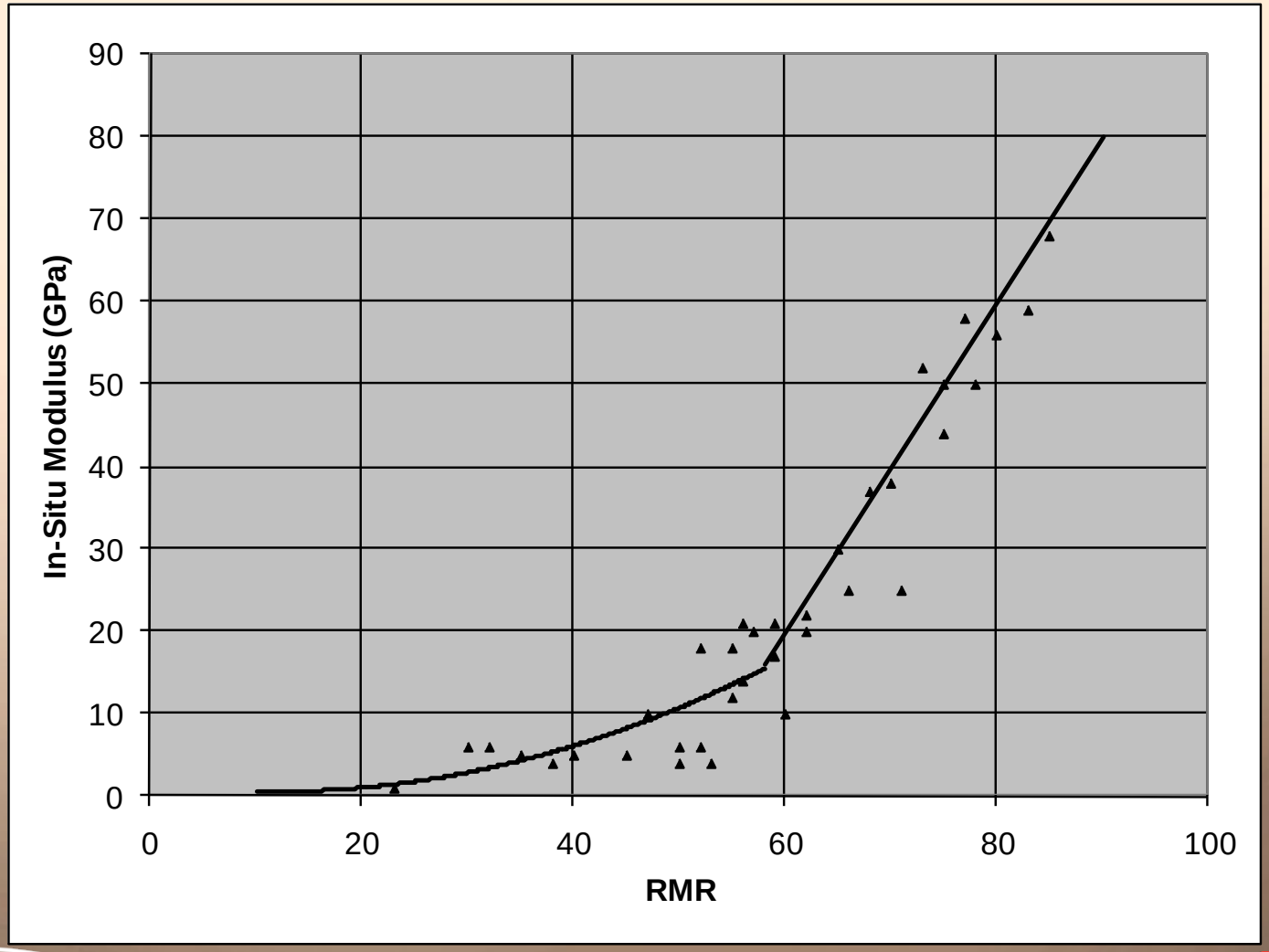
# Rock Mass Modulus

- Can be critical to calculating dam loading
- Is not the laboratory modulus (intact material)
- Is not the geophysical modulus (typically strain “rate” is too fast, strain is too low)
- Is affected by joints and discontinuities

Can use:

- Empirical methods based on correlation of index properties to in situ test results
- Methods based on joint stiffness, joint spacing, and intact rock modulus
- In situ testing using calibrated geophysics and/or jacking tests
- Back calculations to match observed response (e.g. matching natural frequencies measured by in situ forced vibration tests to those calculated by finite element methods)

# Empirical Methods - RMR




Correlations with in-situ jacking tests after Bieniawski

# Example RMR Calculation

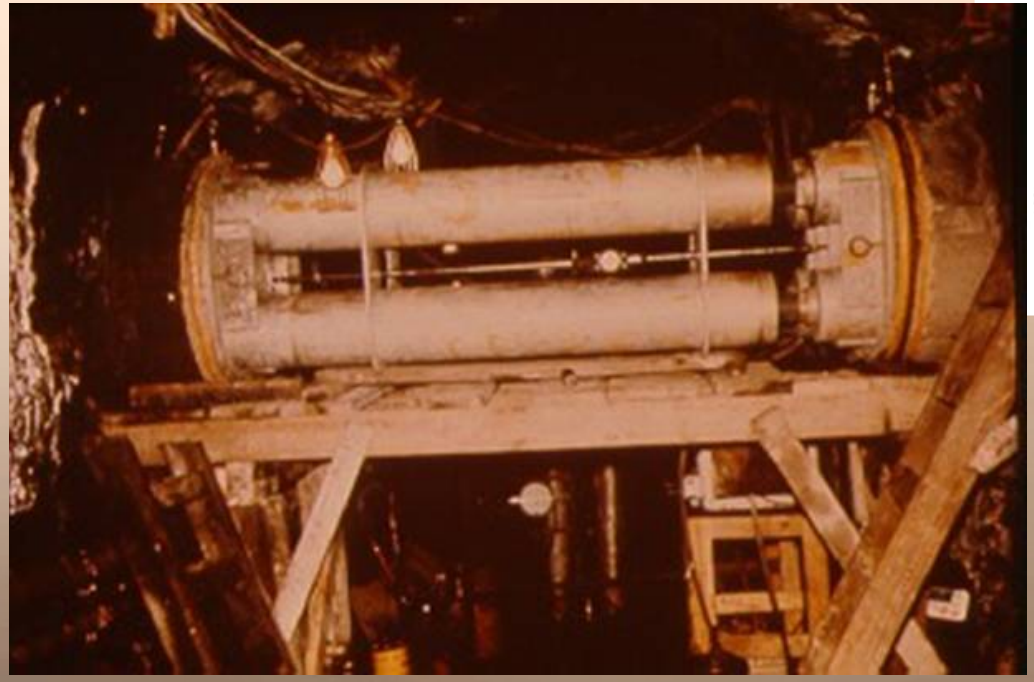
| Parameter | Field Description | Numerical Rating |
|---|---|---|
| Rock Strength | 170 MPa | 13 |
| RQD | 60 | 12 |
| Joint Spacing | Average about 0.5 m | 11 |
| Joint Condition | Slightly weathered, slightly rough, some continuous, some open | 20 |
| Water Conditions | Wet | 7 |
| Orientation Adjustment | Fair (for foundations) | -7 |
| Total | | 56 |
| Modulus, $E = 10^{(56-10)/40} = 14.1$ GPa $= 2.05 \times 10^6$ lb/in$^2$ | | |

Water and Orientation often assumed to cancel

Plots on lower curved portion of correlation

# In Situ Jacking Tests

Equipment and expertise?



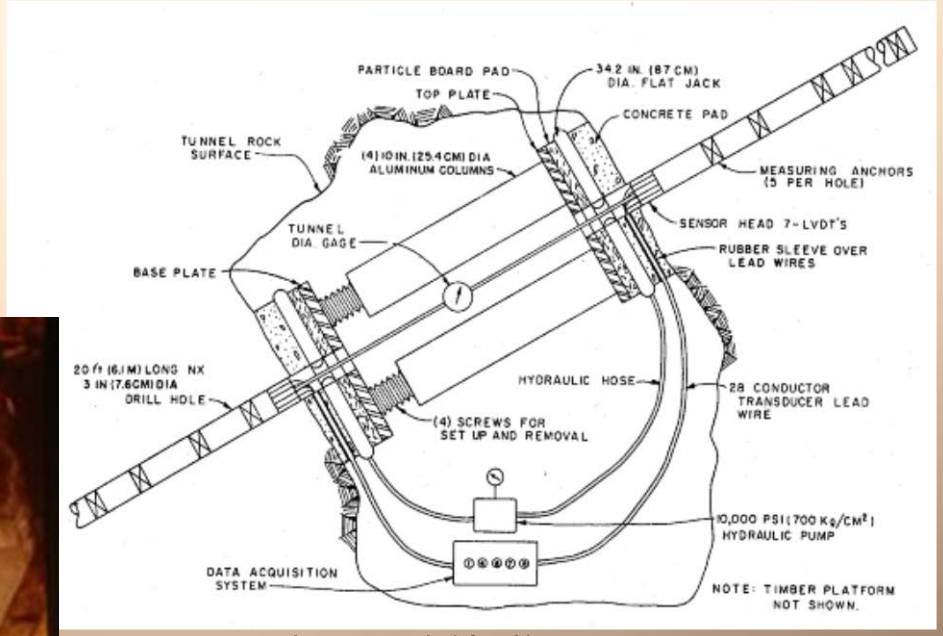



Figure A1. Uniaxial Jacking Test Setup

# Seismic Tomography

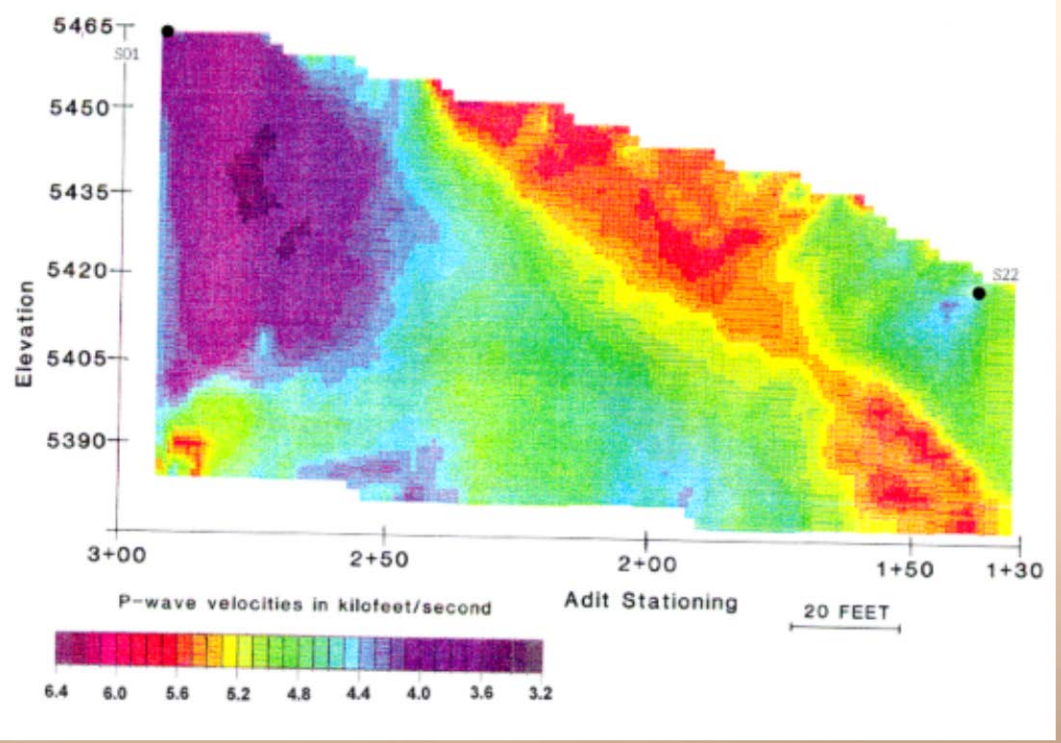



Figure A3. Seismic Velocity Tomogram Developed between Ground Surface and Adit. Note: 1000 ft/s = 305 m/s.

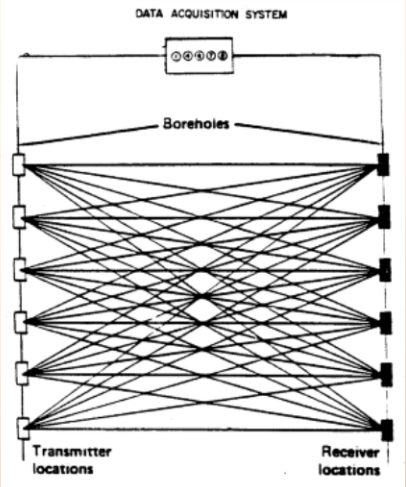



Figure A2. Seismic Tomography Ray Paths

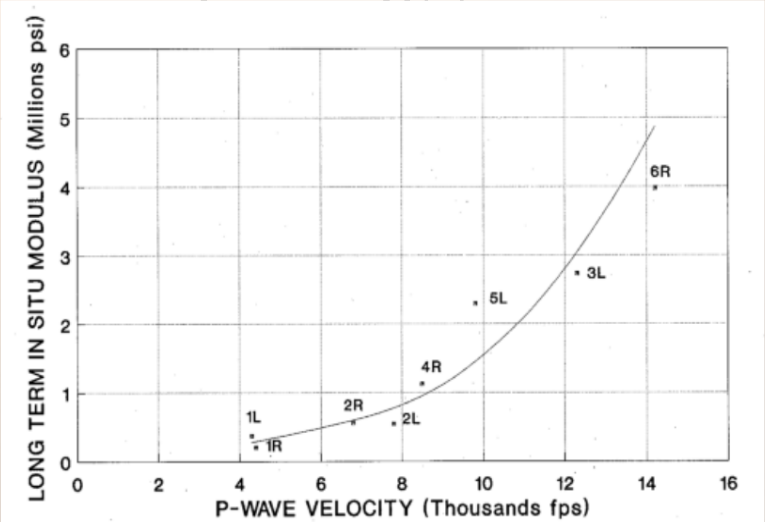


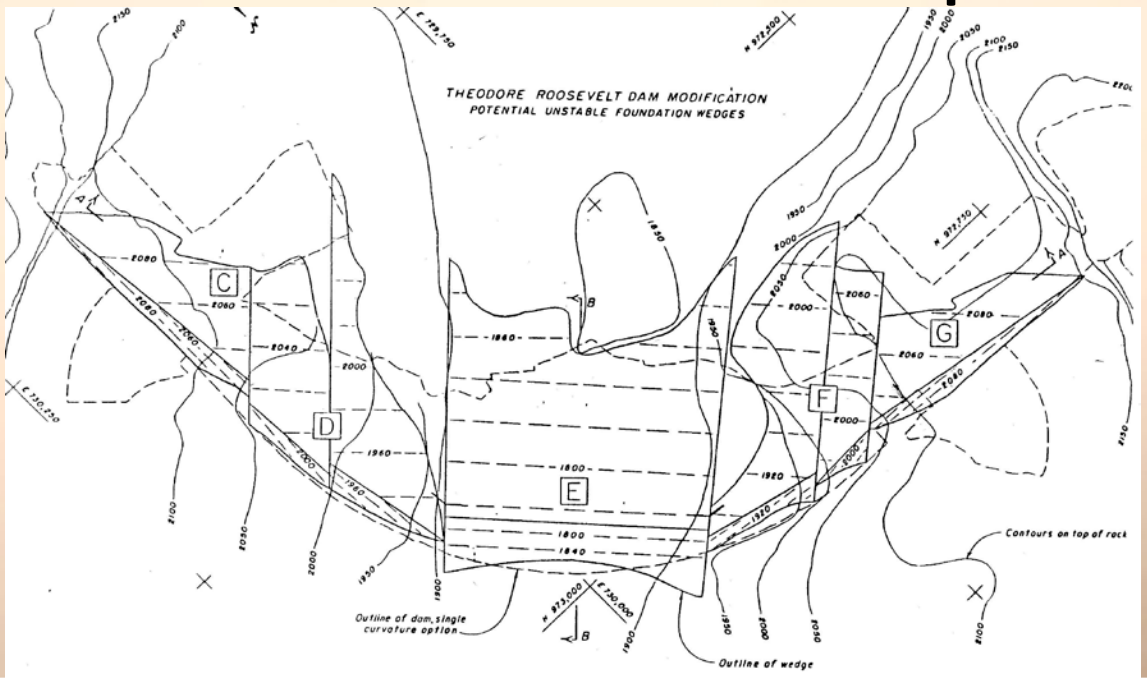

Figure A4. Correlation between Seismic Velocity and Modulus for Calibrating Tomogram. Note: 1000 fps = 305 m/s, 1,000,000 psi = 6.90 GPa.

Correlated with jacking tests

# Effect of Grouting on Modulus

- Not much!
- 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
- Point to point contacts along jointing may control the deformation of the rock before and after grouting
- Starting with thinner grout mixes may result in a relatively deformable grout

# Is Foundation Modulus Important?




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

# Dynamic Considerations

- Too small of a foundation modulus can over-dampen the system calculations (i.e. low value is <u>not</u> conservative)
- Alpha greater than 0.8 can over-dampen the system
- Calibration to shaking tests desirable

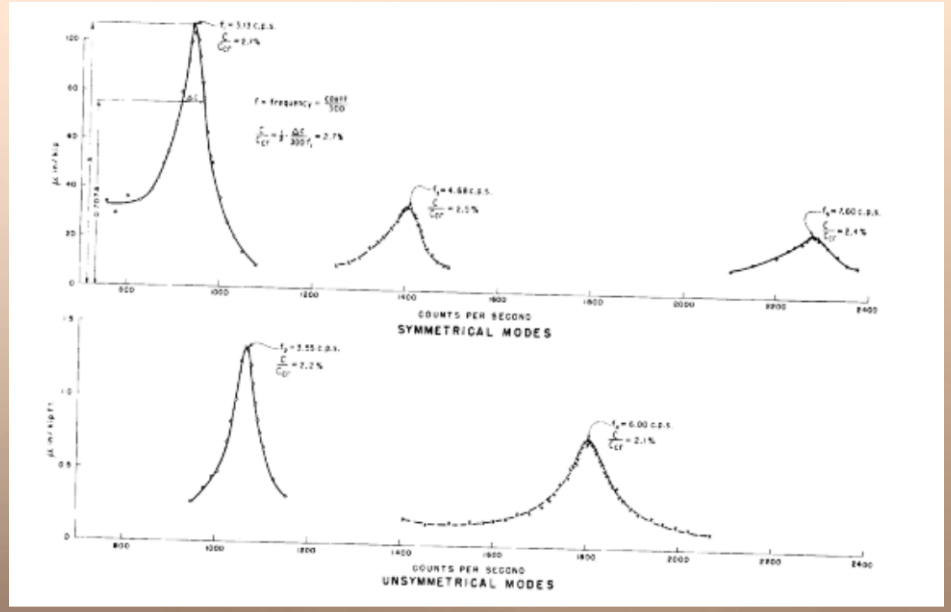



Figure 12. Results of Forced Vibration Tests at Monticello Dam.

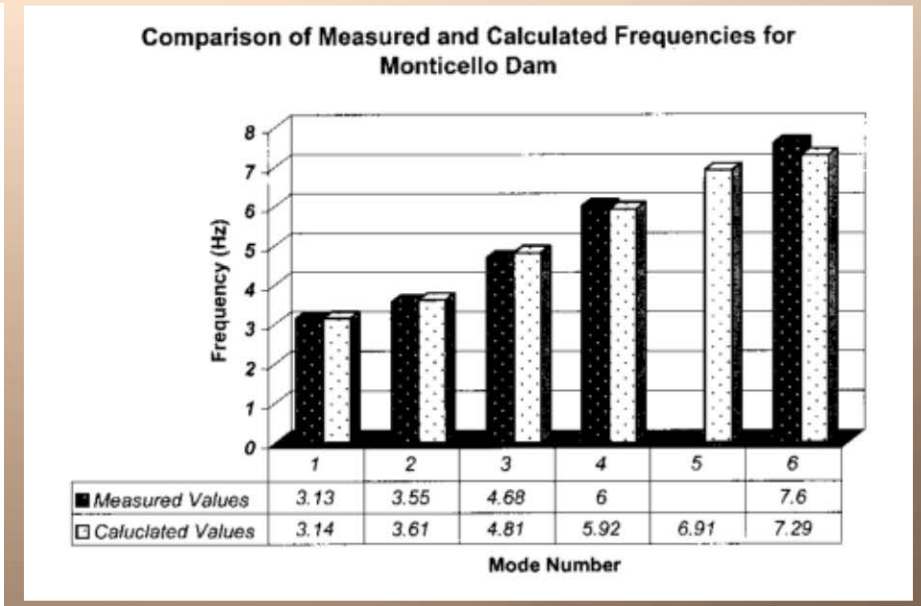



Figure 13. Comparison of Measured and Calculated Frequencies at Monticello Dam

# Foundation Modulus Considerations

- It is often desirable to have different foundation modulus values for static vs. dynamic loads
- Linear-elastic analyses with load super-position can do this, but more difficult with nonlinear explicit analyses
- Typically, stiffer foundation modulus values are more conservative relative to structural response and loading
- But, should perform sensitivity studies to see what the difference is with respect to foundation load and stress distribution

# Multi-Block Foundation Systems

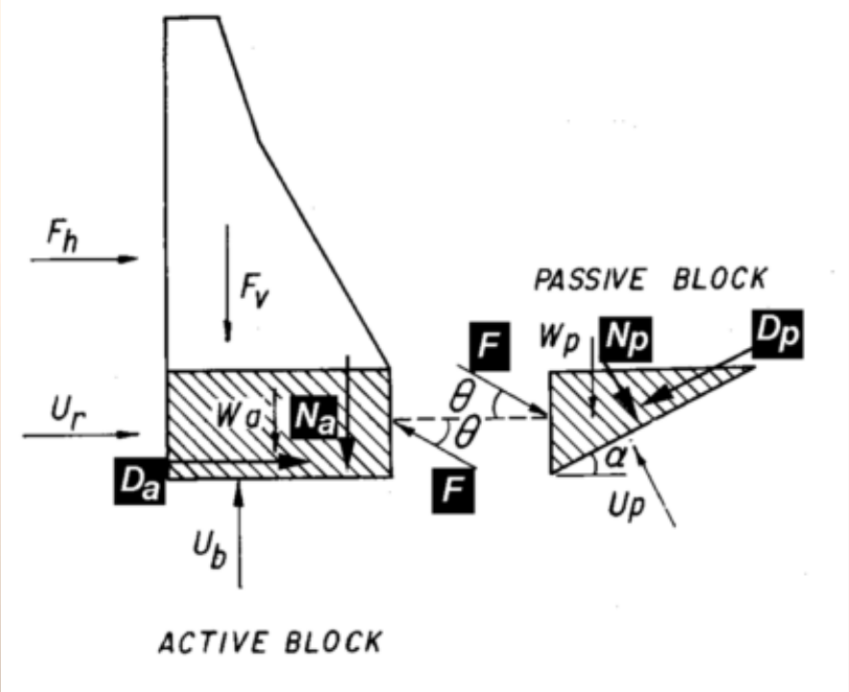



Figure E1. Forces Acting on Two Block System. Forces in Black Boxes Represent Summation of Forces Resolved into the Shown Directions

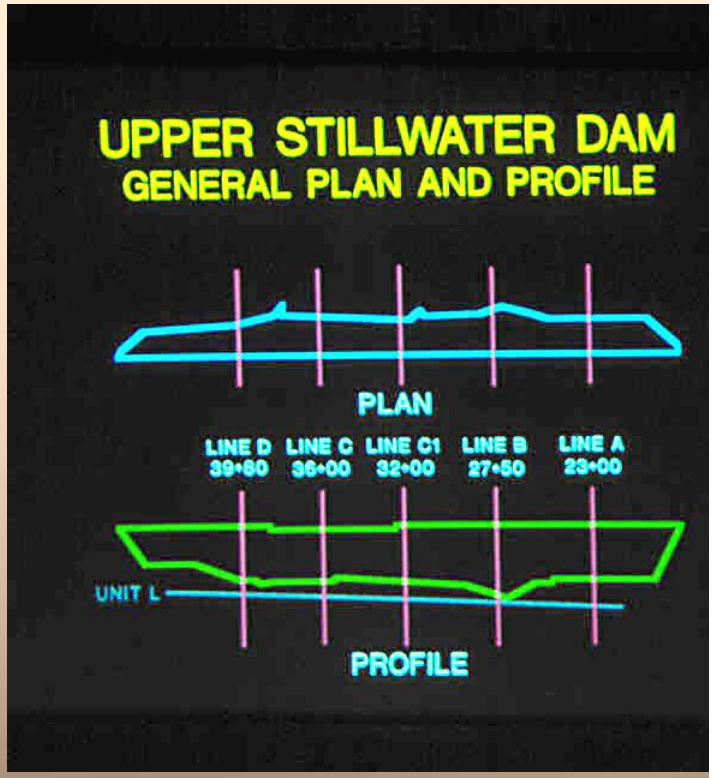
- Unless passive block is very thin, shearing through passive rock mass is unlikely unless the rock material is weak or there is an adversely oriented discontinuity
- There must also be shearing along a near vertical feature between blocks
- Results are highly sensitive to assumed interblock force angle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

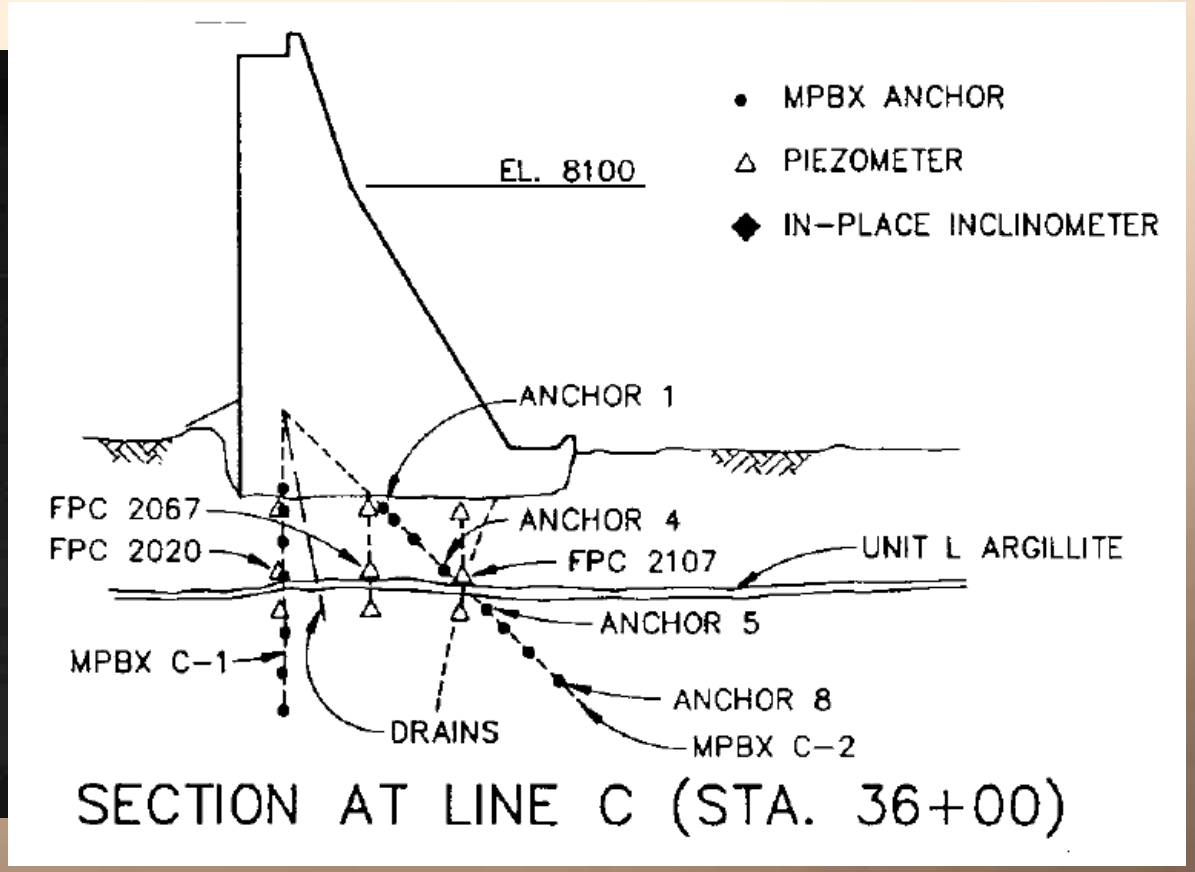
# Upper Stillwater Dam

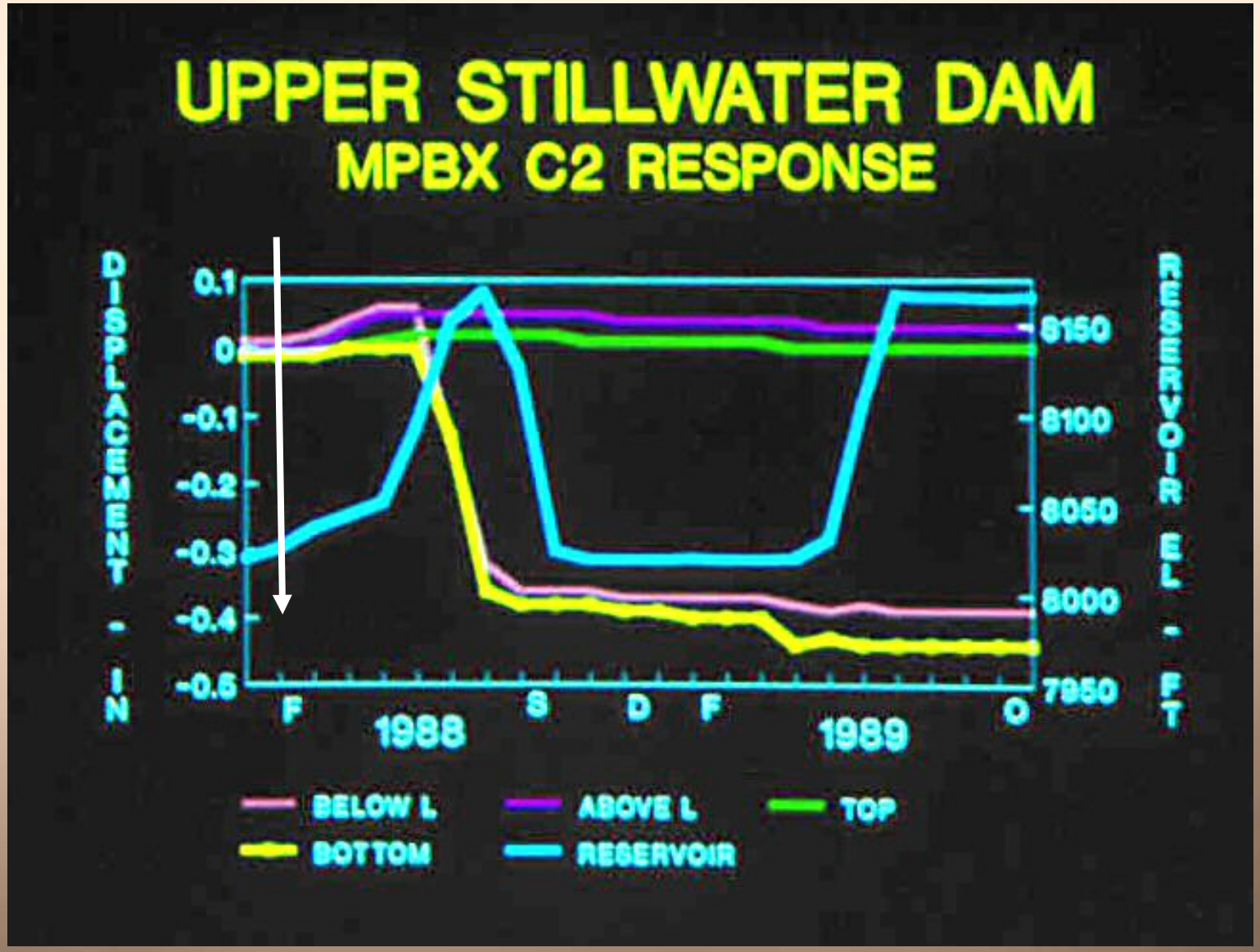
- RCC gravity dam
- 270 ft. high
- South flank Uinta Mountains, Utah

# Upper Stillwater Dam Foundation

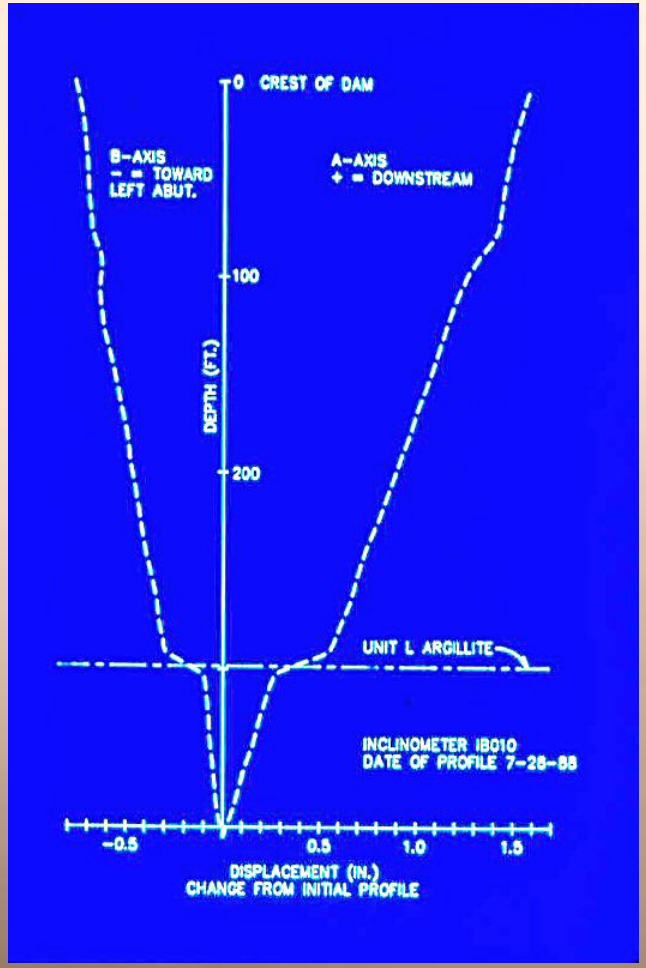
# Upper Stillwater Instrumentation



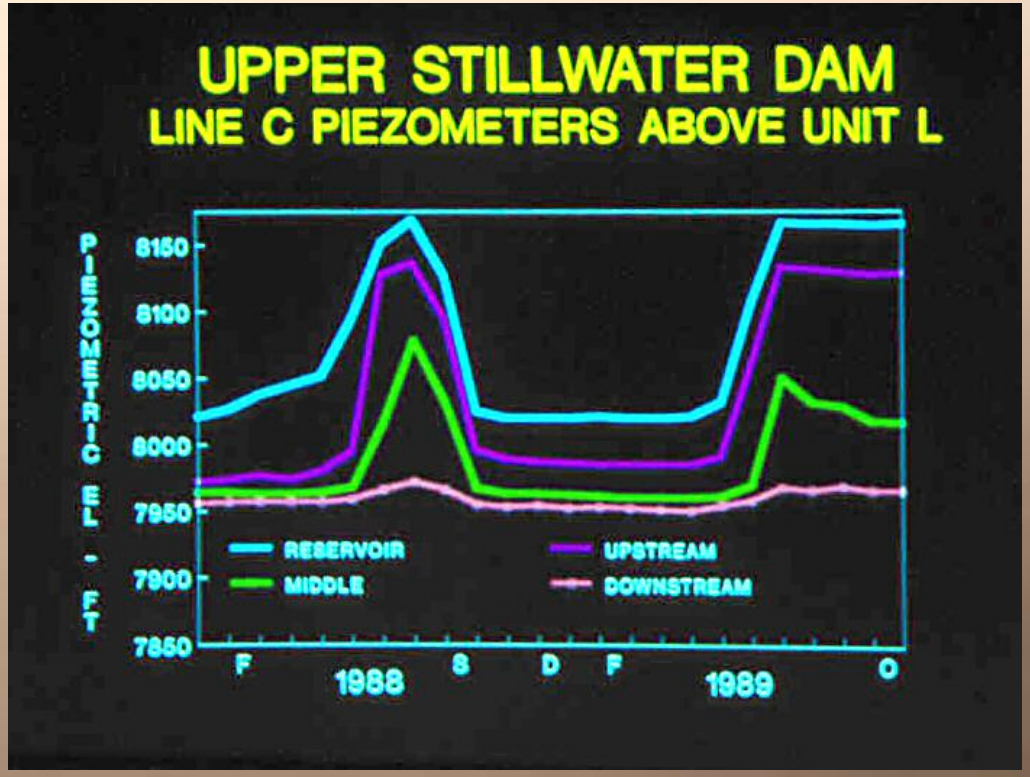




UPPER STILLWATER DAM
MPBX C2 RESPONSE
DISPLACEMENT - IN
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
F
1988
S
D
F
1989
O
RESERVOIR EL - FT
8150
8100
8050
8000
7950
BELOW L
ABOVE L
TOP
BOTTOM
RESERVOIR

# Response of Other Instruments




4th of July weekend - so, what do you do?



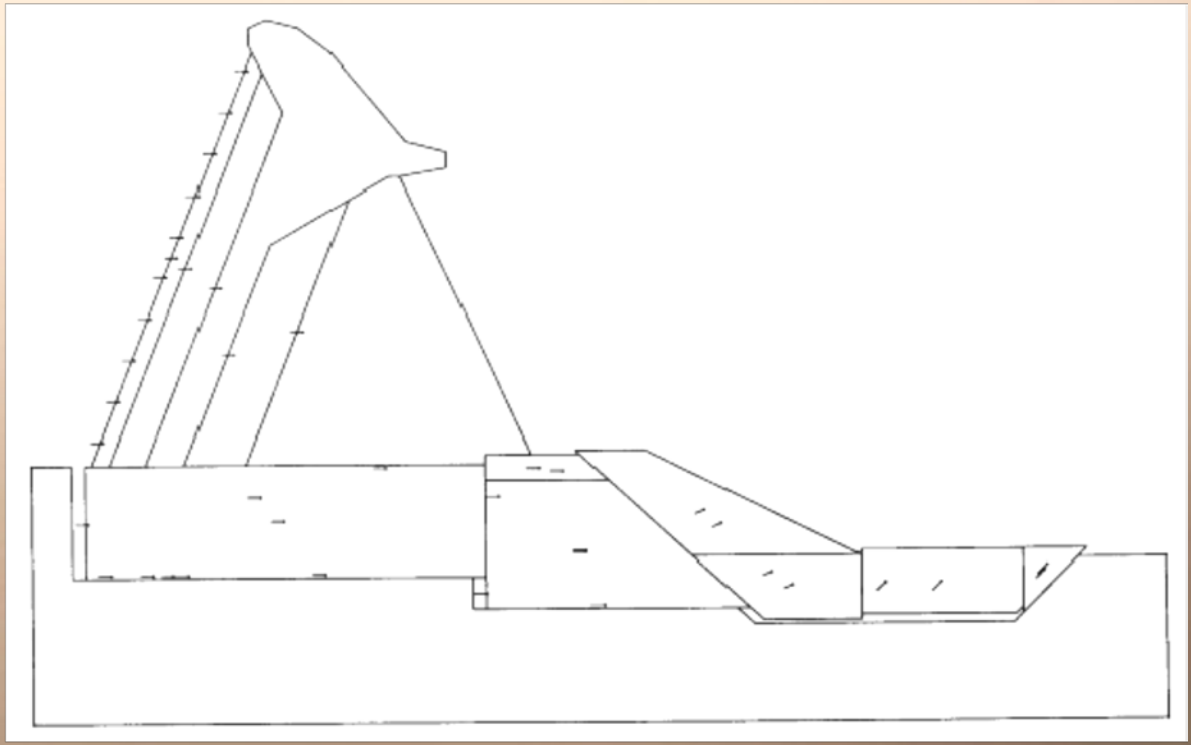
# UPPER STILLWATER DAM
## MOBILIZATION OF D/S ROCK MASS

- MOVEMENT AT CONSTANT RATE WITH INCREASING RESERVOIR
- ABRUPT TERMINATION OF MOVEMENT WHEN RESERVOIR FILLING STOPPED
- NON-UNIFORM MOVEMENT ACROSS SITE
- NON-UNIFORM DIRECTION OF MOVEMENT

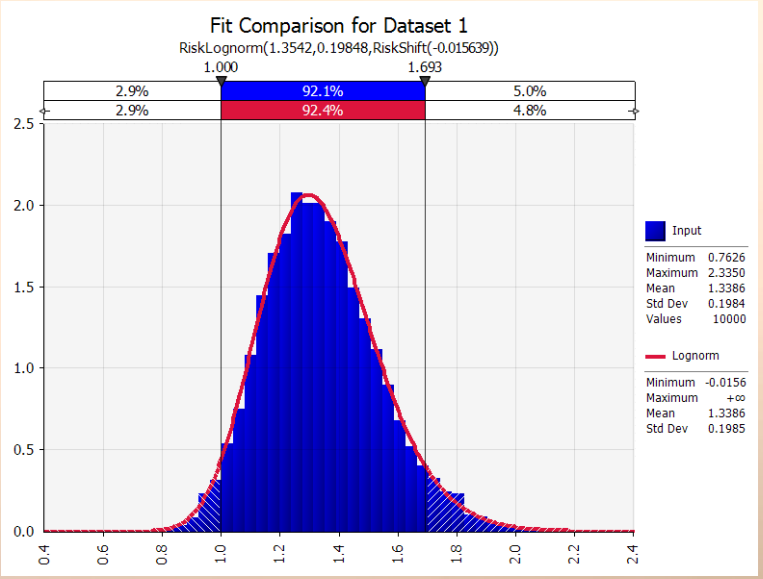
Closing of joints and deformation of passive block opened existing thermal cracks – crack treatment required but no failure

# 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




1.0

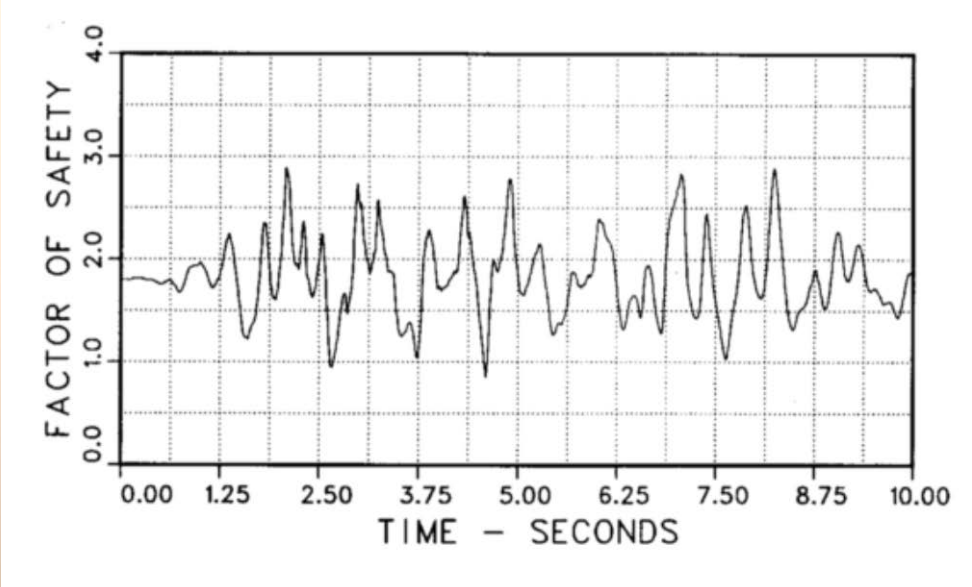


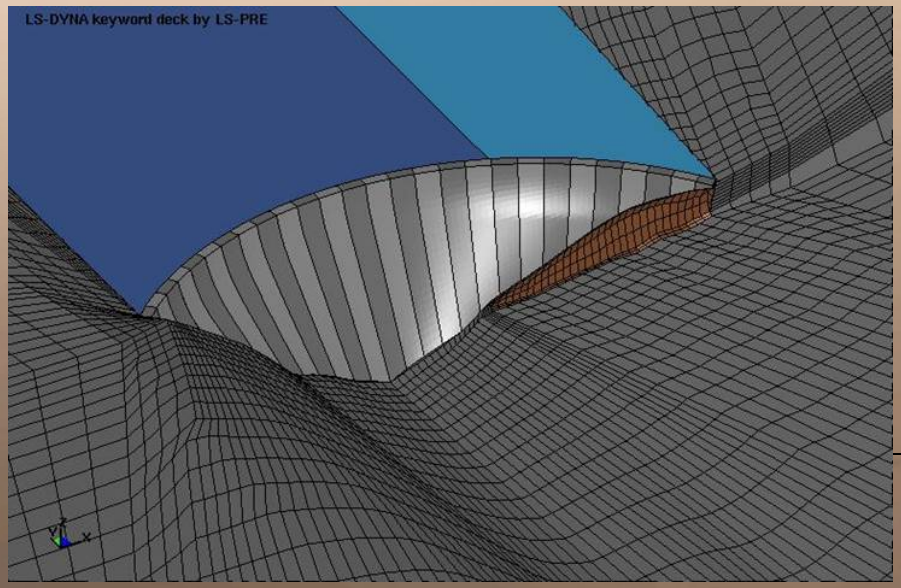

Figure 28. Factor of Safety as a Function of Time for Dynamic Analysis of Foundation Block

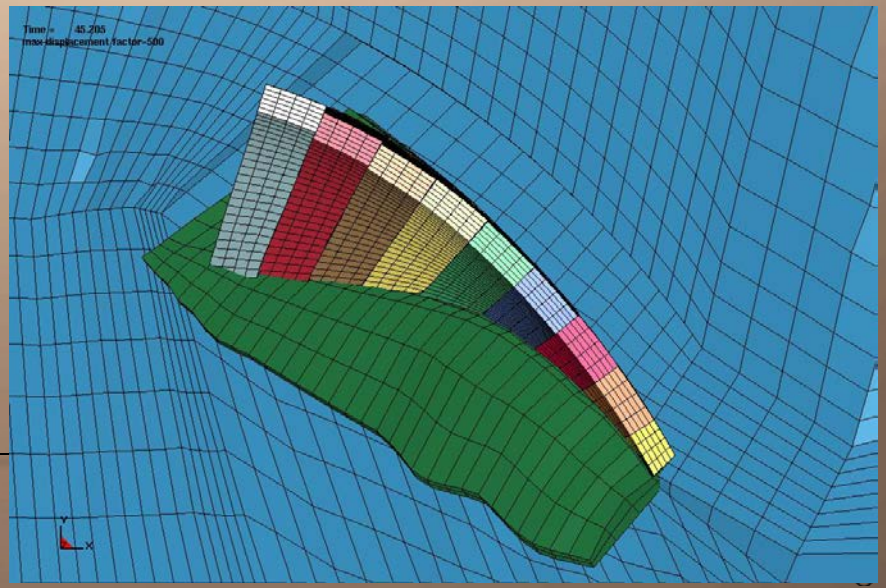
Results from probabilistic factor of safety calculations

When factor of safety drops below 1.0 for dynamic analysis consider calculating "Newmark" displacements, but large displacements would be unrealistically conservative for uncoupled analyses

# Nonlinear Coupled Analysis

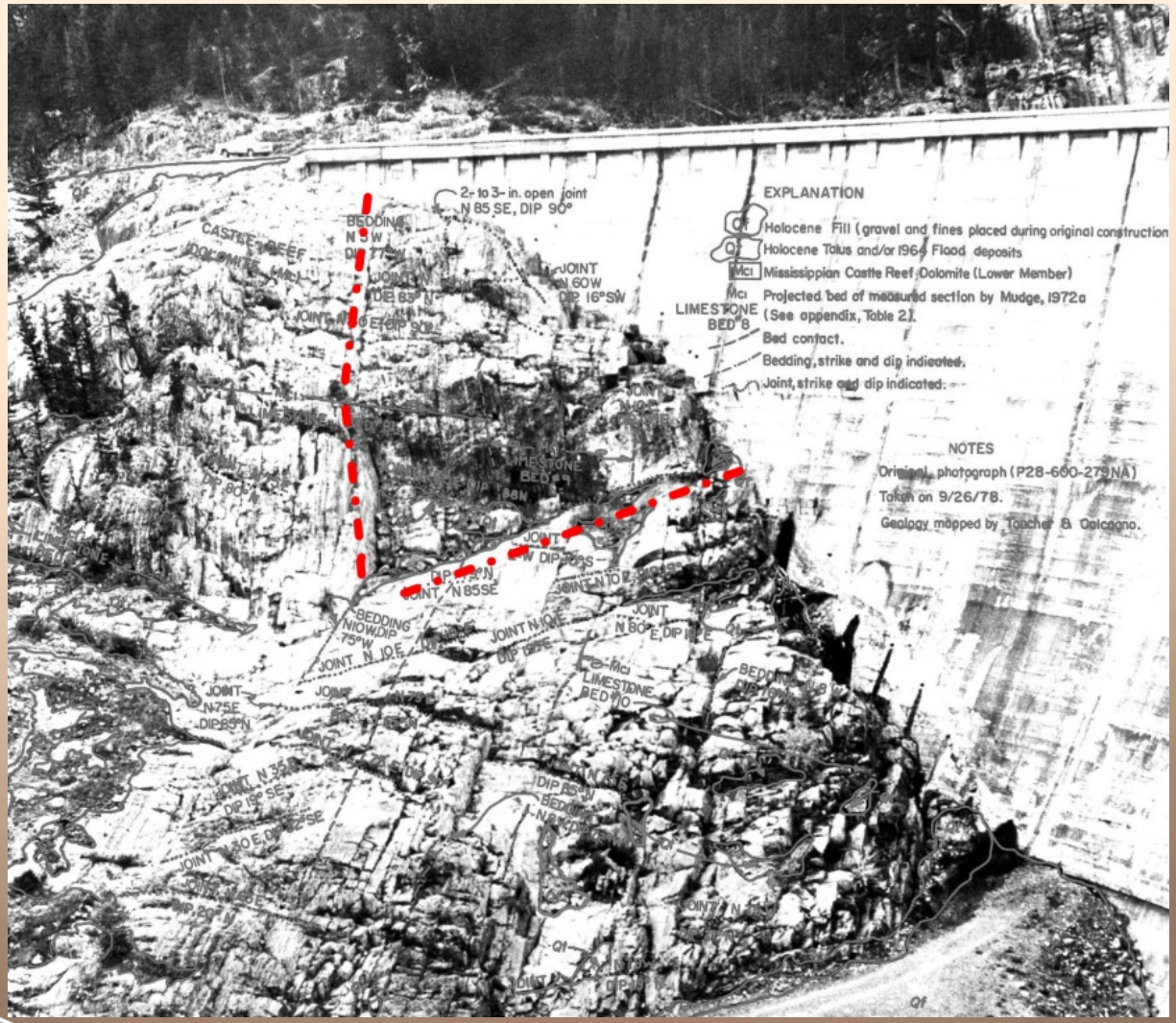
- Usually only undertaken if uncoupled analysis shows problems (i.e. large displacements) and it is believed a coupled analysis might show the foundation is o.k. (i.e. load redistribution keeps displacements small and structure stable)
- Usually time consuming and expensive
- Requires thorough exercising and testing of the model to convince reviewers that the model is behaving properly and the results are reasonable



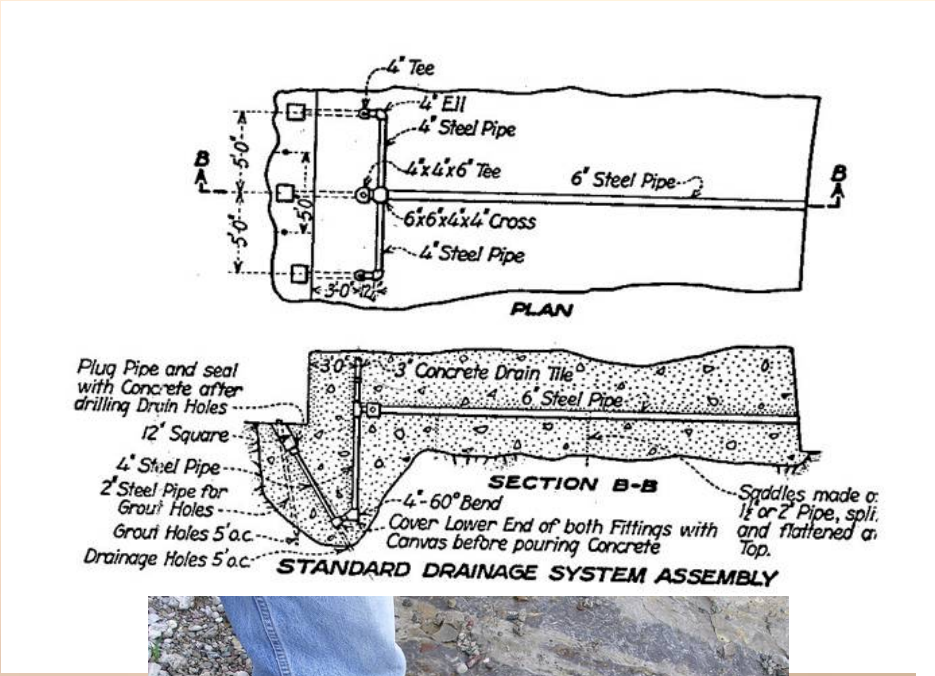



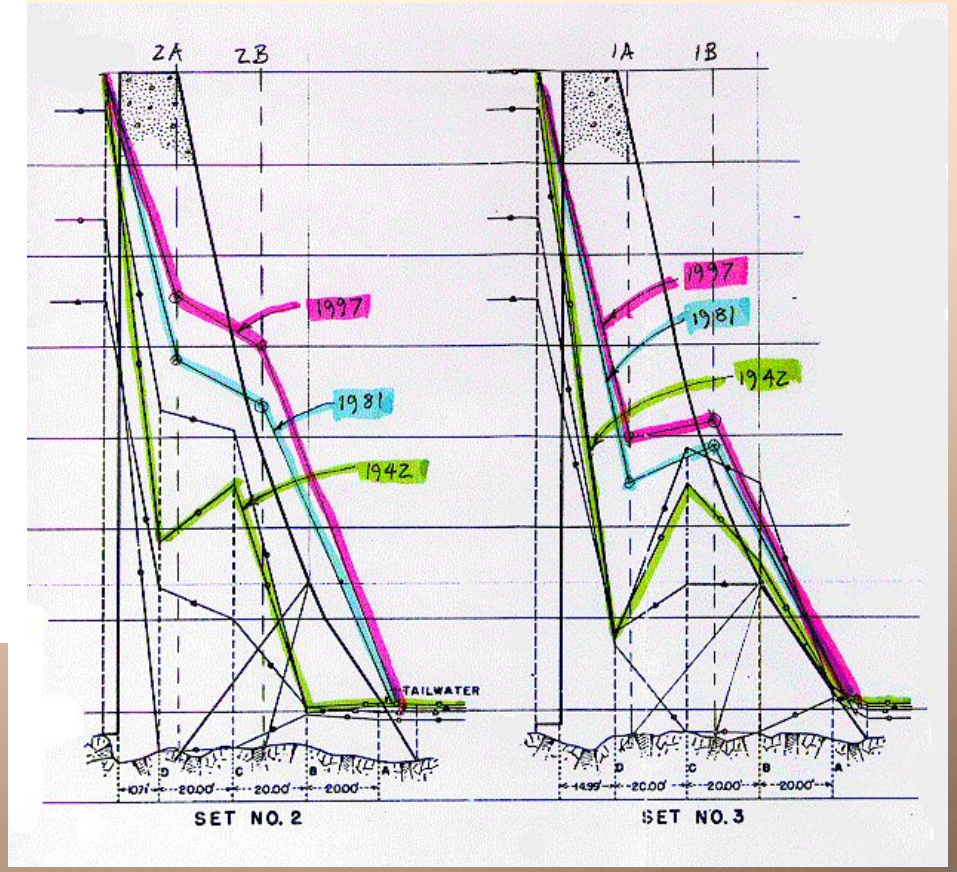
# Example Concrete Dam Fdn. Risk Analysis

# Potential Failure Mode



# Potential Failure Mode






Apparent Vulnerability = Potential Failure Mode

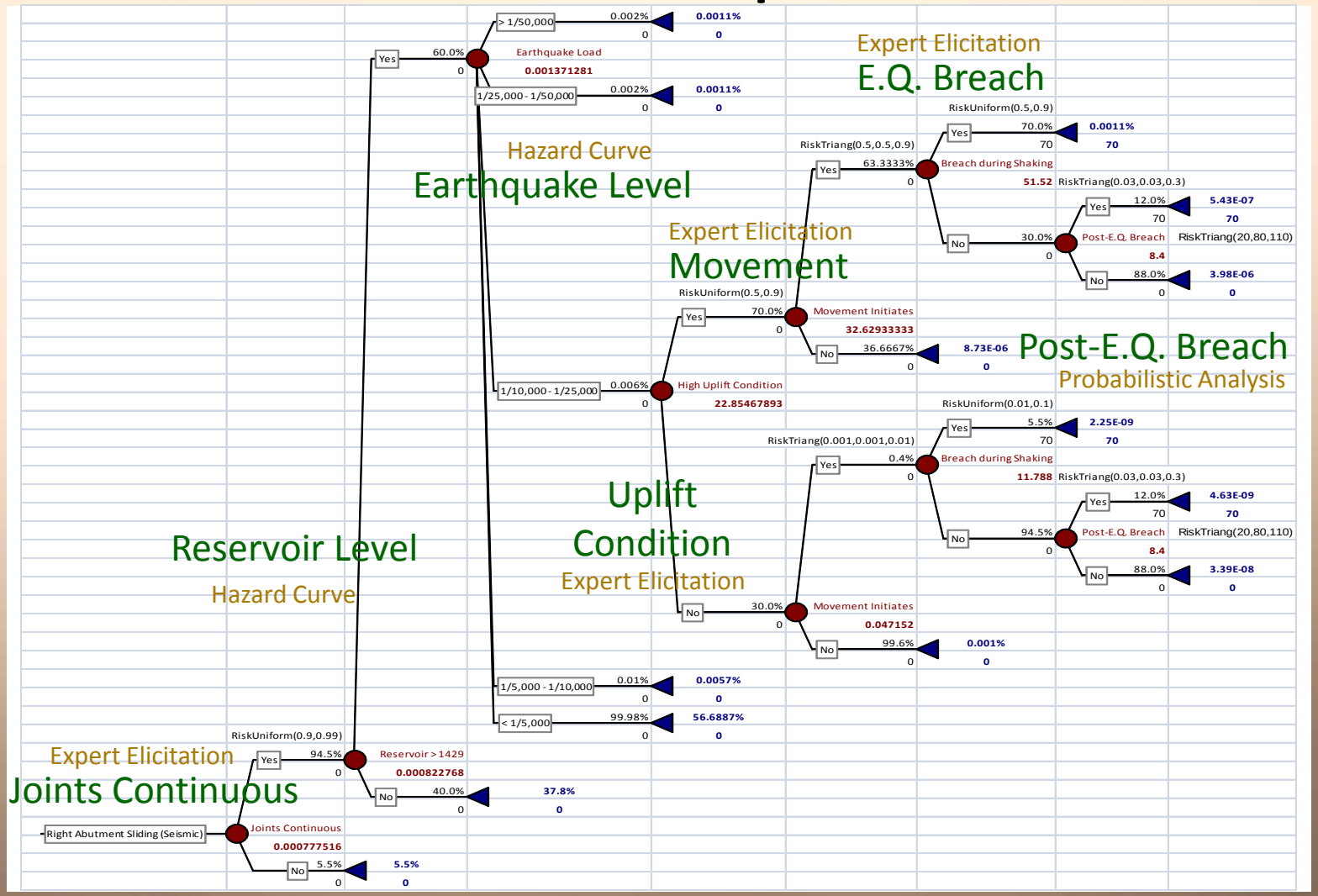
# Potential Failure Mode

- **Unedited –** (insufficient detail): Sliding of the concrete arch dam foundation
- **Edited –** Initiator: High reservoir, continued increase in uplift, earthquake.

  Step-by-step: Block (formed by bedding plane & joints) slides, uplift increases (as joints open), load is not re-distributed, foundation block displaces taking arch Blocks 1 thru 7 with it.

  Breach: Rapid rupture of Blocks 1 thru 7 followed by partial collapse of upper dam where arch action lost.

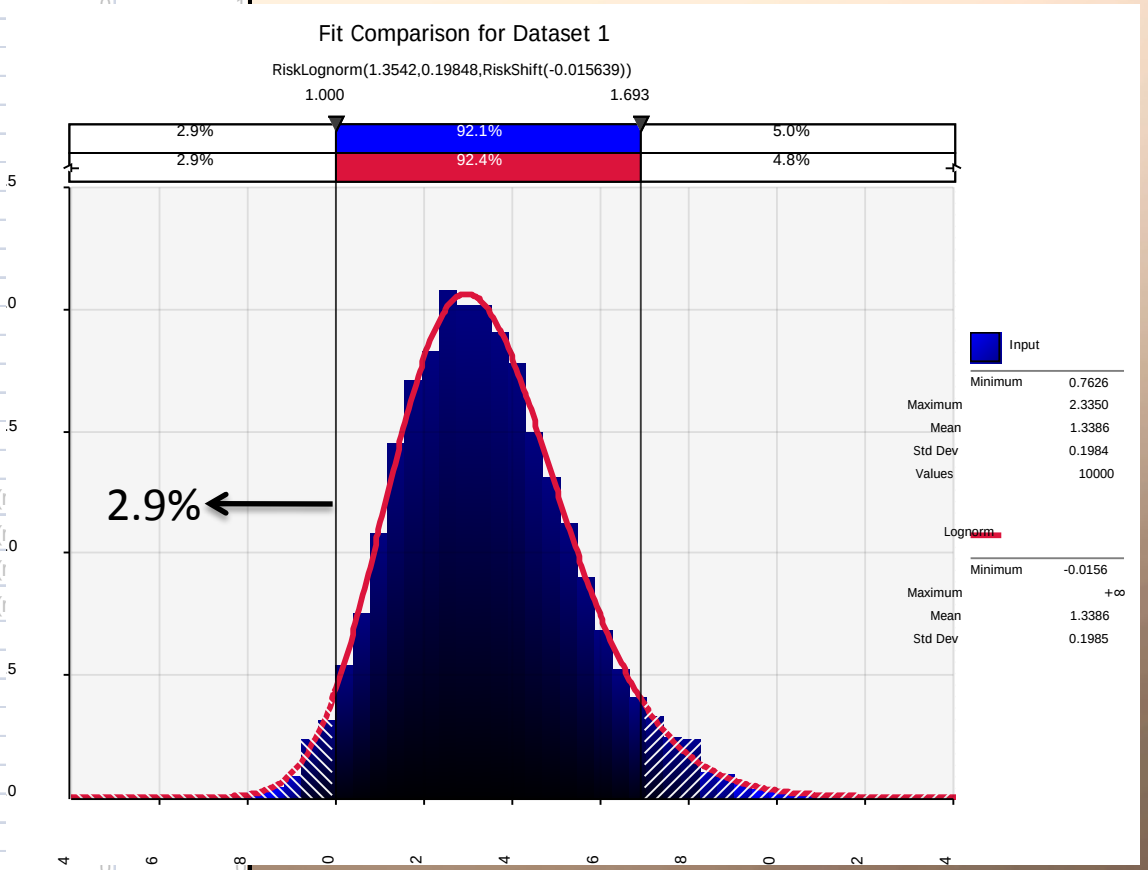
# Event Tree – Example Arch Dam



# Probabilistic Analysis

| | | | | |
|---|---|---|---|---|
| Enter the estimated weight of the wedge | 5.12E+07 | 5.12E+07 | | |
| 8 | | | | |
| Enter the x (E) component of Q | 2.94E+07 | | | |
| Enter the y (N) component of Q | 8.60E+06 | | | |
| Enter the z (UP)component of Q | -3.05E+07 | | | |
| | | | | |
| Input the dip of joint set 1 (degrees) Base | 14 | 0.2443461 | 0.4712389 | 1 |
| Input the dip of joint set 2 (degrees) Side | 75 | 1.30899694 | 4.60766923 | 1 |
| Input the dip of joint set 3 (degrees) Back | 83 | 1.44862328 | 0.26179939 | 1 |
| Input the dip of joint set X (degrees) | 0 | 0 | 0 | 1 |
| | | | | |
| Input the joint set 1 dip direction (CW w/r N) | 27 | Base | | |
| Input the joint set 2 dip direction (CW w/r N) | 264 | Side R | | |
| Input the joint set 3 dip direction (CW w/r N) | 15 | Back | | |
| Input the joint set X dip direction (CW w/r N) | 0 | Extra | | |
| | | | | |
| Block is above (0) or below (1) Joint Set 1? | 0 | 0 | | |
| Block is above (0) or below (1) Joint Set 2? | 0 | 0 | | |
| Block is above (0) or below (1) Joint Set 3? | 0 | 0 | | |
| Block is above (0) or below (1) Joint Set X? | 0 | 0 | | |
| | | | | |
| Enter the magnitude of the water force along 1 | 4.00E+07 | 5.61E+08 | | |
| Enter the magnitude of the water force along 2 | 2.00E+07 | 1.78E+08 | | |
| Enter the magnitude of the water force along 3 | 8.00E+06 | 2.65E+08 | | |
| Enter the magnitude of the water force along X | 0.00E+00 | 5.98E+08 | | |
| | | | | |
| Enter $\phi_1$, the Joint Set 1 friction angle | 35 | 0.61086524 | | |
| Enter $\phi_2$, the Joint Set 2 friction angle | 35 | 0.61086524 | | |
| Enter $\phi_3$, the Joint Set 3 friction angle | 35 | 0.61086524 | | |
| Enter $\phi_X$, the Joint Set X friction angle | 0 | 0 | | |
| | | | | |
| **********RESULTS********** | | | | |
| | | | | |
| The failure mode (see below) is failure mode #: | 5 | | | |
| The sliding factor of safety for the failure mode: | 1.32 | | | |
| | | | | |
| ***List of possible failure modes:*** | | | | |
| | | | | |
| 1. The wedge will be unstable in the absense of cohesion | | | 0 | 0 |
| 2. The resultant force points into the rock | | | 0 | ∞ |
| 3. The failure mode is sliding along $I_{23}$ | | | 0 | -0.77 |
| 4. The failure mode is sliding along $I_{13}$ | | | 0 | -4.47 |
| 5. The failure mode is sliding along $I_{12}$ | | | 1 | 1.32 |
| 6. The failure mode is sliding along plane 1 | | | 0 | 0.56 |
| 7. The failure mode is sliding along plane 2 | | | 0 | 0.52 |
| 8. The failure mode is sliding along plane 3 | | | 0 | 0.37 |

RiskTriang(10,14,18)




1.0 Factor of Safety

Post-EQ Stability

# Probabilistic Analysis

| Parameter | Spreadsheet Cell | Regression Coefficient |
|---|---|---|
| Joint set 3 dip direction (CW w/r N), Back | B22 | 0.058 |
| Joint set 2 dip direction (CW w/r N), Side | B21 | -0.527 |
| Joint set 1 dip direction (CW w/r N), Base | B20 | 0.154 |
| Dip of joint set 3 (degrees), Back | B17 | 0.019 |
| Dip of joint set 2 (degrees), Side | B16 | 0.048 |
| Dip of joint set 1 (degrees), Base | B15 | -0.333 |
| Estimated weight of the wedge | C9 | 0.044 |
| f3, the Joint Set 3 friction angle, Back | B37 | 0 |
| f2, the Joint Set 2 friction angle, Side | B36 | 0.367 |
| f1, the Joint Set 1 friction angle, Base | B35 | 0.648 |

# Example of Expert Elicitation

Example Arch Dam, High Uplift Condition Exists

| Adverse ("More Likely") | Favorable ("Less Likely") |
|---|---|
| Drains cannot be maintained | Conservative uplift perhaps used in analyses |
| Piezometer levels are increasing | Piezometers are not at base of block |
| Water squirts from rockbolt holes | Rockbolt holes are downstream of block |

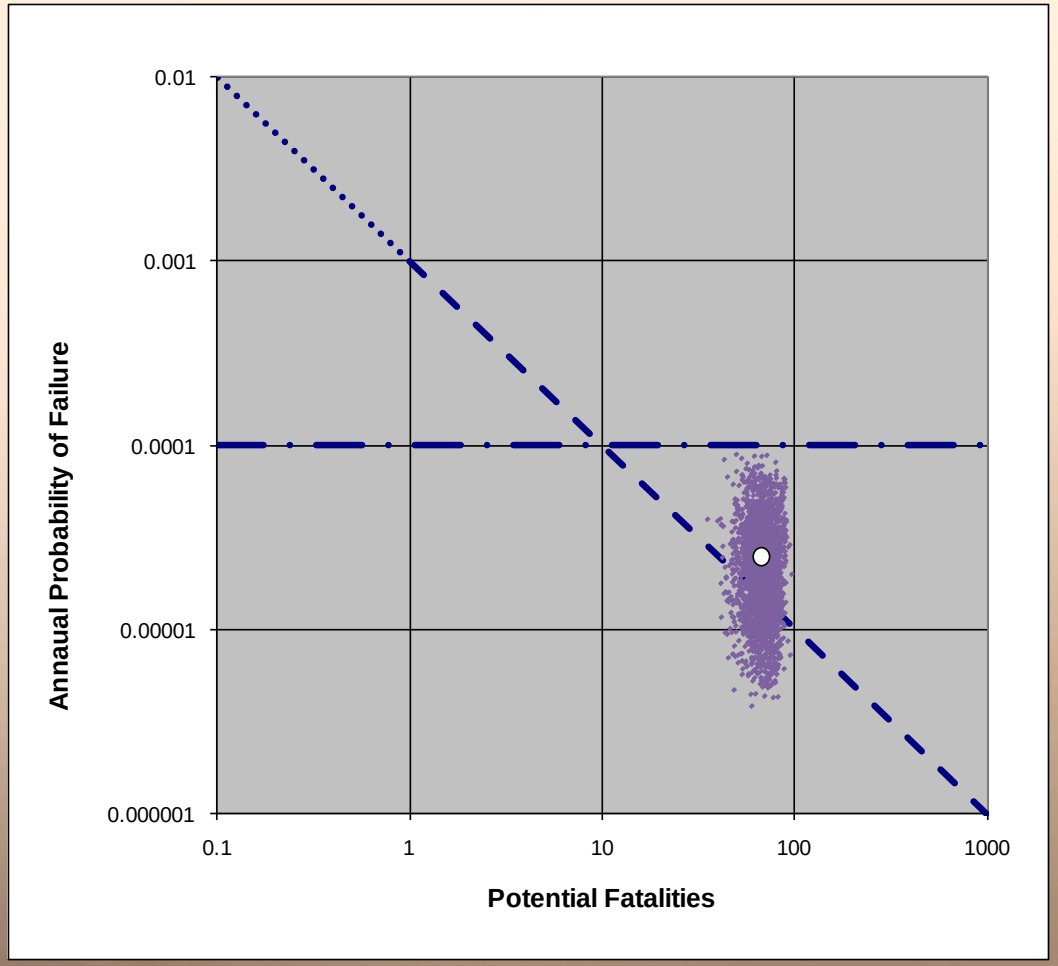
Team estimate: 0.5-0.9

Rationale: Adverse factors weighted more heavily, clear indications of plugging drains and higher water pressures

# Consequences

- Primary consequences due to scattered residences in narrow canyon downstream
- Population at risk in this reach about 60 to 80
- High severity flooding can be expected in this reach with little warning associated with an earthquake failure

# Uncertainty

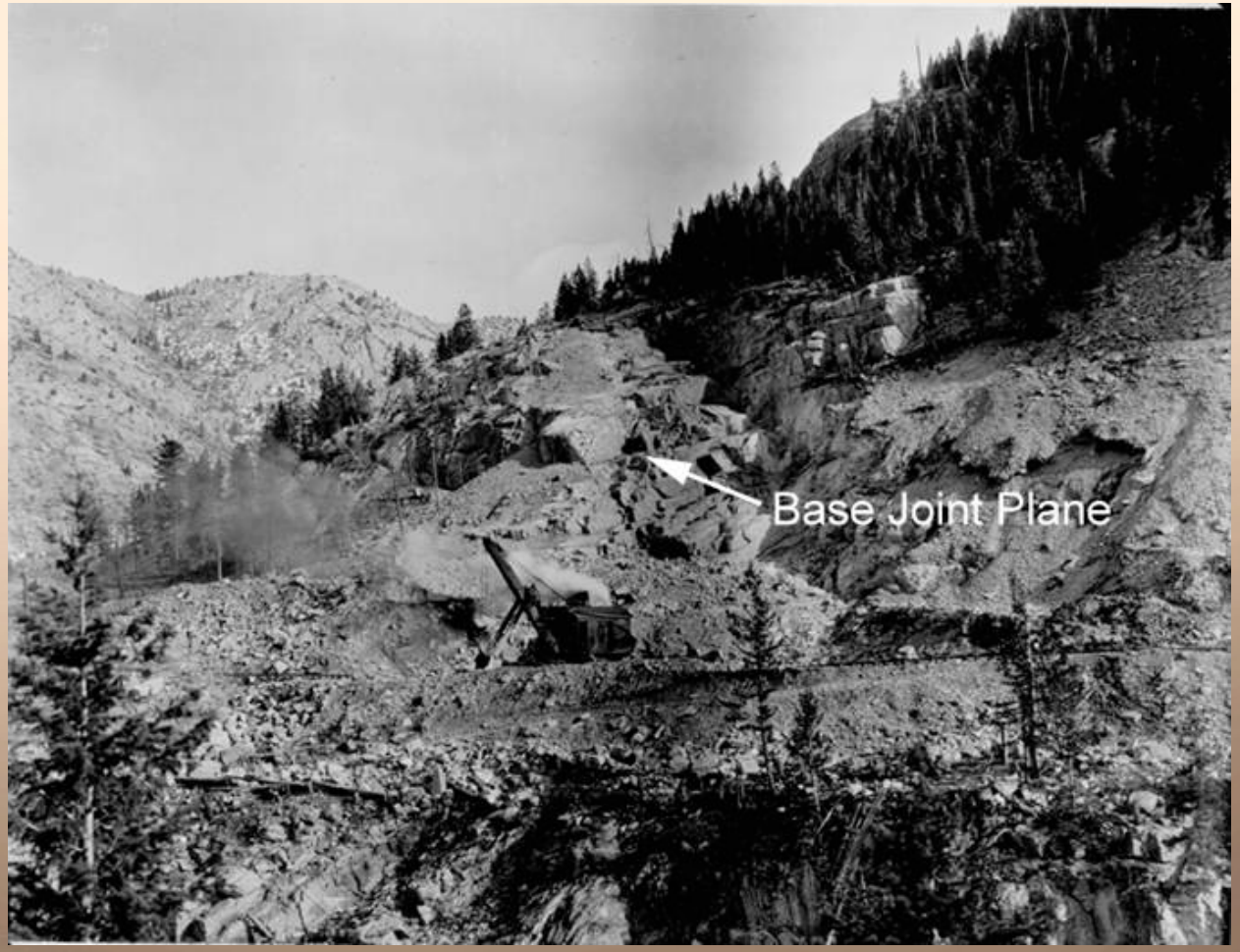



Mean Annualized Life Loss = 2.8E-03

# Example Dam Safety Case

- Claim: The probability that the right abutment is founded on potentially unstable block bounded by continuous joints is high to very high (0.9-0.99)
- Evidence to support the claim
  - Continuous side plane bedding joint mapped d/s of dam
  - Continuous base plane joint mapped d/s of dam
  - Construction photo shows base plane joint crosses foundation excavation
  - Although no specific release plane was identified, this area is in tension and joint sets mapped u/s of dam could connect to form such a release surface

# Building the Case

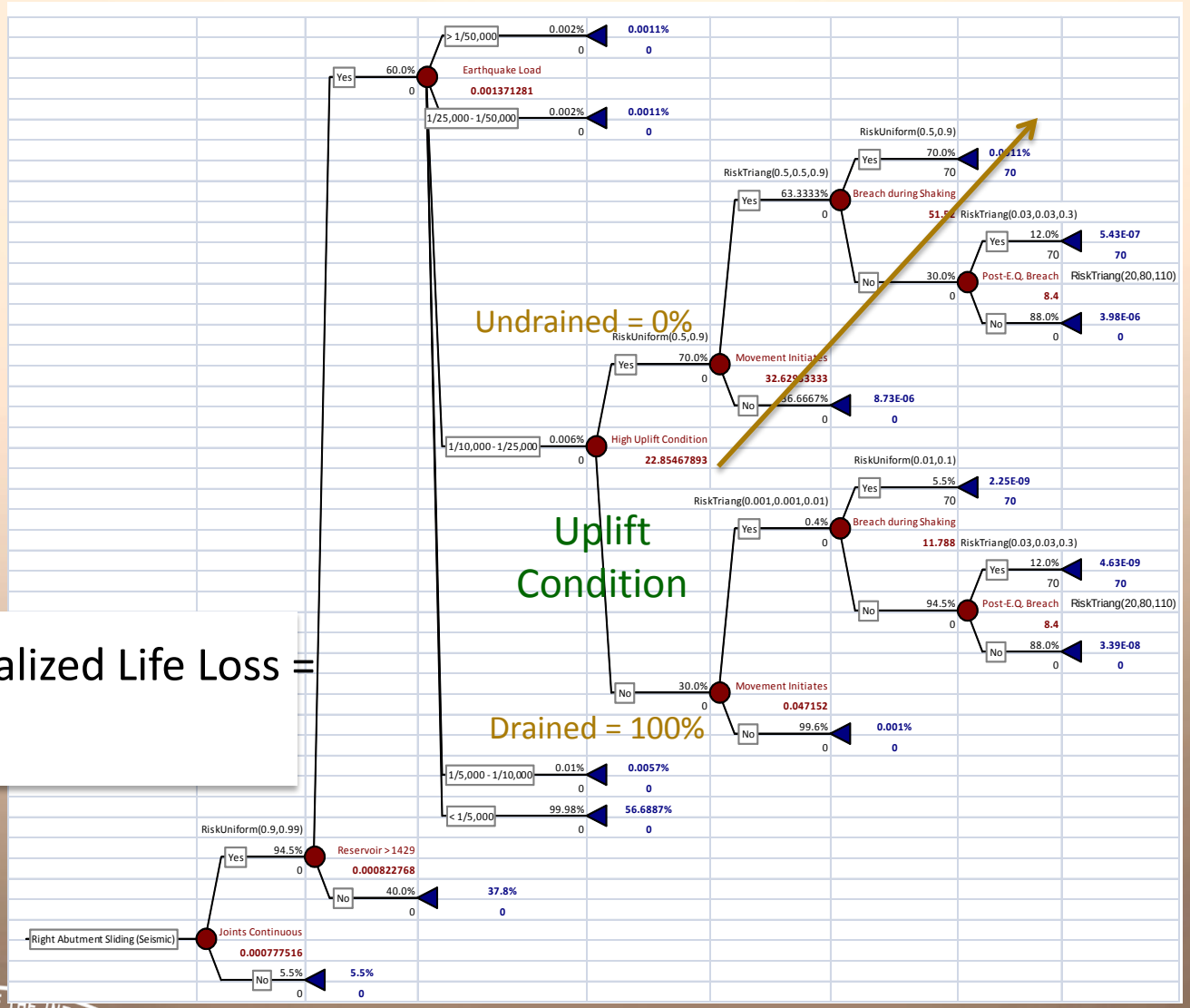


# Assessing Risks

Example Dam:

- Risks above societal risk guidelines
- Case and evidence compelling
- Urgency is moderate
- Confidence high (additional work unlikely to change results)
- Corrective action recommended
  - Install piezometers
  - Drain abutment (drilled holes)

# Risk Reduction Assessment




Mean Annualized Life Loss = 4.7E-05

# Construction Risk

- Temporarily accept higher risk in order to secure long term risk reduction
- Example Dam: Increased risk from introducing drilling water into joints
  - Relatively high static factor of safety
  - Drill water pressures localized
  - Drilling would occur late spring while reservoir being drafted
  - Drains drilled from lower level at upward or at shallow angles – will not charge the holes with hydrostatic head

# Installing Piezometers

# Risk Reduction & Verification

- Piezometer Measurements
- Uplift Distribution
- Calculated FS
- Risk Estimate Verification

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