Earthquake Analysis, Design, and Safety Evaluation of Concrete Gravity Dams

Electricity Generating Authority of Thailand

Bangkok, Thailand

December 7-8, 2010

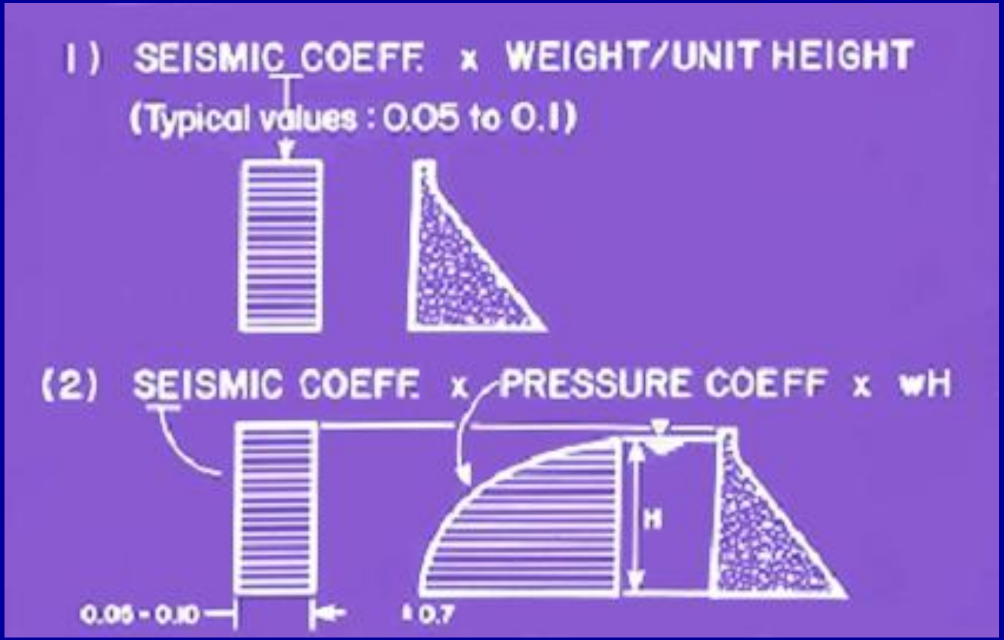
Anil K. Chopra

University of California, Berkeley

Earthquake Performance of Koyna Dam

Traditional Design Procedures

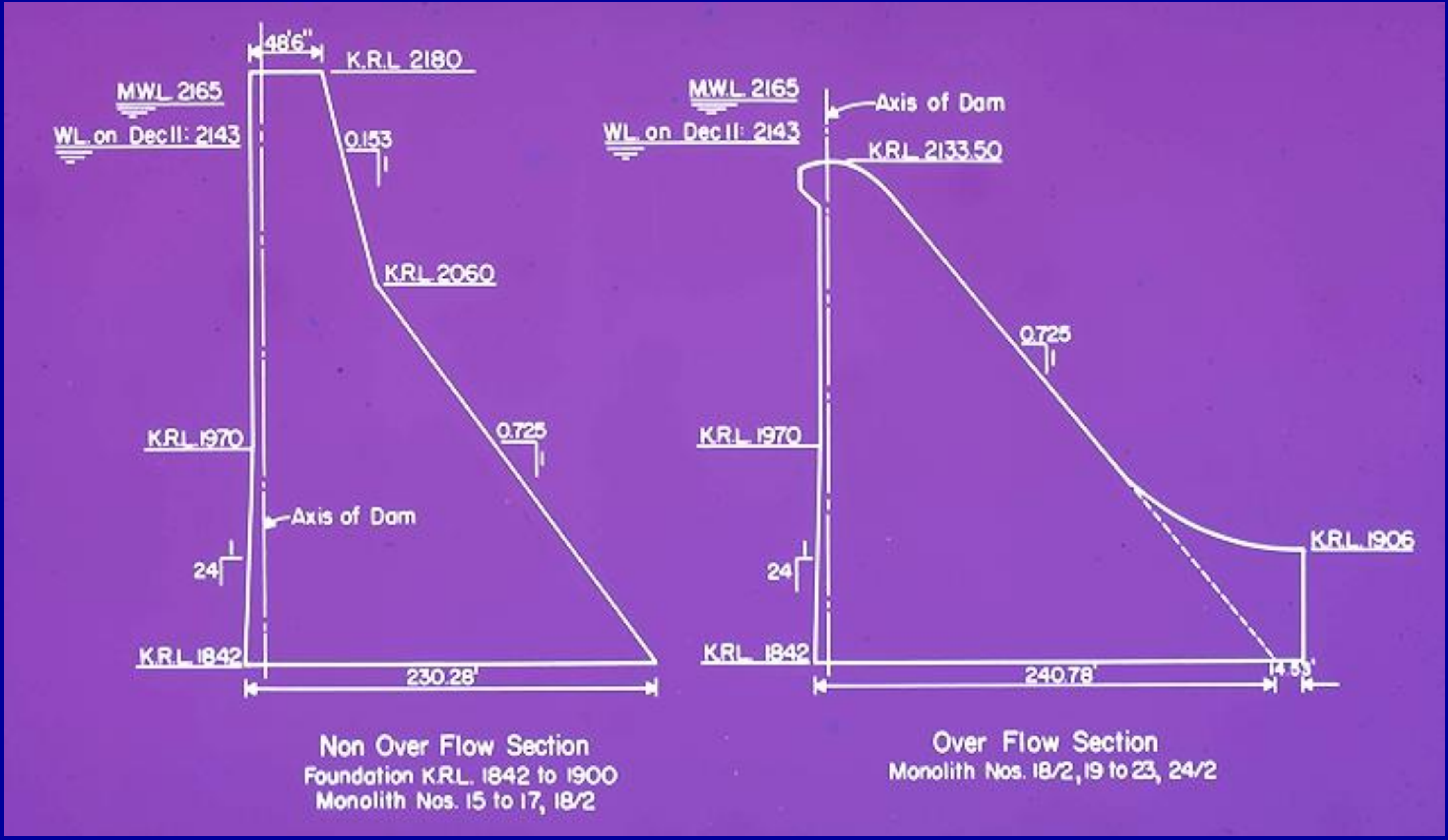
- Lateral Earthquake Forces



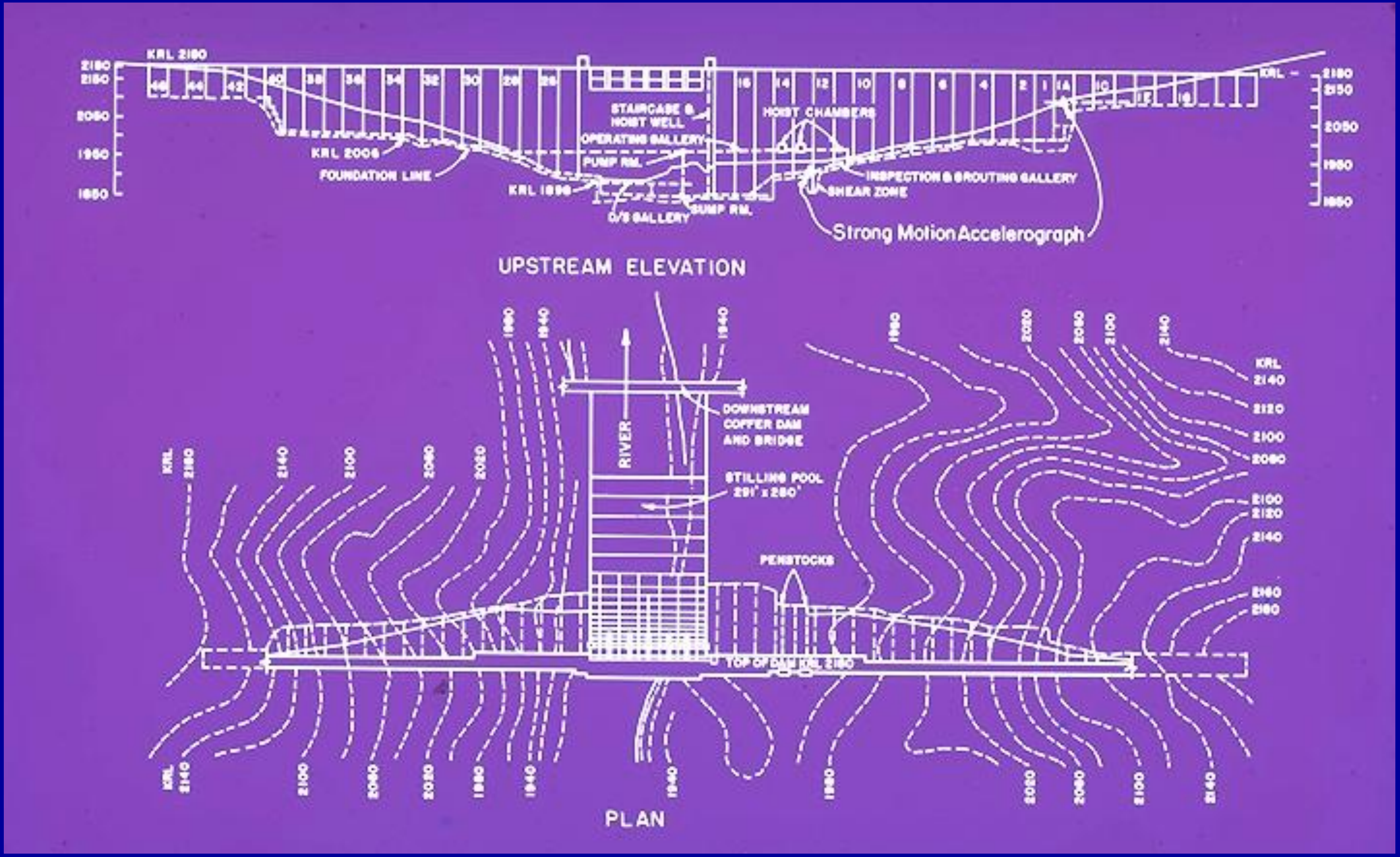
- Design Criteria
  - –Factors of safety against
    - •Overturning
    - •Sliding
    - •Overstressing in compression
  - –At most small tension permitted
    - •Cracking possibility not considered
- Stresses generally do not control design

Koyna Dam

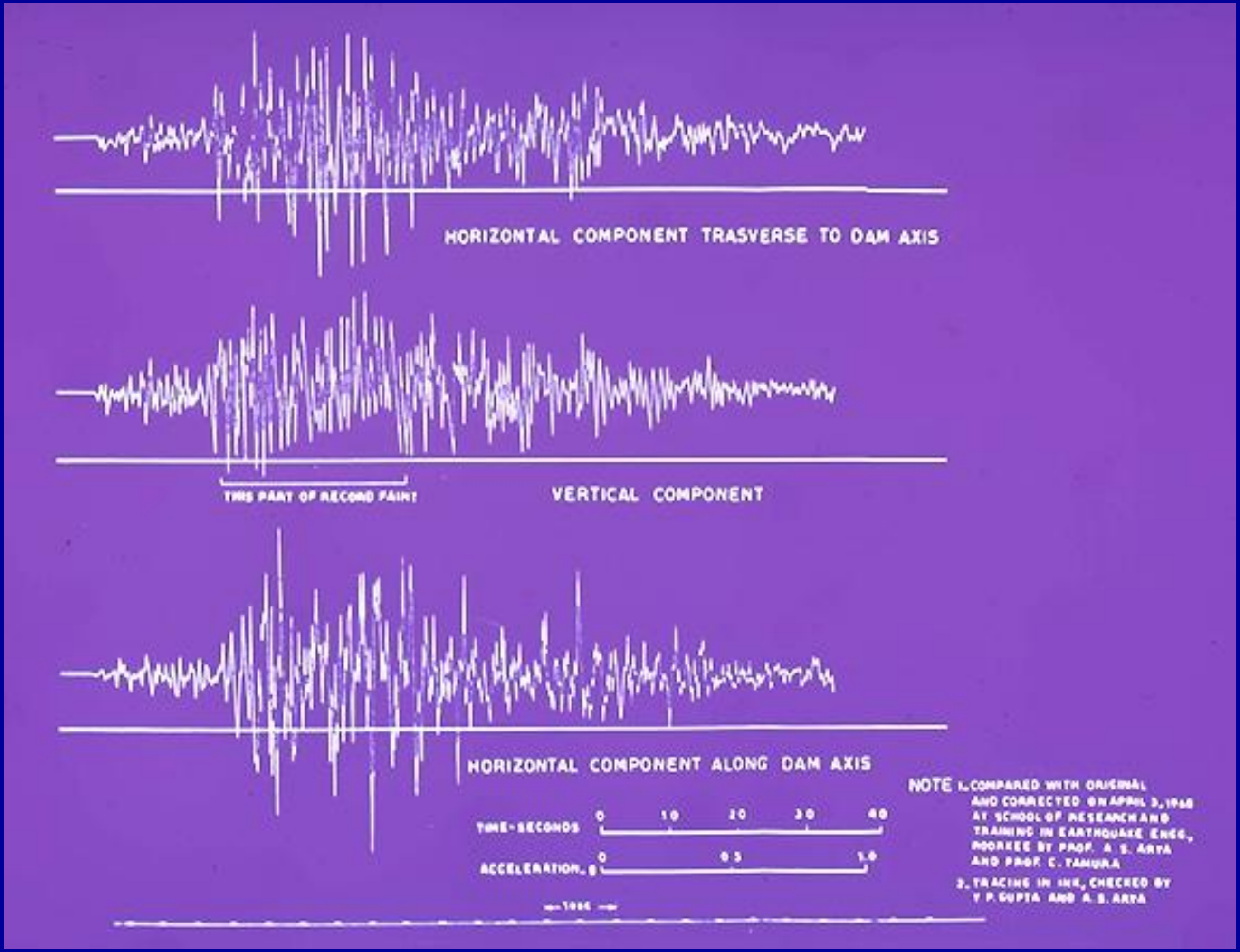
Koyna Dam - Sections



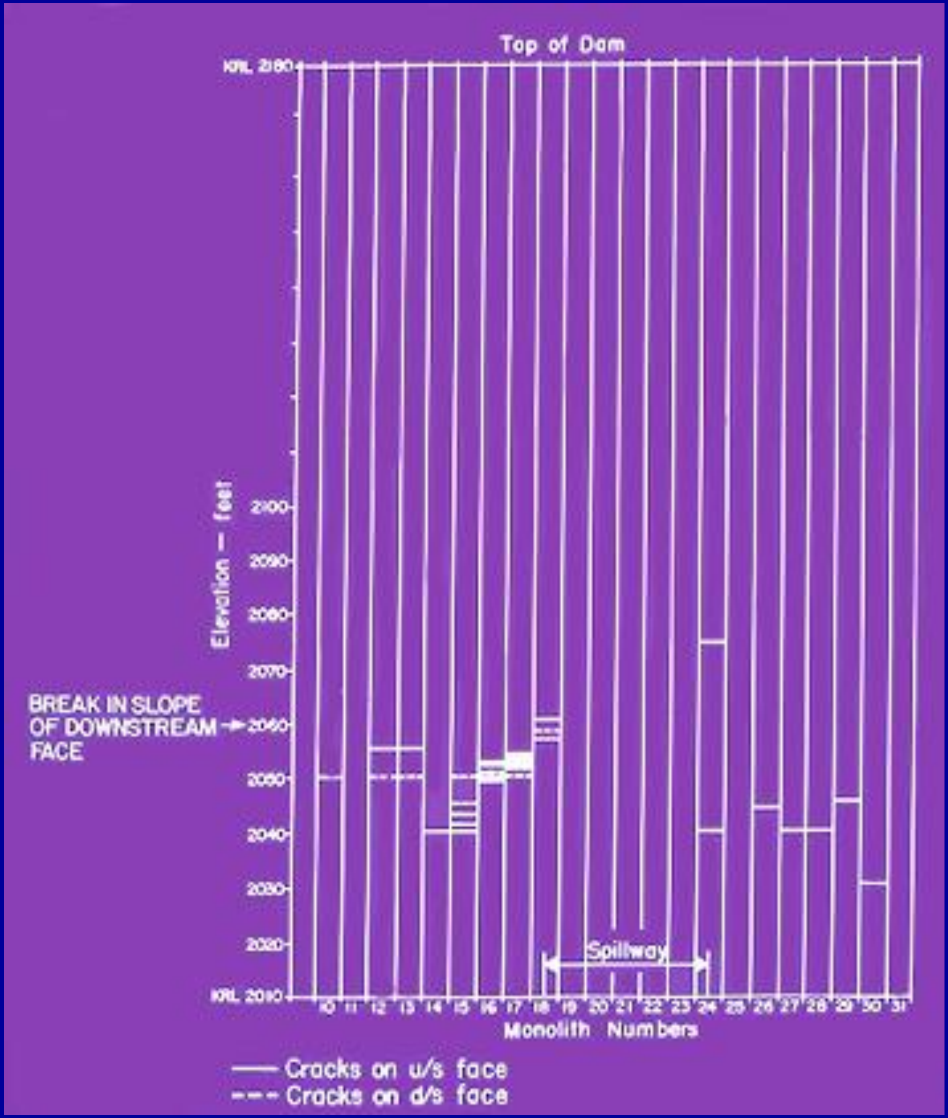
Koyna Dam – Plan and Elevation



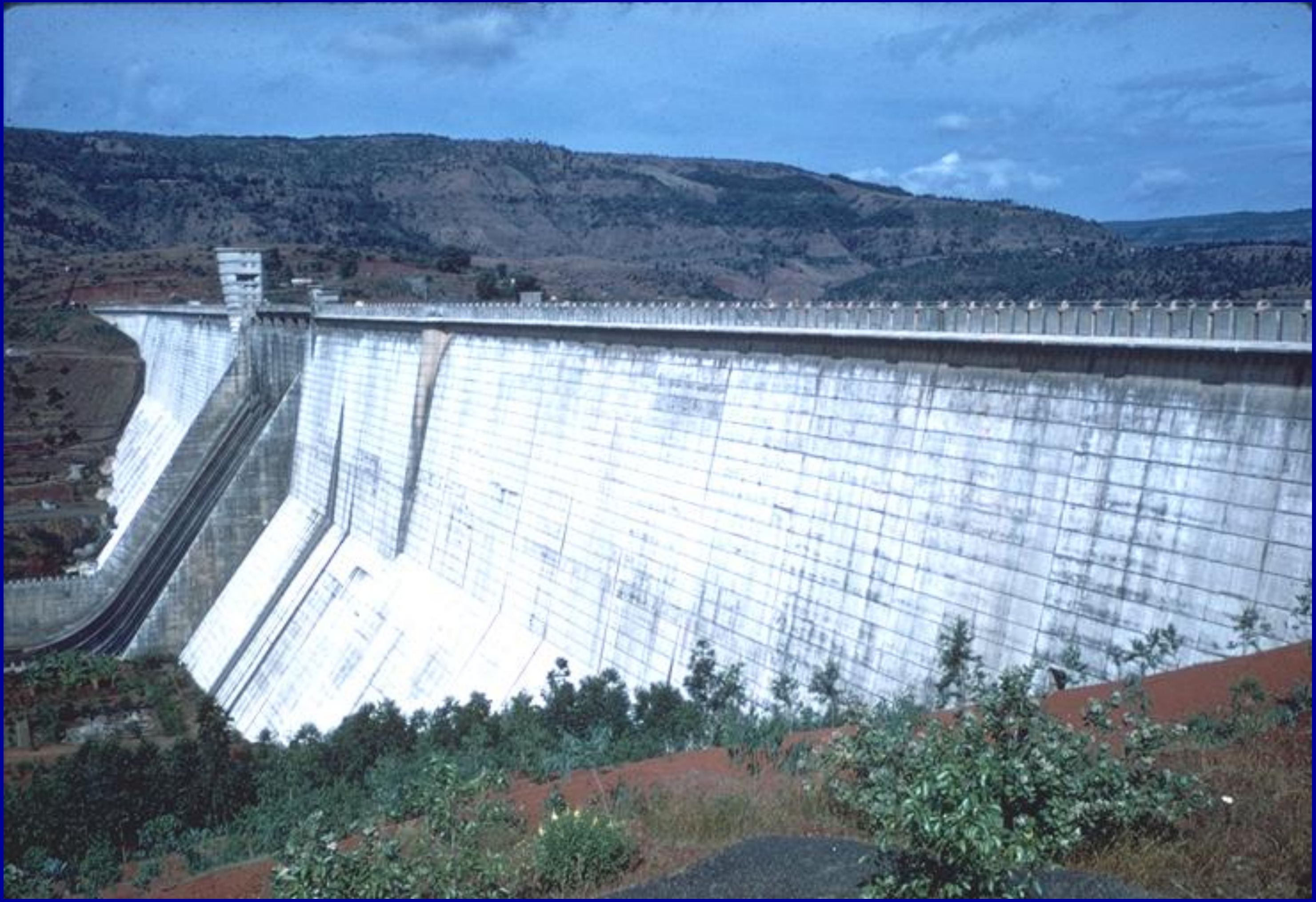
Accelerogram Recorded at Block 1-A of Koyna Dam on Dec. 11, 1967



Locations of Cracks in Koyna Dam Caused by Earthquake



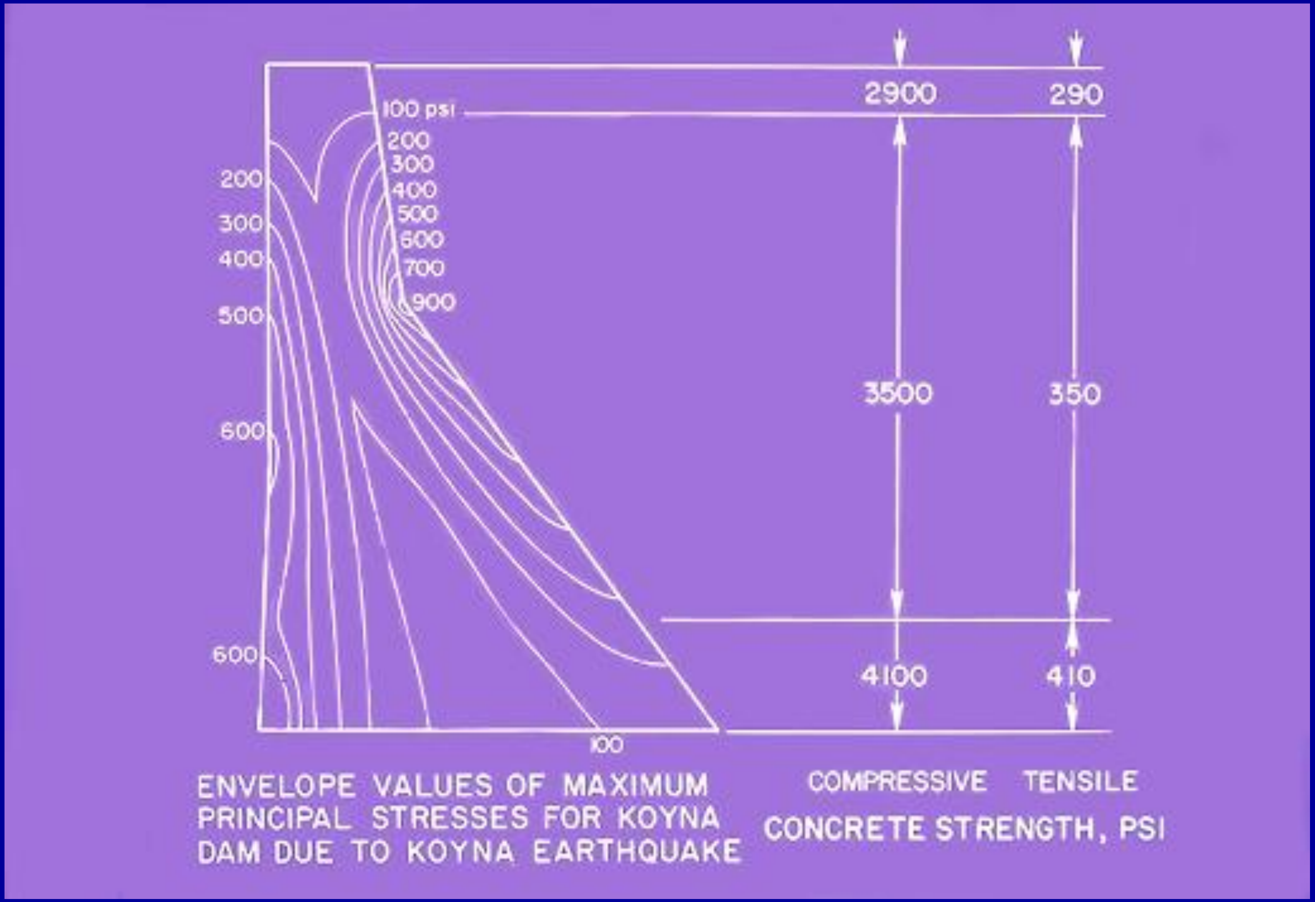
Koyna Dam: Downstream Face



Koyna Dam: Construction of Butresses

Koyna Dam After Adding Butresses

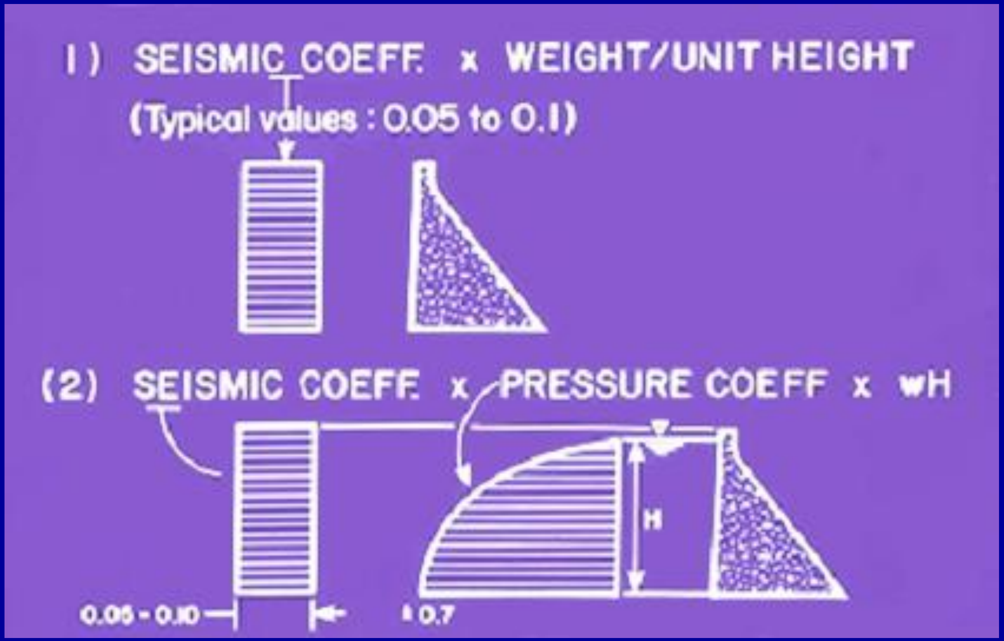
Computed Stresses v's Concrete Strength in Koyna Dam



Limitations of Traditional Design Procedures

Traditional Design Procedures

- Lateral Earthquake Forces



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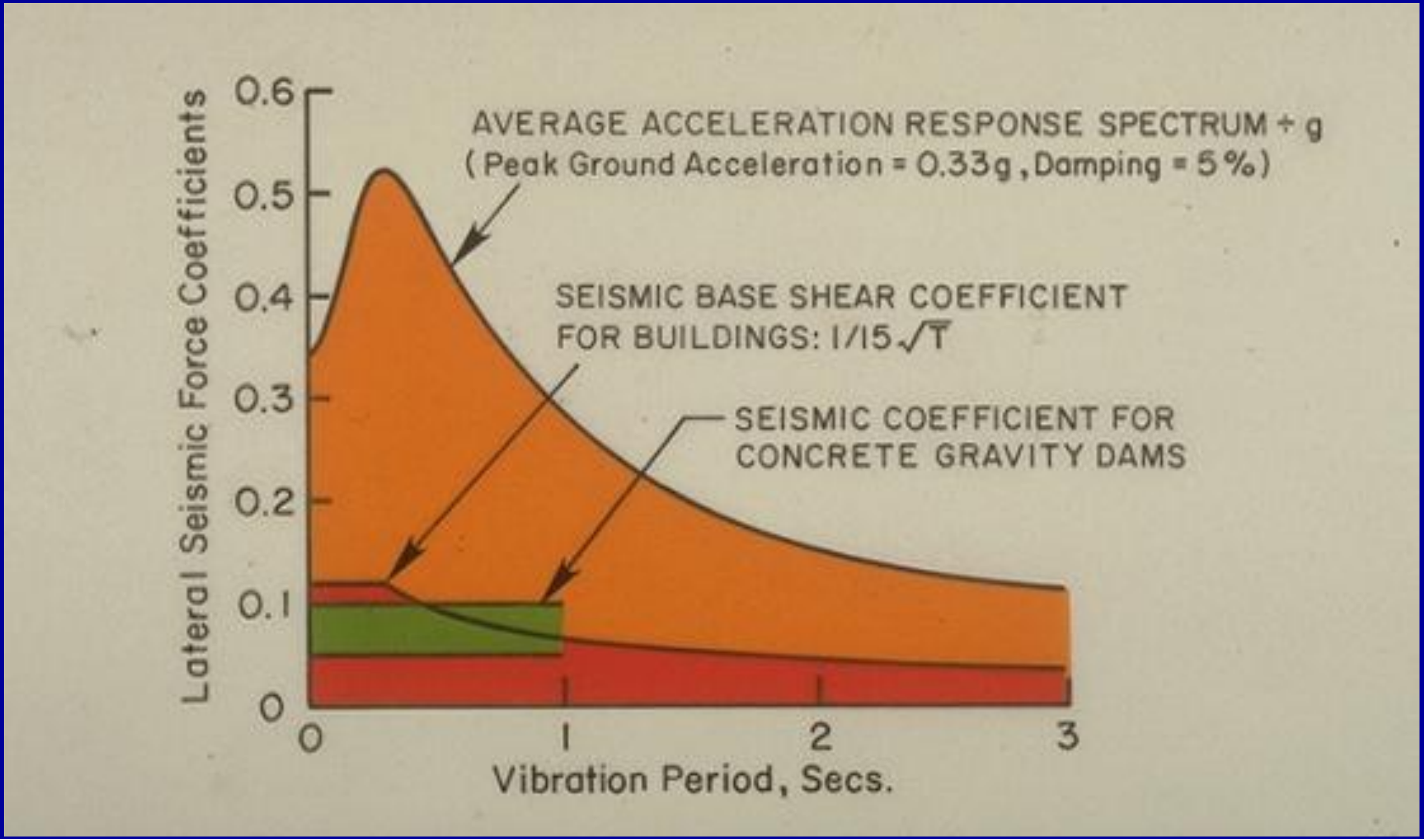
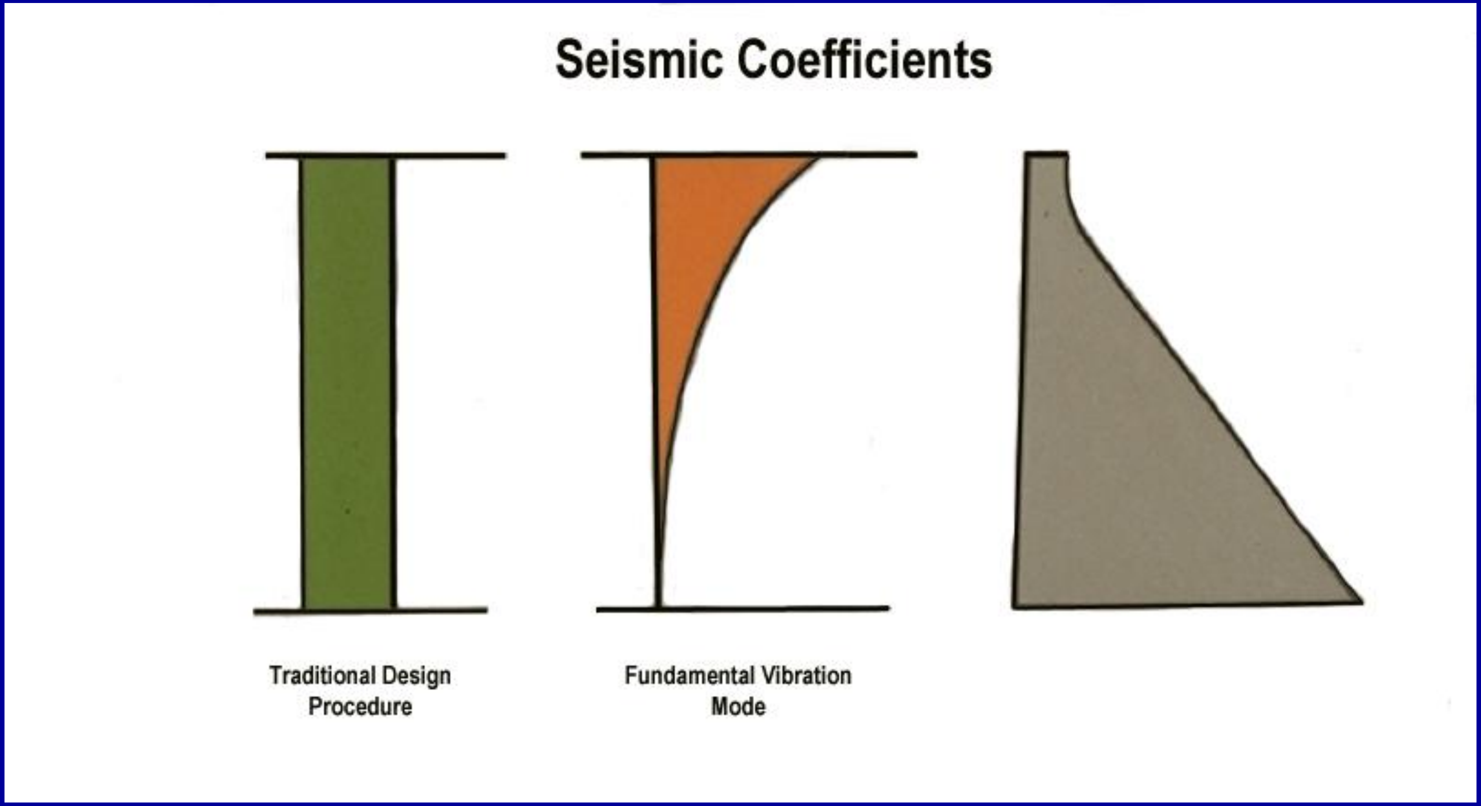
Traditional Procedures v’s Dynamic Response

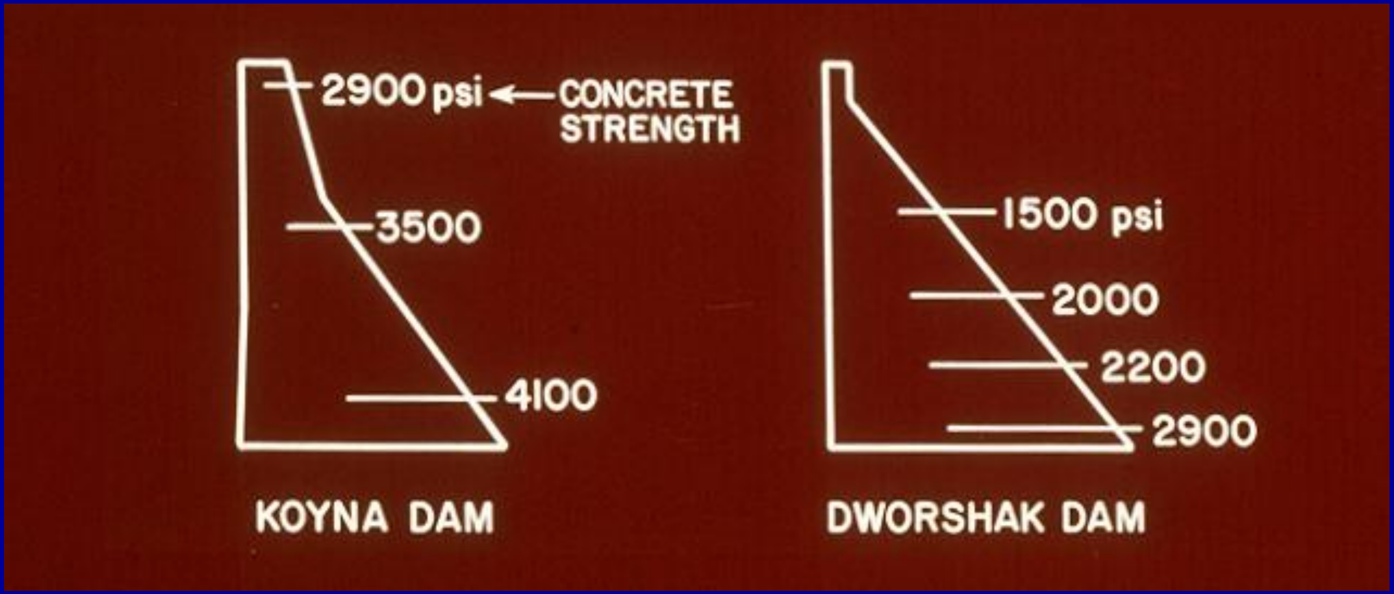


Traditional Procedures v's Dynamic Response

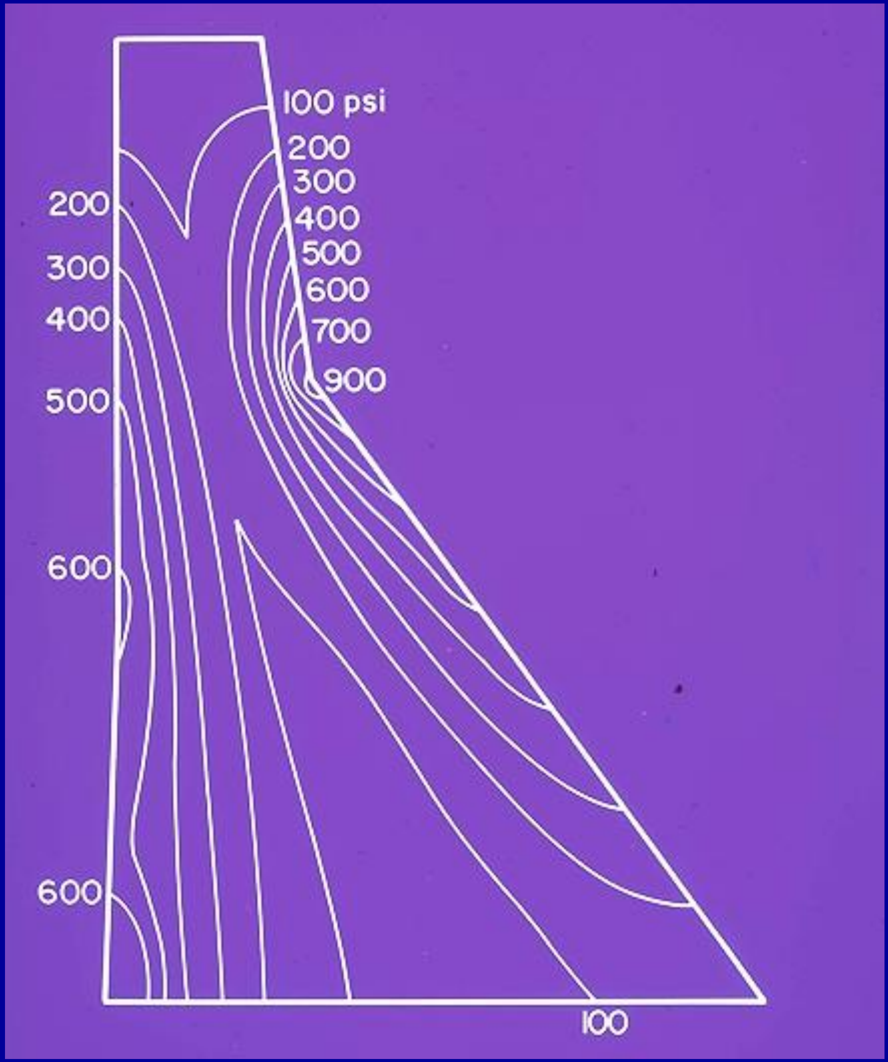


Uniform Seismic Coefficient: Undesirable Results

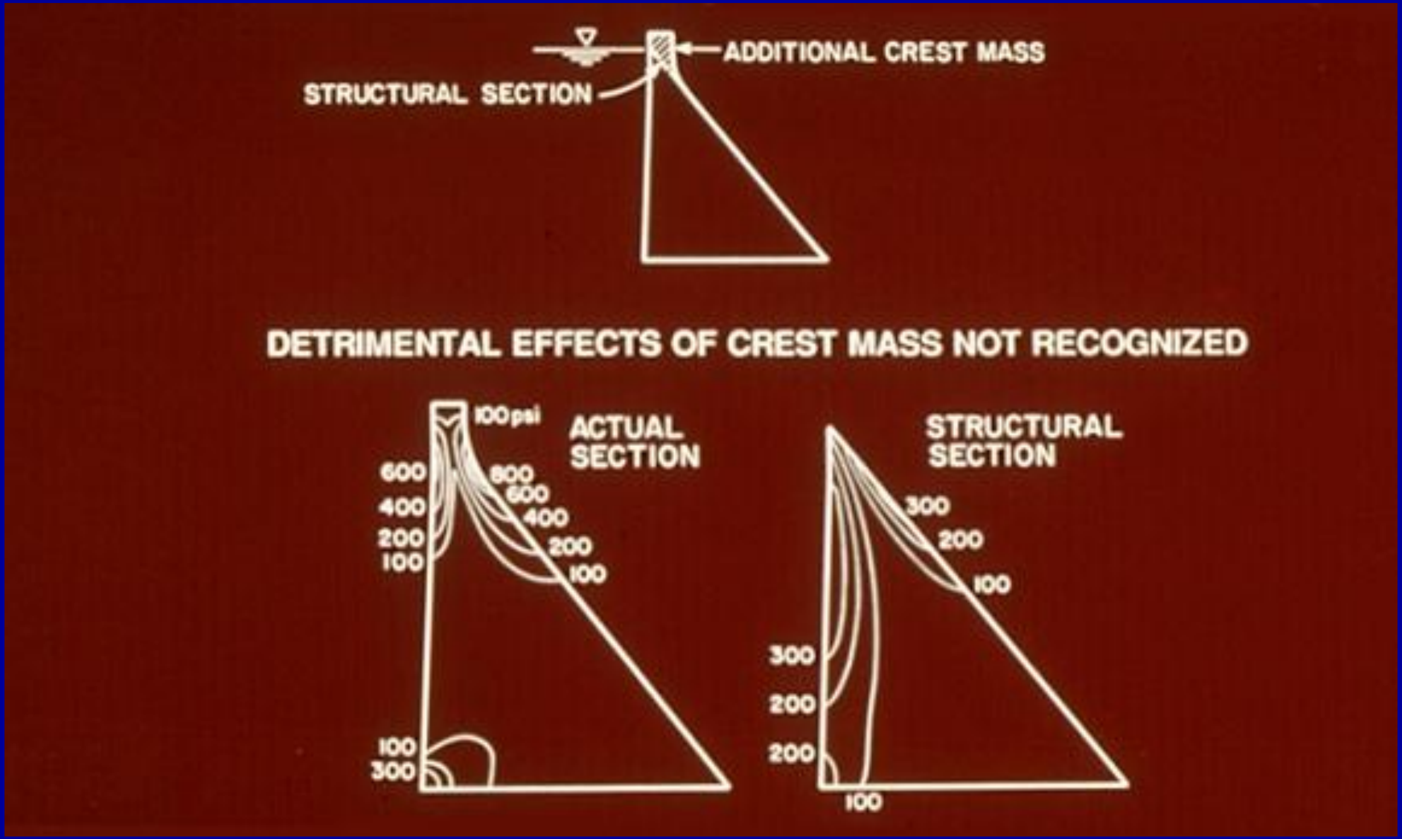
Decreasing Concrete Strength with Increase in Elevation



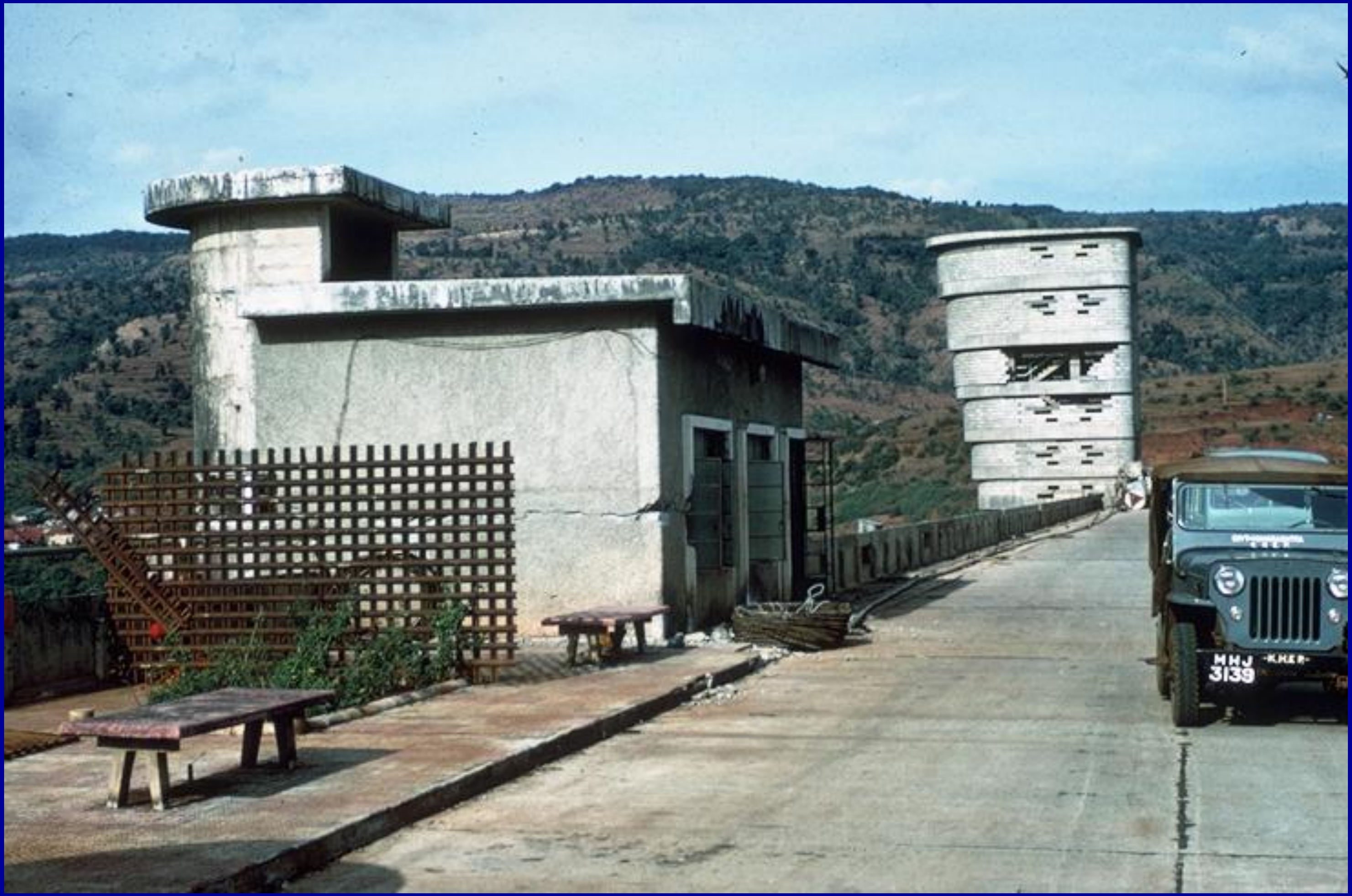
Envelope Tensile Stresses in Koyna Dam Due to Koyna Earthquake



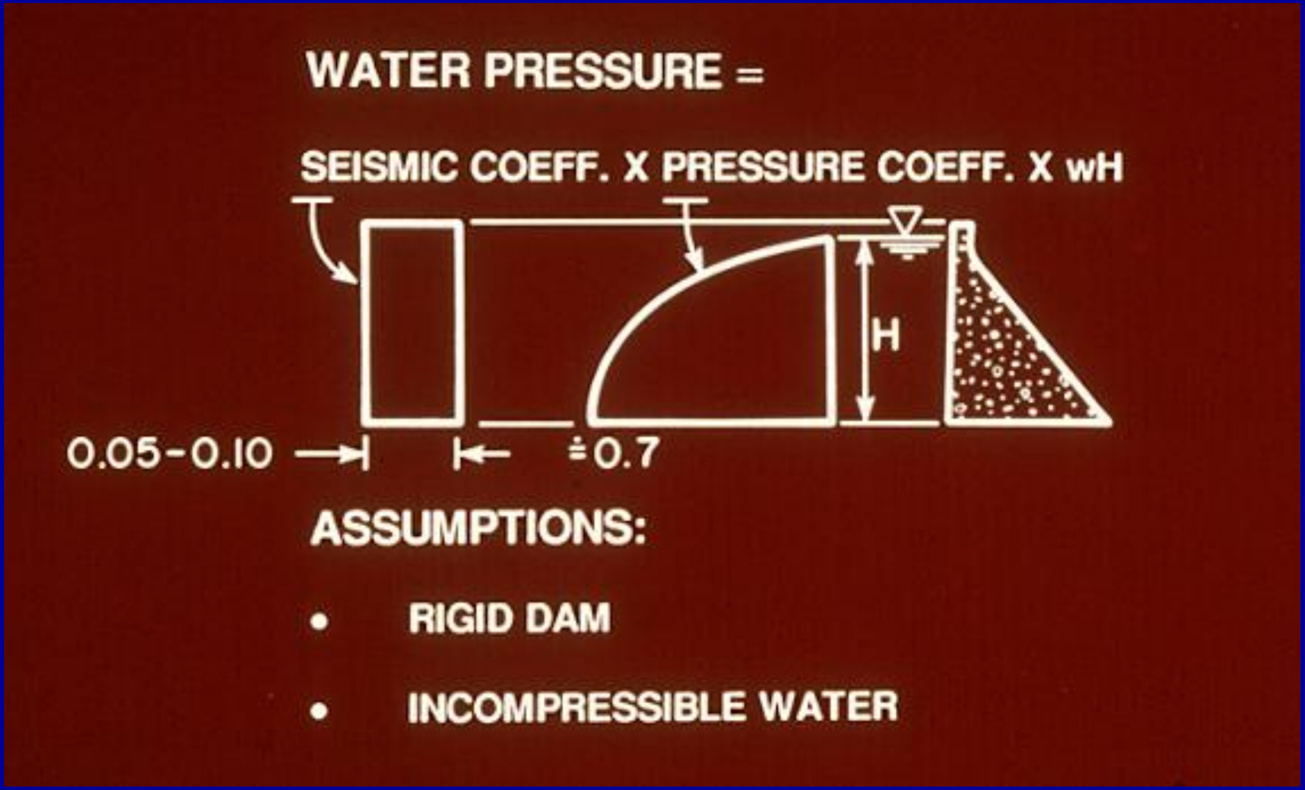
Uniform Seismic Coefficient: Undesirable Results



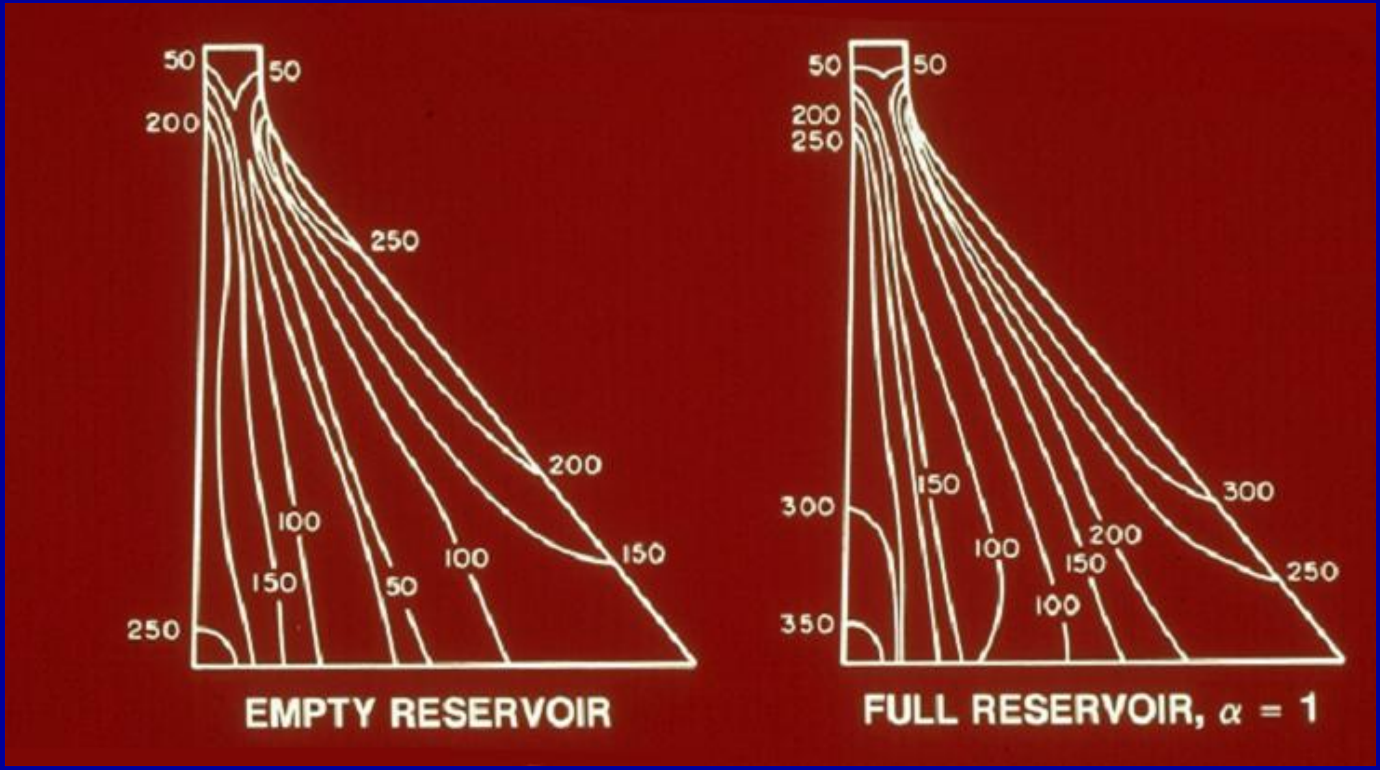
Structures on Dam Crest



Traditional Design Procedures



Hydrodynamic Effects
Upstream Ground Motion

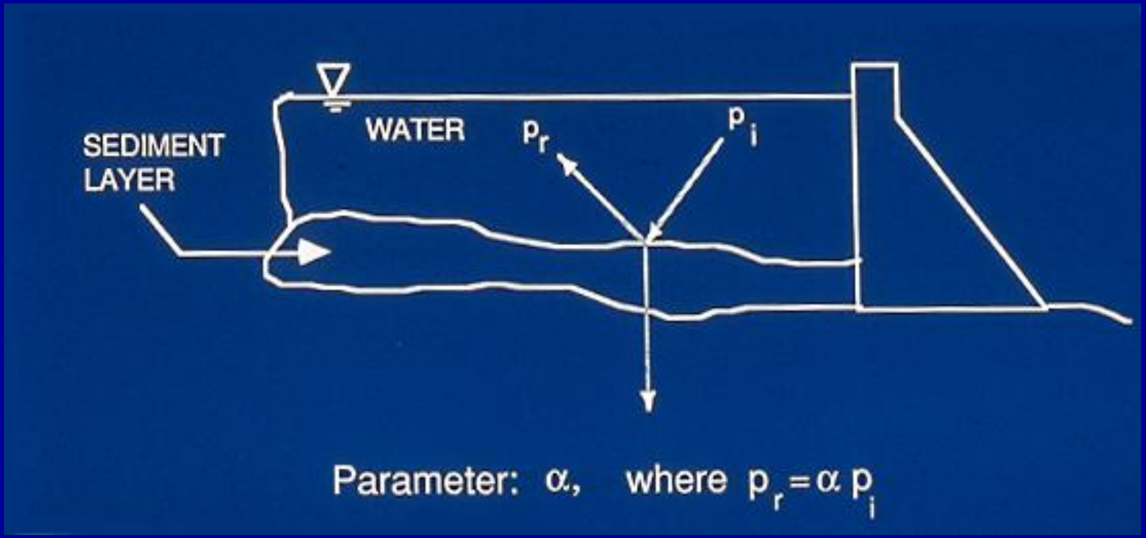


Analyses in Traditional Design Procedures Do Not Recognize:

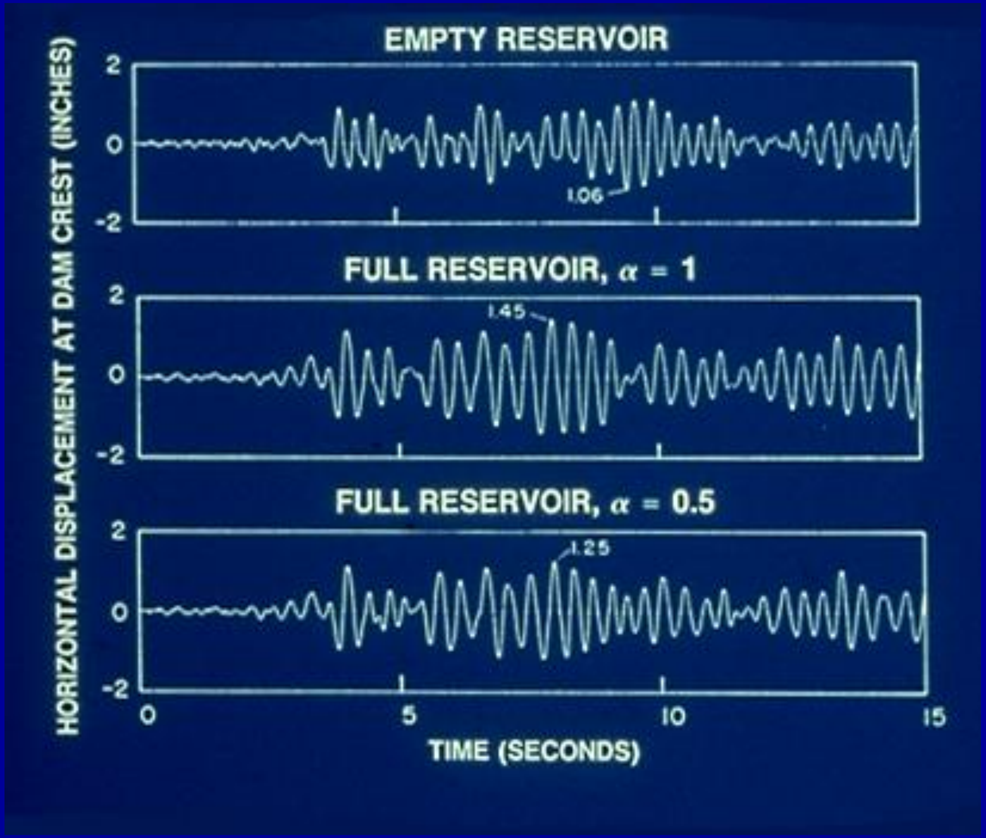
- Dynamic response of dam
- Hydrodynamic effects
- Earthquake ground motion properties
- Dam-foundation rock interaction

Factors To Be Considered in Dynamic Analysis

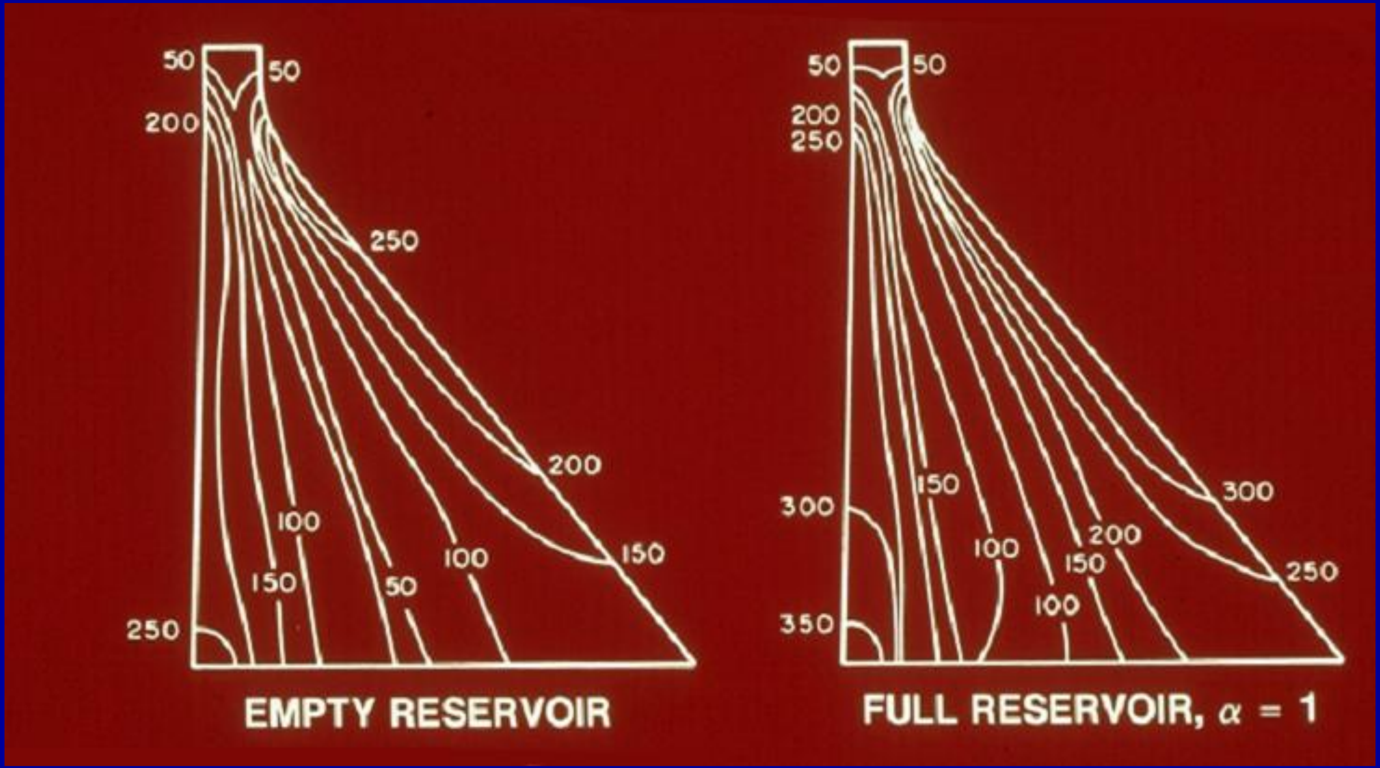
Approximate Interaction Model



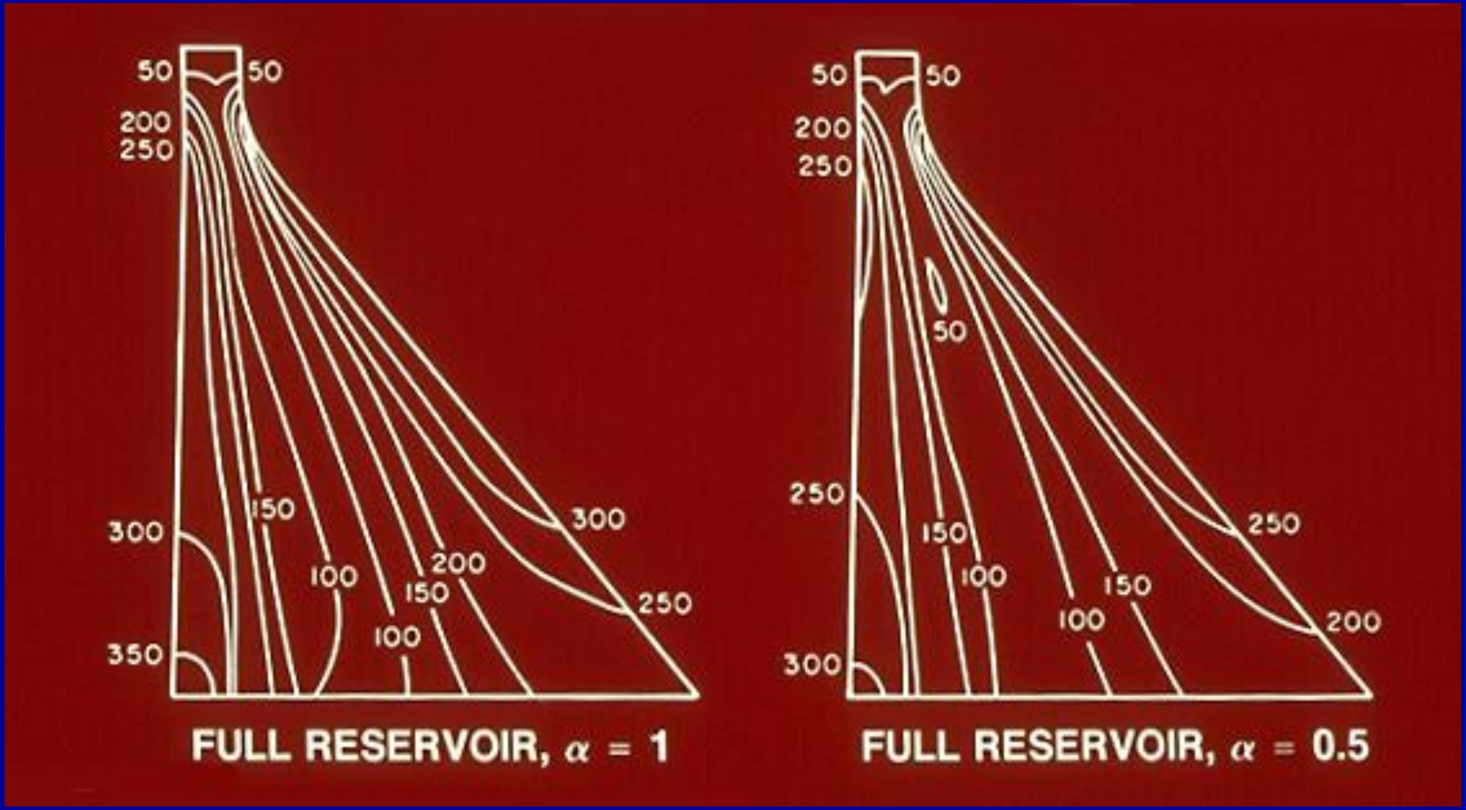
Hydrodynamic and Reservoir Bottom Absorption Effects
Upstream Ground Motion



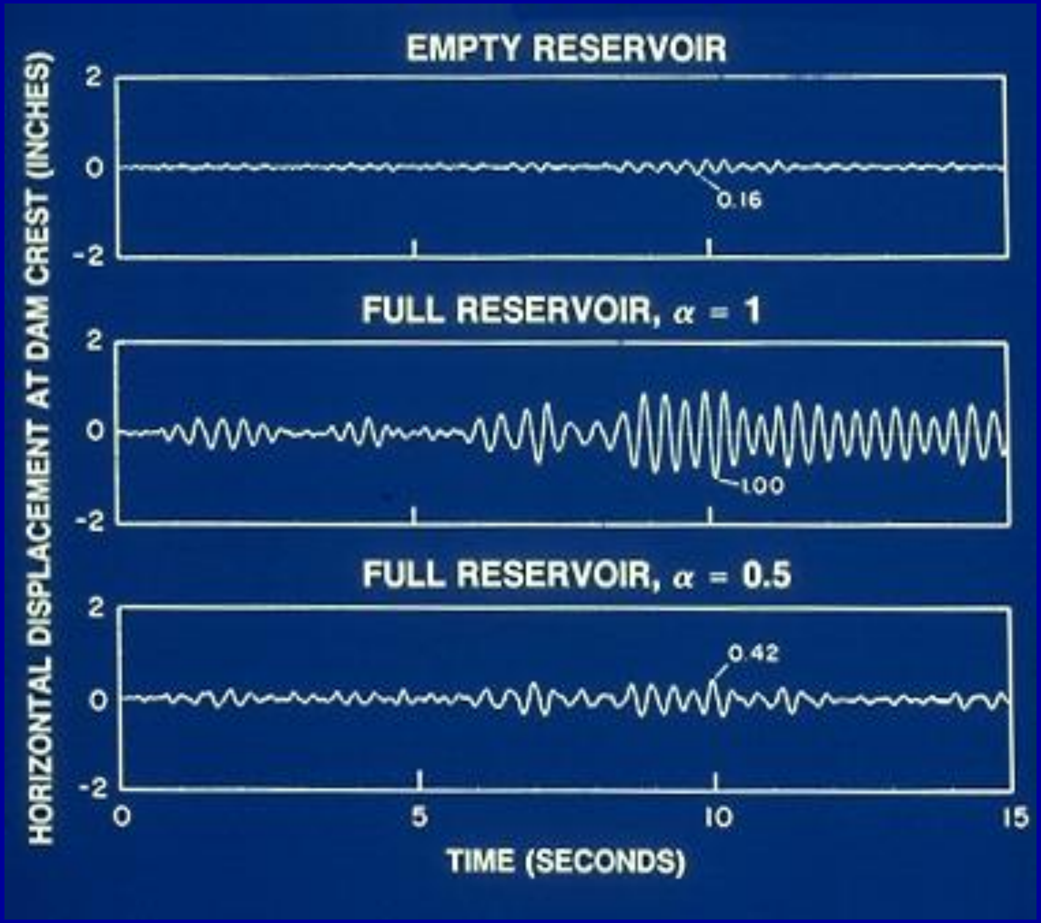
Hydrodynamic Effects
Upstream Ground Motion



Reservoir Bottom Absorption Effects Upstream Ground Motion

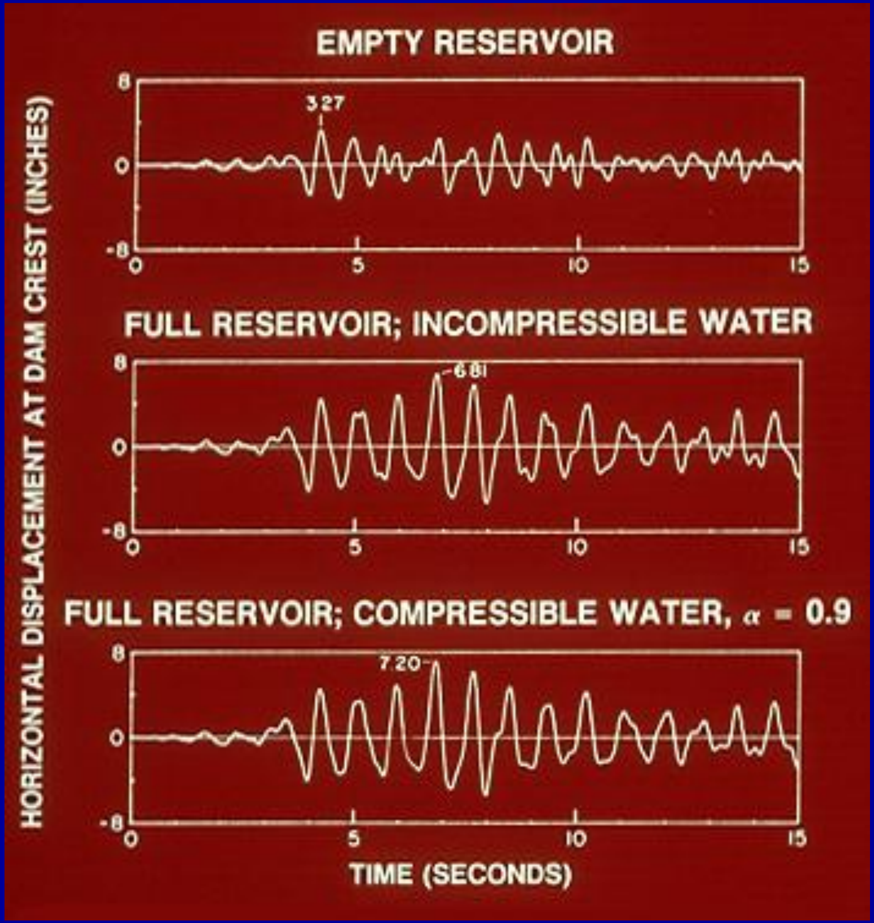


Hydrodynamic and Reservoir Bottom Absorption Effects
Vertical Ground Motion



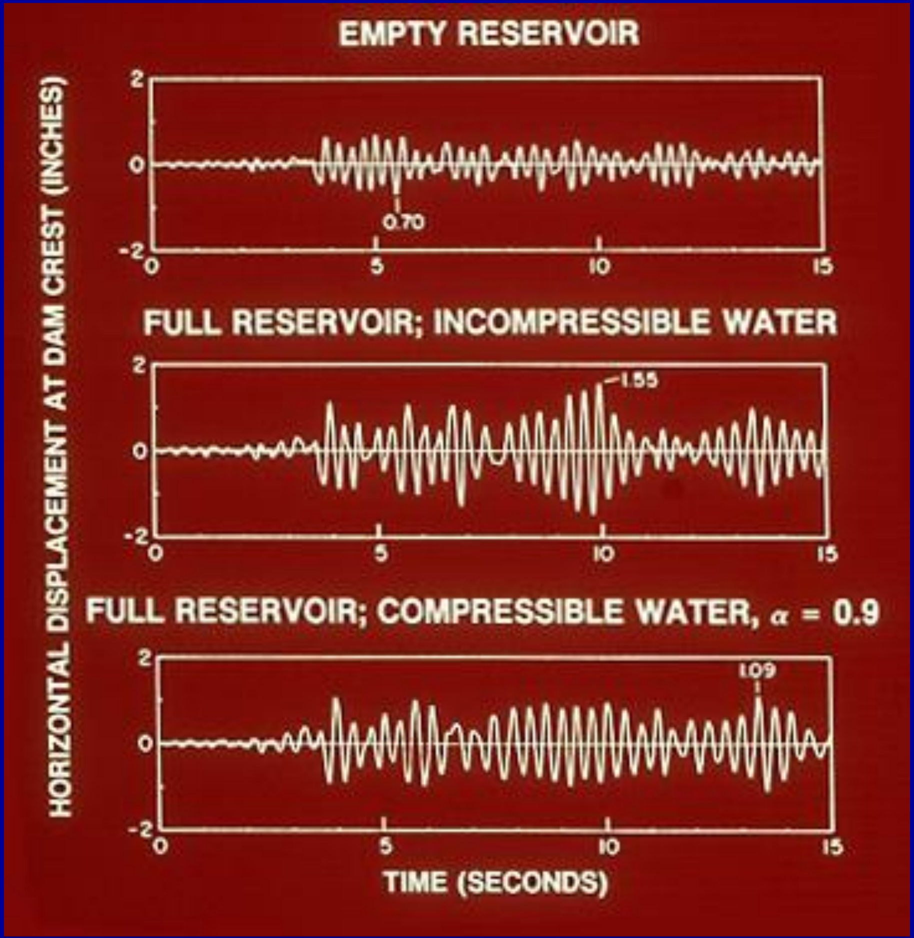
Water Compressibility Effects Upstream Ground Motion

E_s = 0.65 million psi

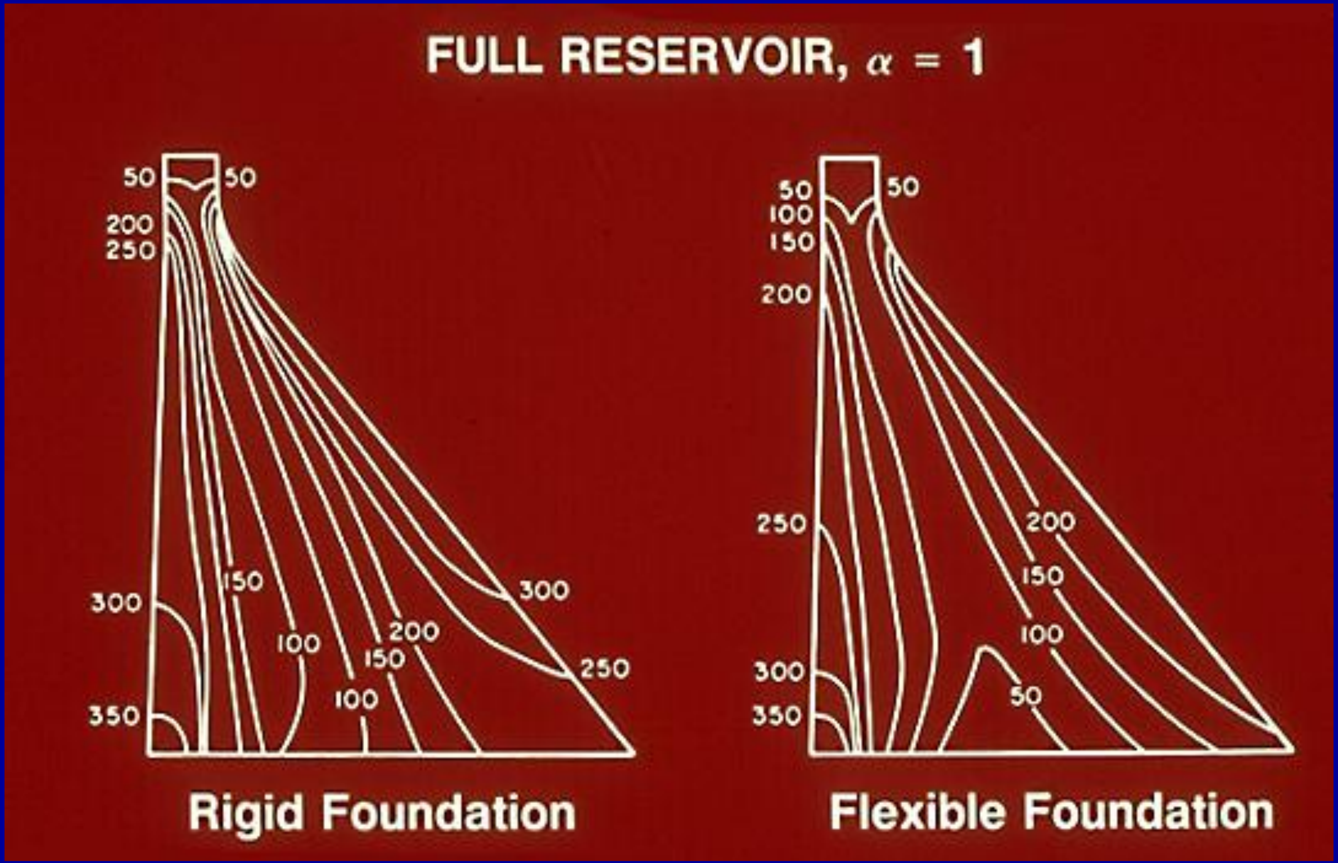


Water Compressibility Effects Upstream Ground Motion

E_s = 4.0 million psi



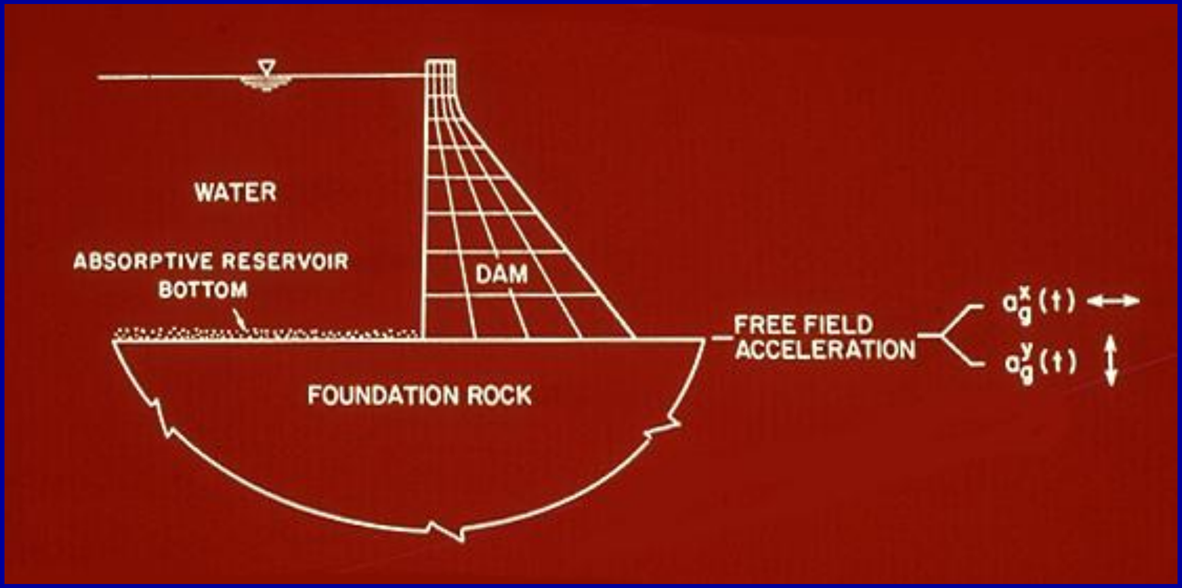
Foundation Interaction Effects
Upstream Ground Motion



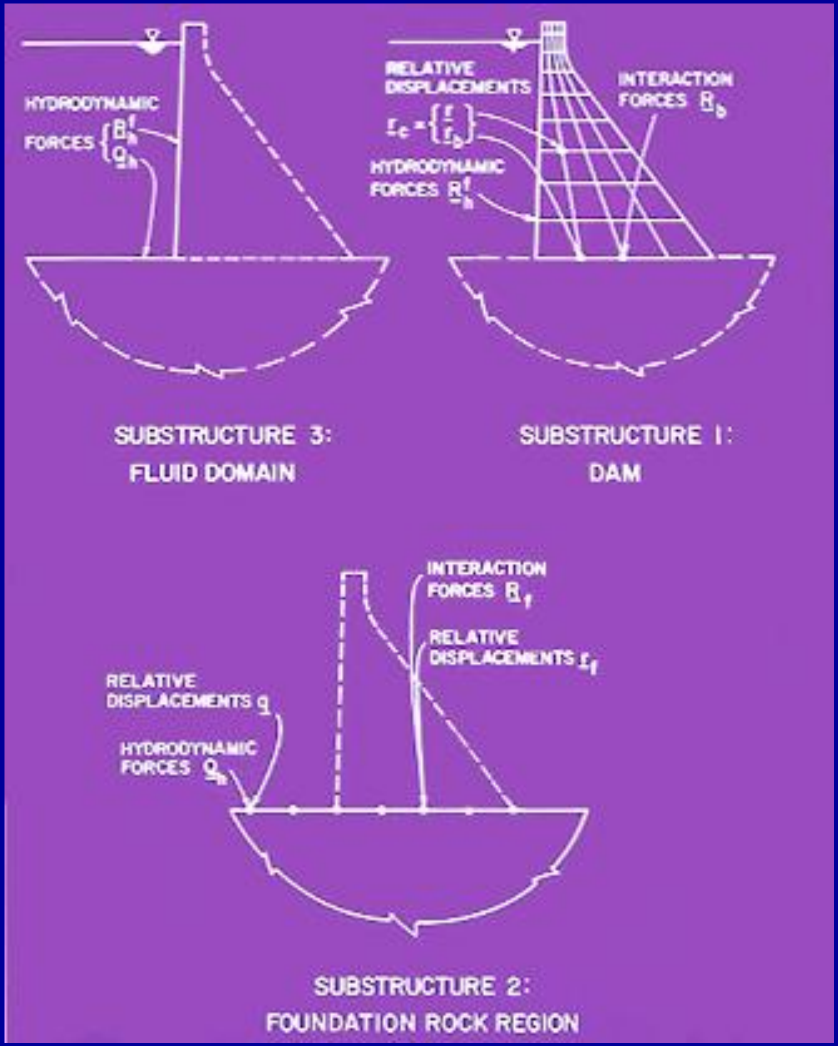
Dynamic Analysis Procedures

Dam-Water-Foundation Rock System

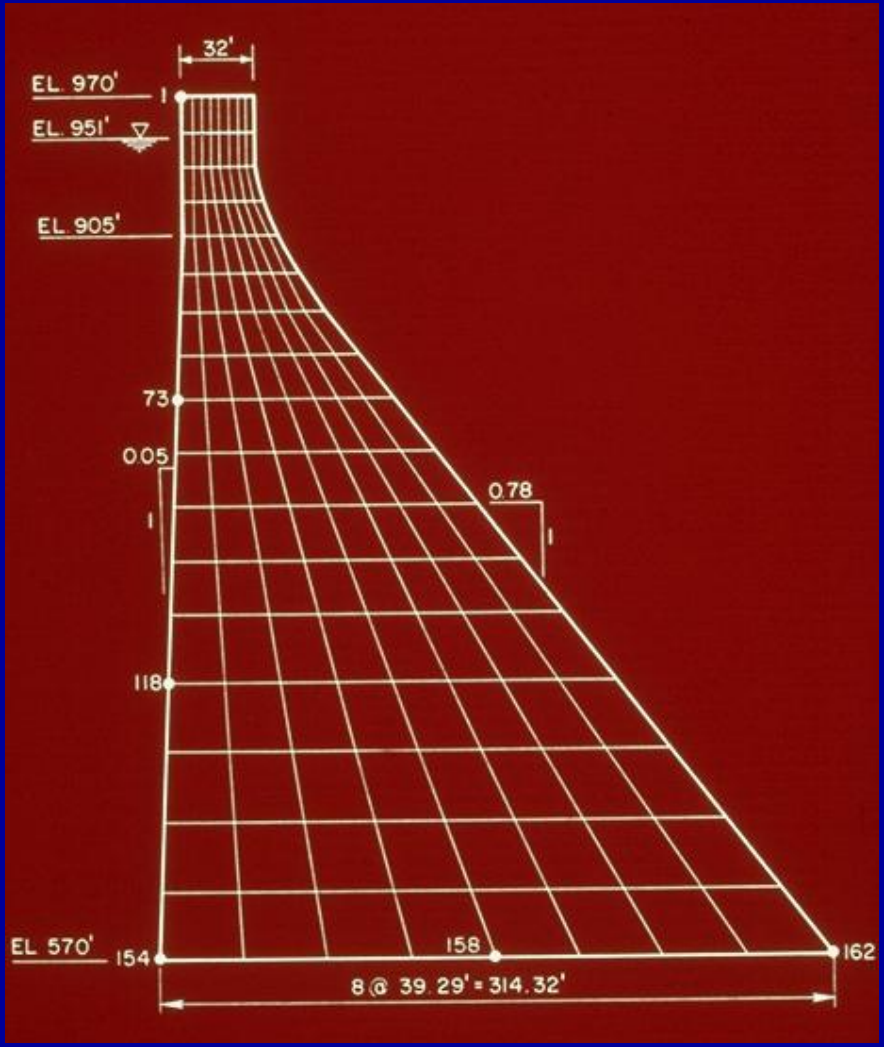
- Factors to consider
  - Dynamics of system
  - Dam-water interaction including water compressibility
  - Reservoir bottom absorption
  - Dam-foundation rock interaction



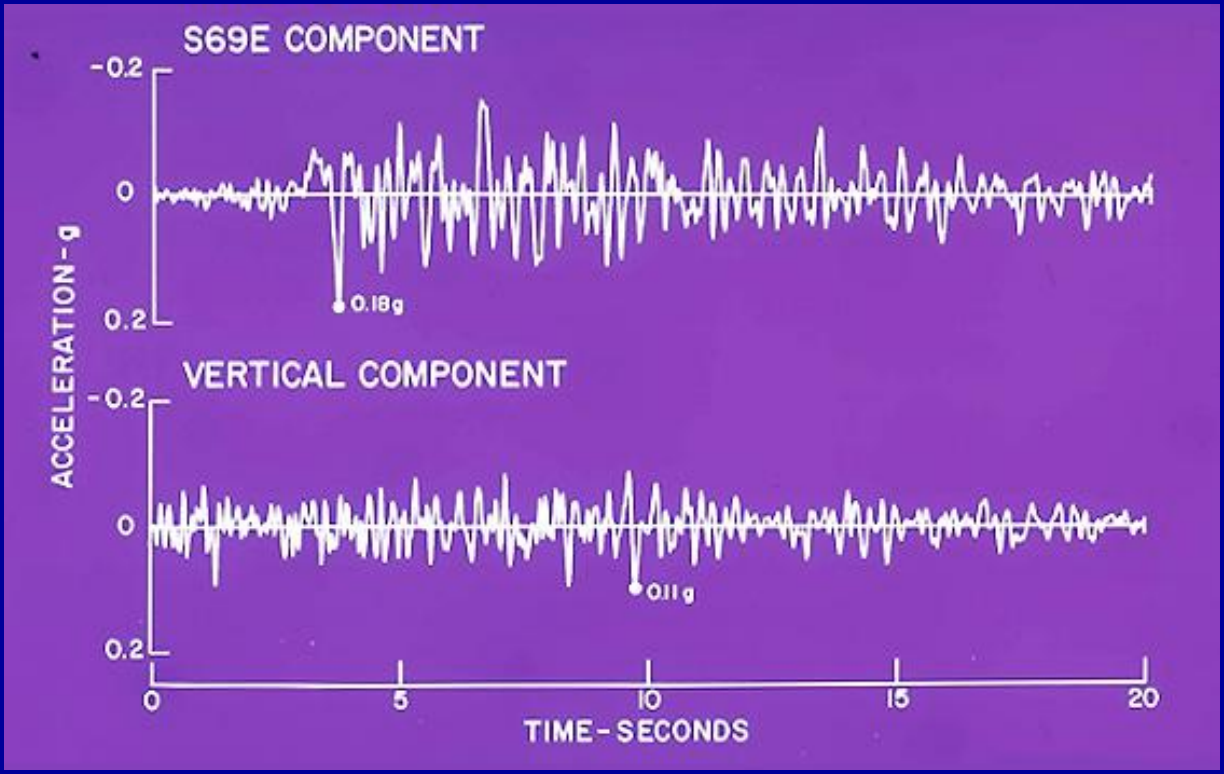
Substructure Representation of Dam-Water-Foundation Rock System



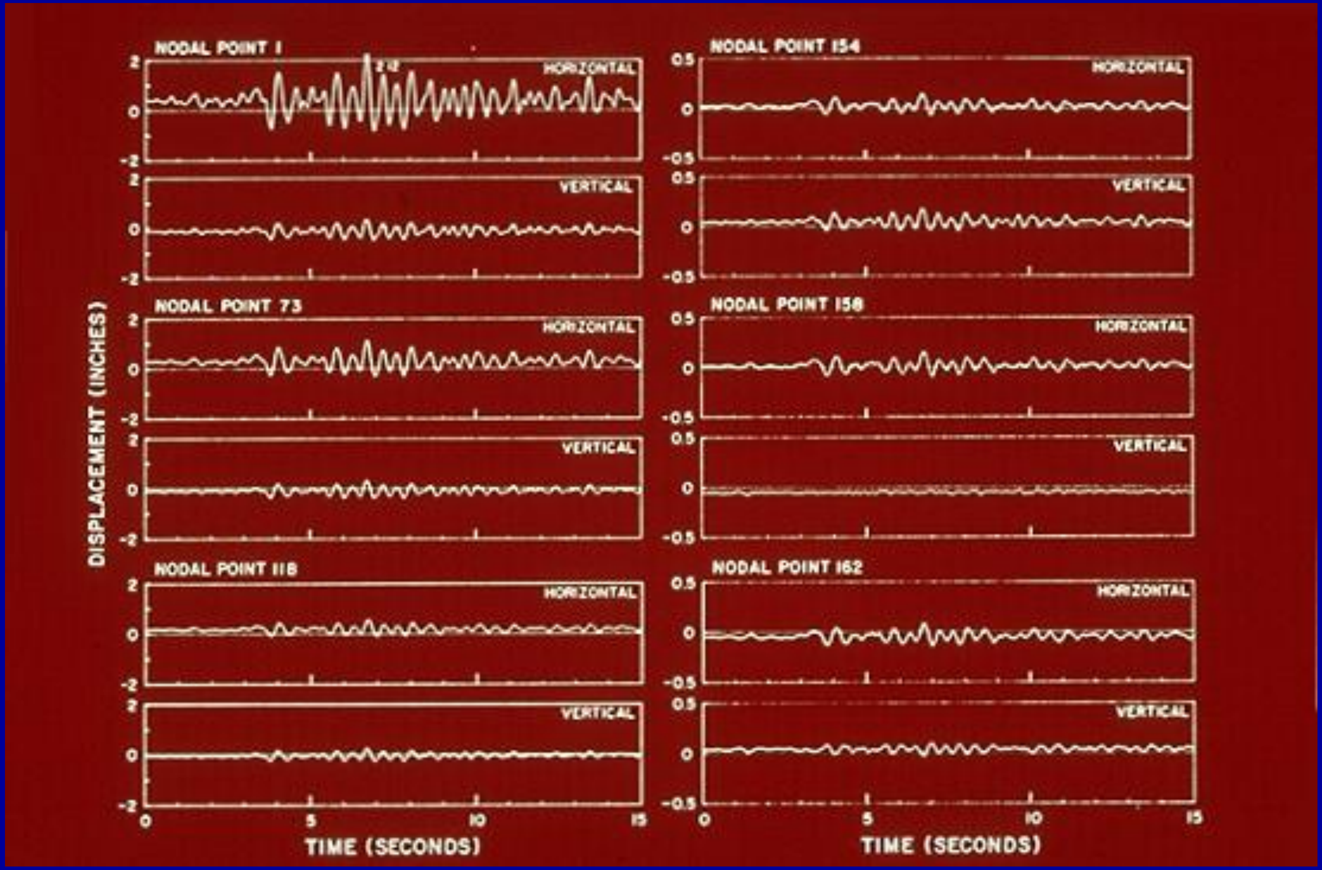
Pine Flat Dam: Finite Element Model



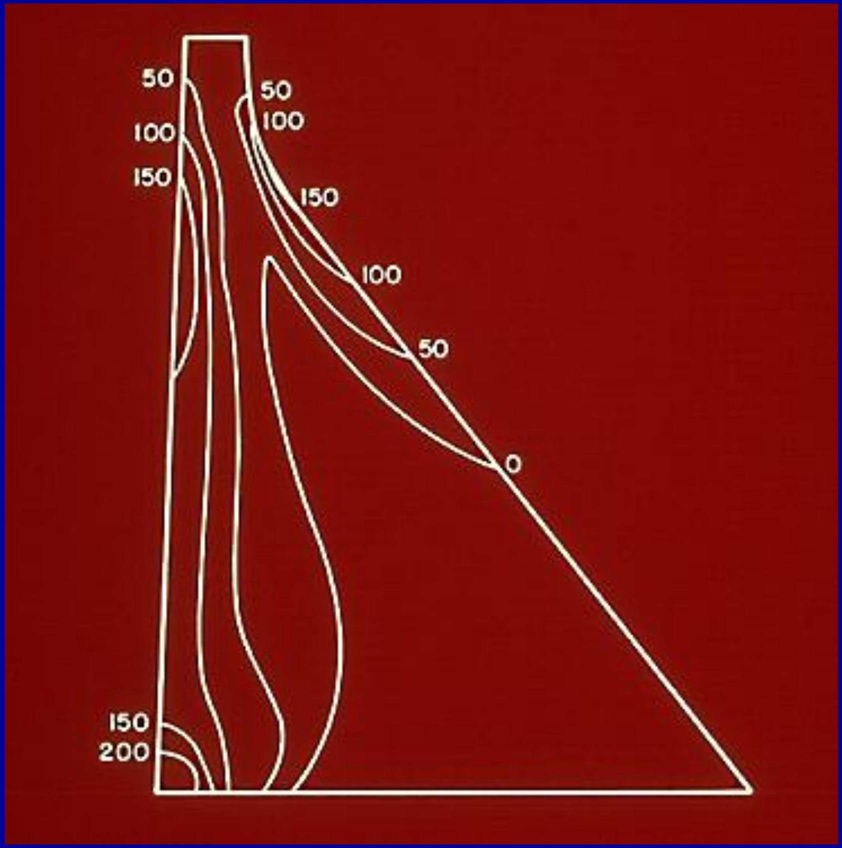
Taft Ground Motion, 1952



Displacement Response
Pine Flat Dam – Taft Ground Motion



Critical Stresses
Pine Flat Dam – Taft Ground Motion



Pine Flat Dam

Forced Vibration Generator

Hydrodynamic Pressure Gauge

Acceleration and Pressure Frequency Responses

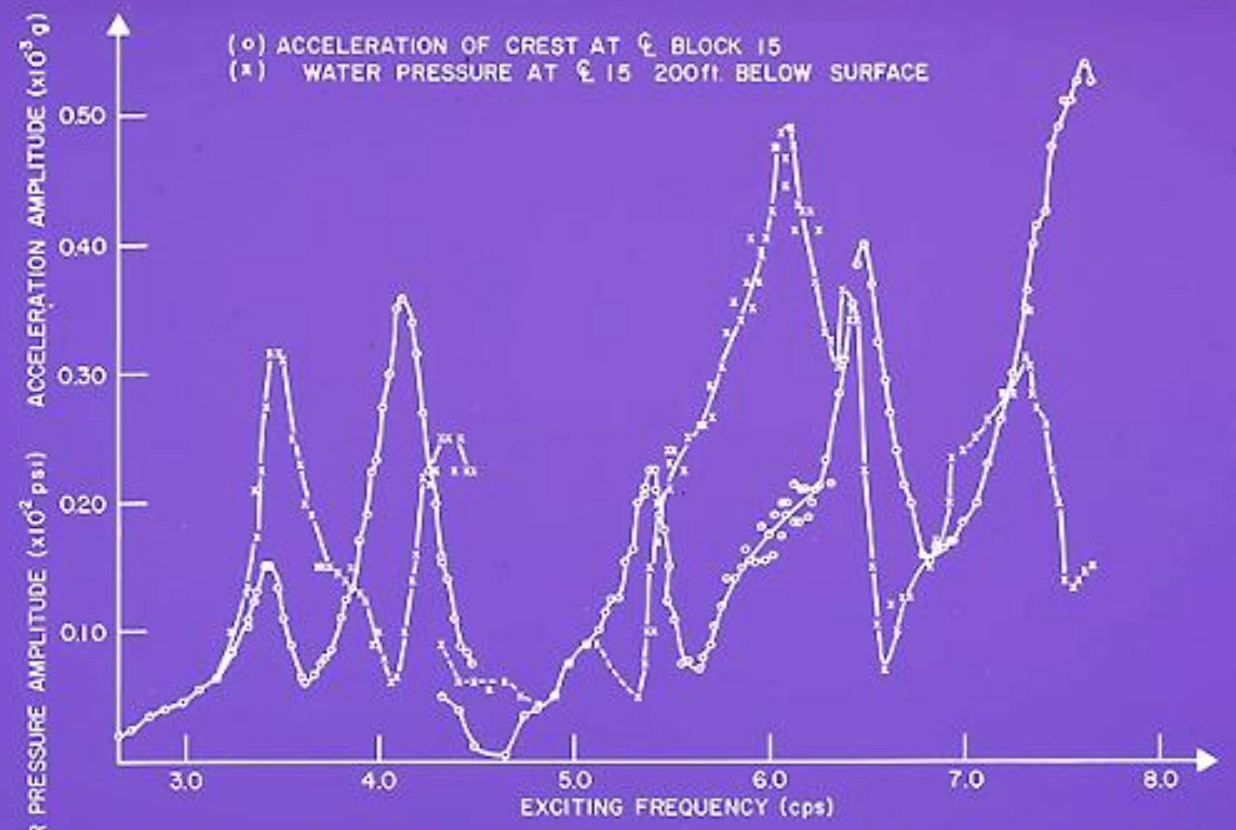
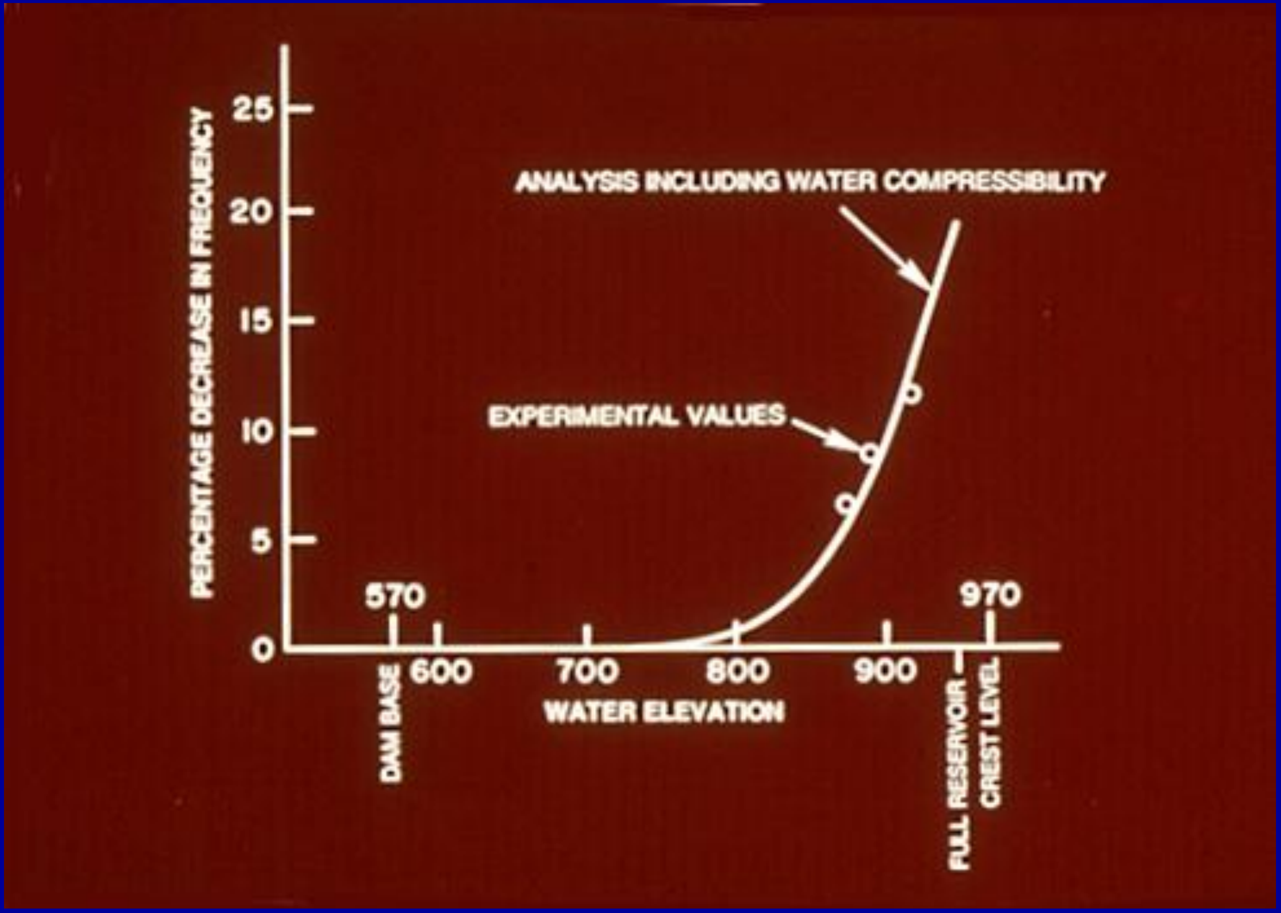


FIG.12 CORRESPONDING ACCELERATION AND PRESSURE FREQUENCY RESPONSES: JAN-FEB, 1971

Reduction in Fundamental Frequency Due to Water Analytical v's Experimental Results

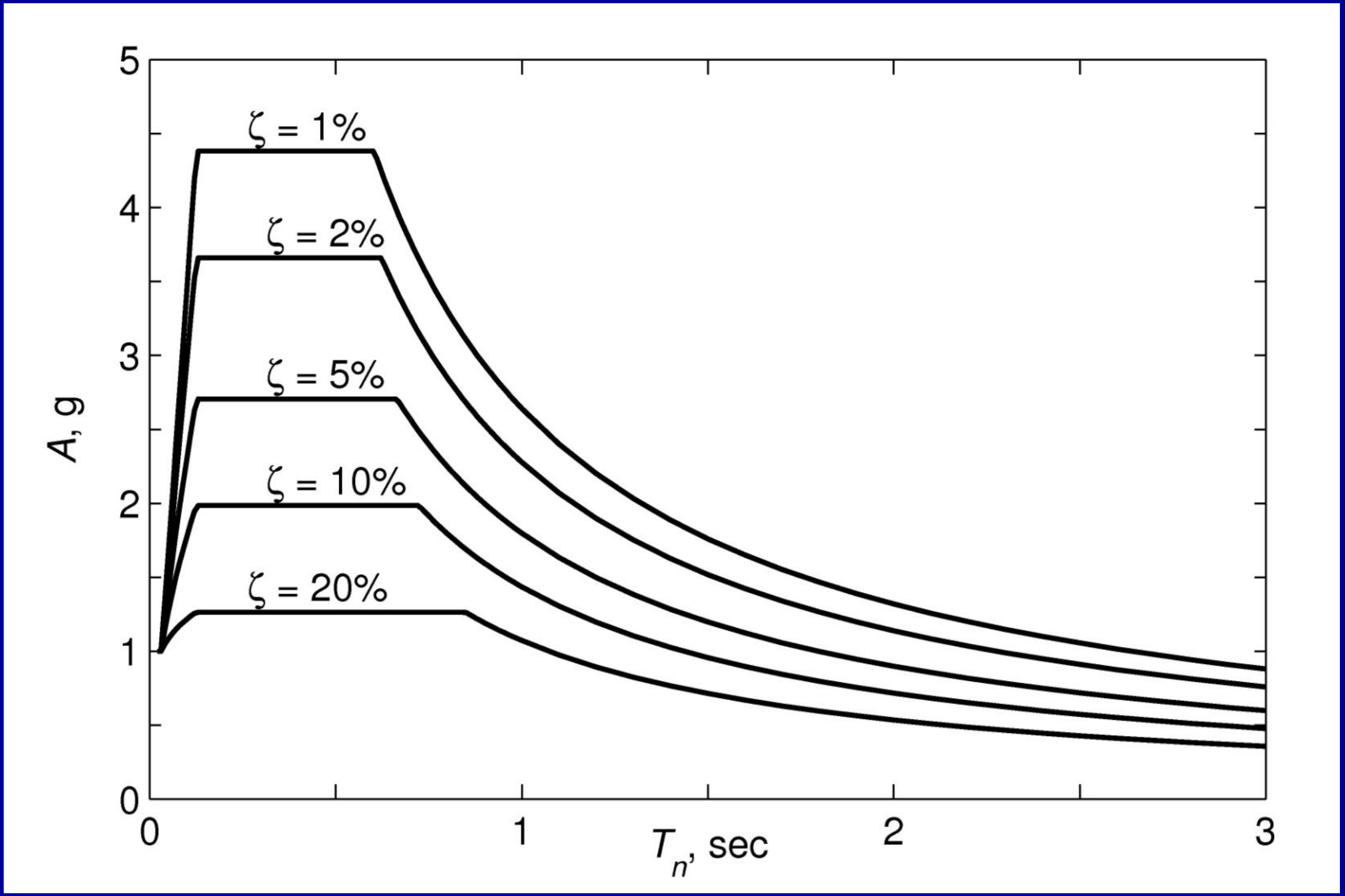


Simplified Analysis Procedure

Simplified Analysis Procedure

- Purpose: Preliminary design and safety evaluation
- Objective: Maximum forces from earthquake spectrum
- Concepts:
  - Fundamental mode response (considering dam-water-foundation rock interaction) from an equivalent SDF system
  - Higher mode response (neglecting both interaction effects) by “static correction” method
  - SRSS combination of the two responses

Earthquake Design Spectrum



Critical Stresses

Lateral Forces → static analysis → Stresses

$f_1(y)$ $\quad$ r_1

$f_{sc}(y)$ $\quad$ r_{sc}

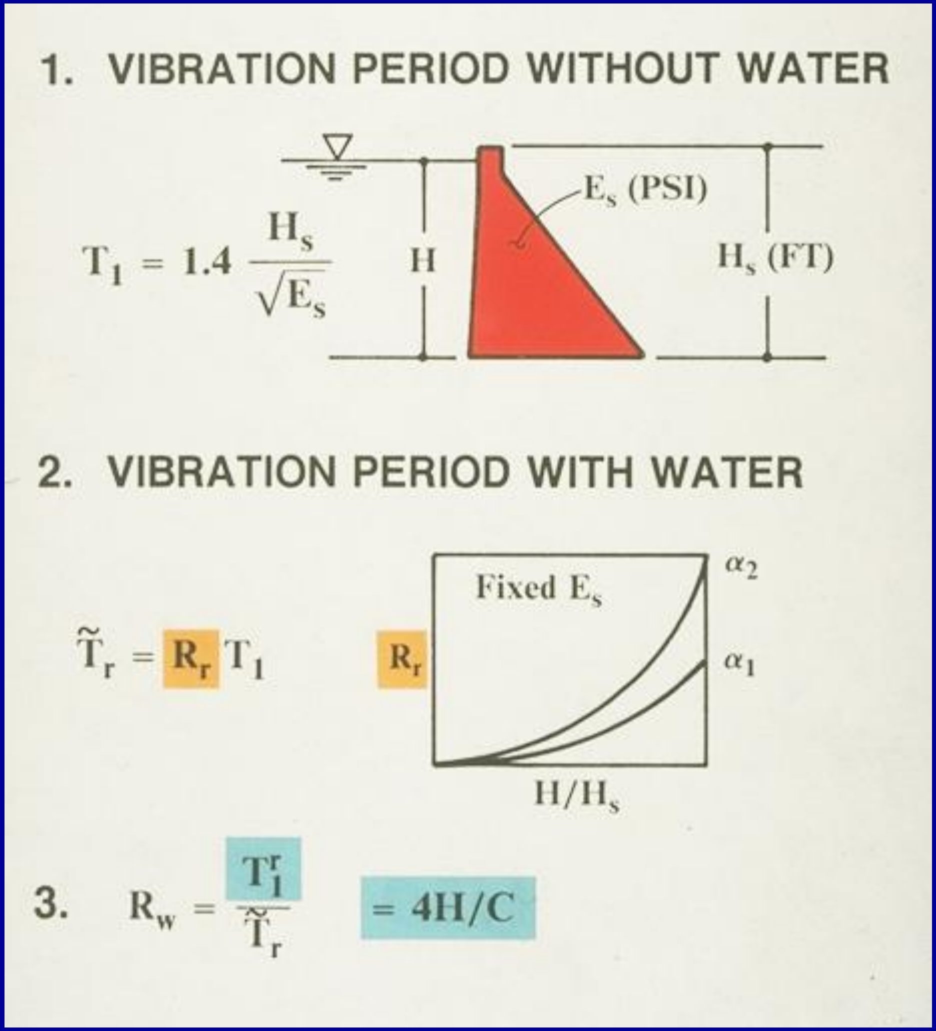
Dynamic Response

$$r_d = \sqrt{(r_1)^2 + (r_{sc})^2}$$

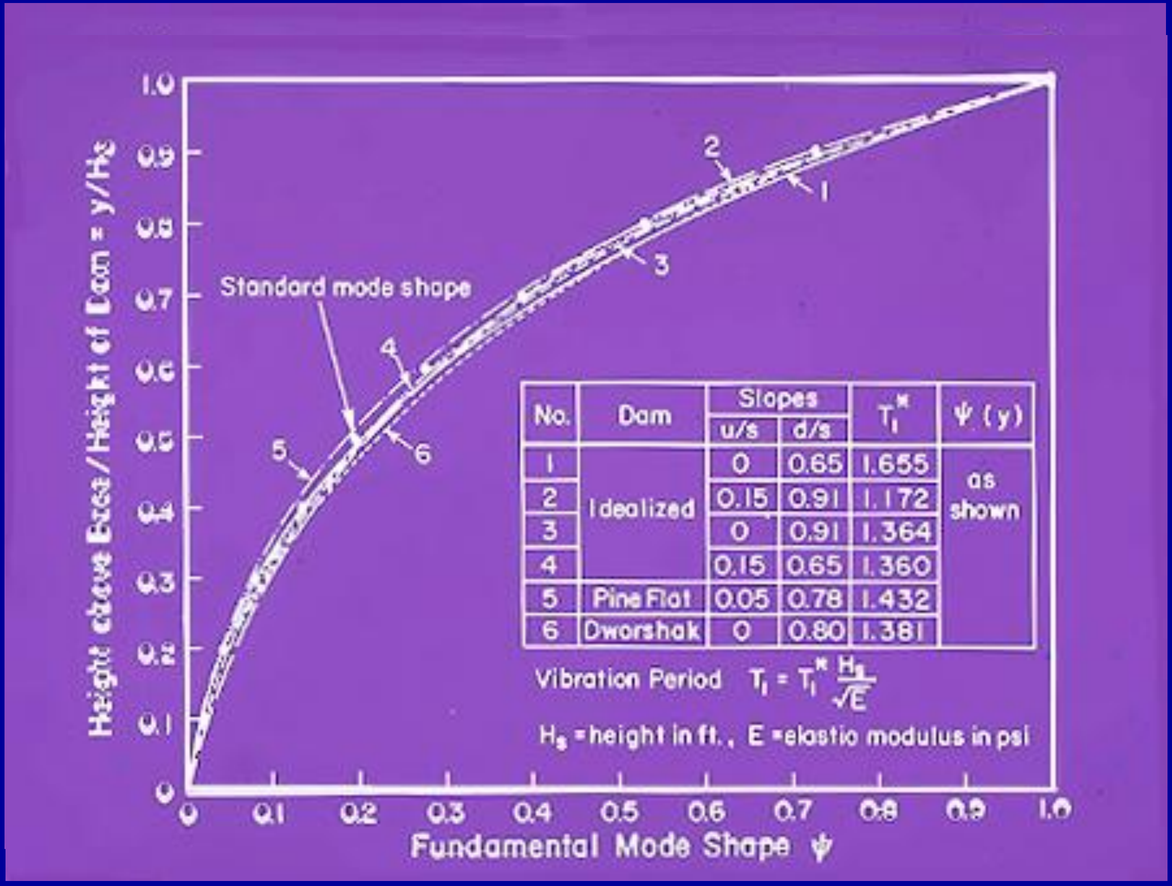
Total Response

$$r_{\max} = r_{st} \pm \sqrt{(r_1)^2 + (r_{sc})^2}$$

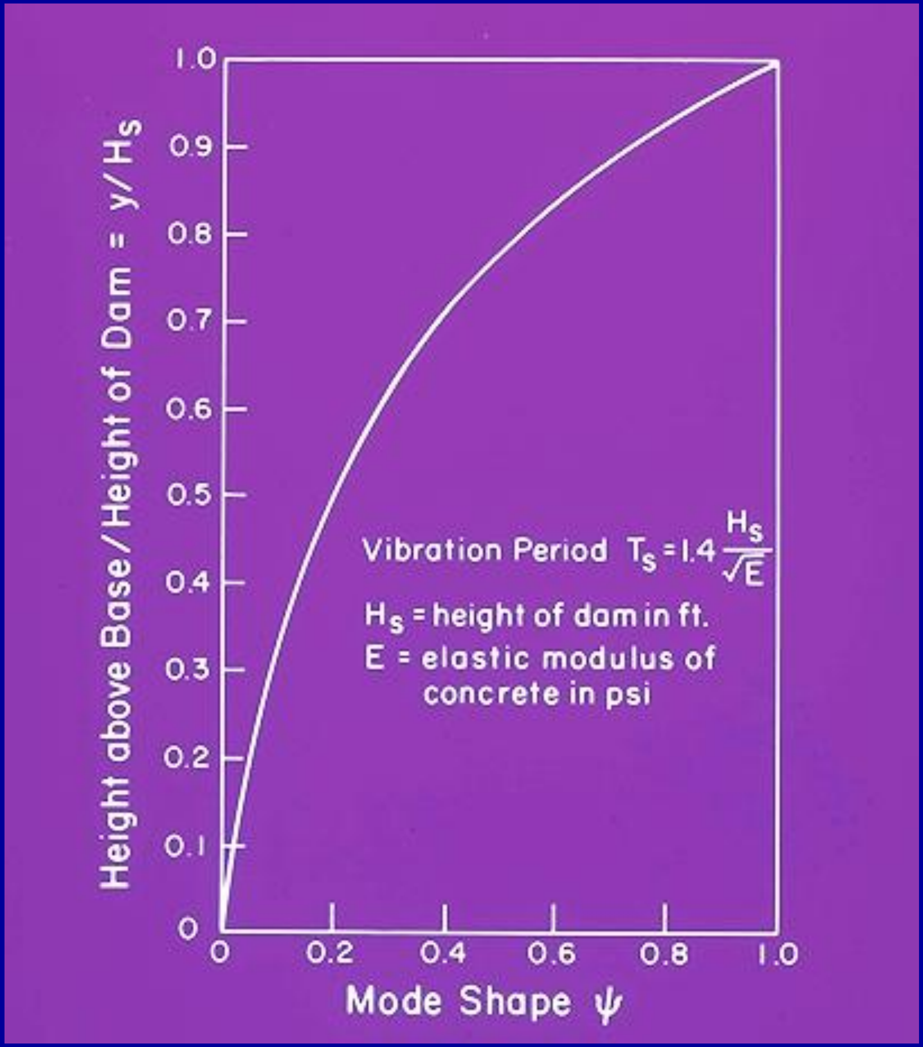
Lateral Earthquake Forces
Fundamental Vibration Mode



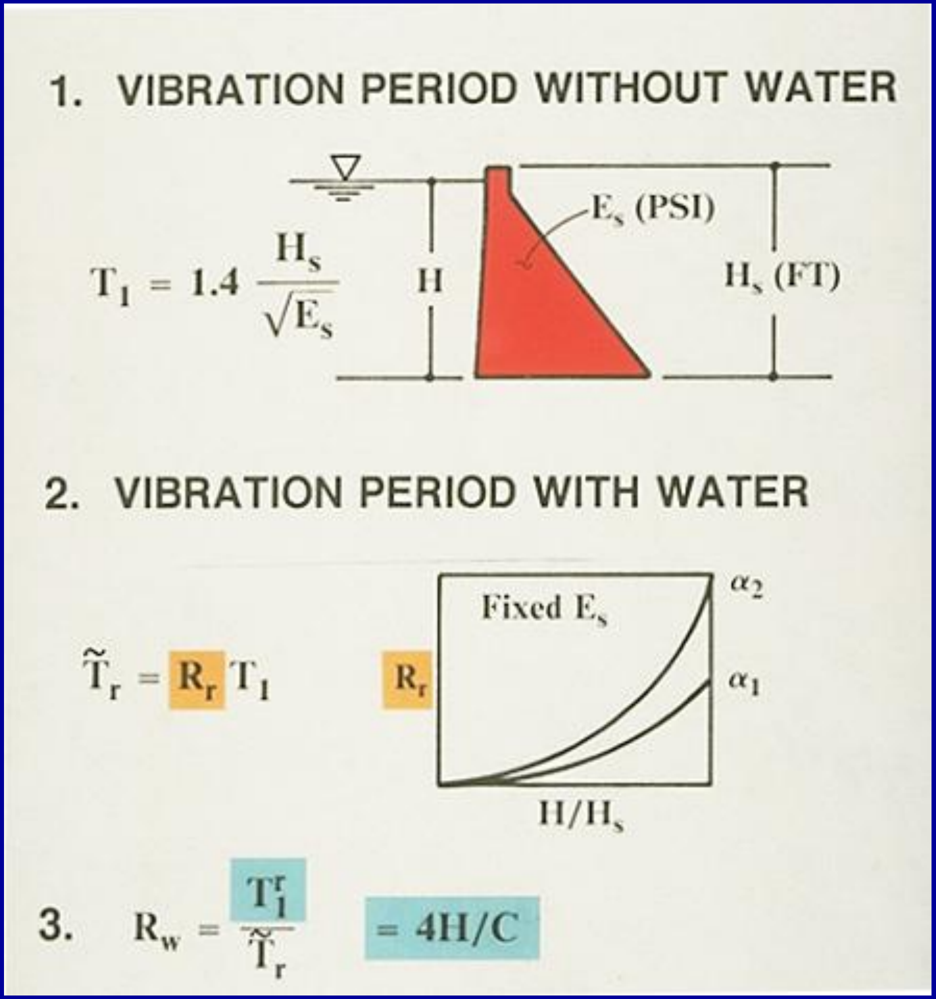
Fundamental Vibration Period and Mode: Several Cross Sections



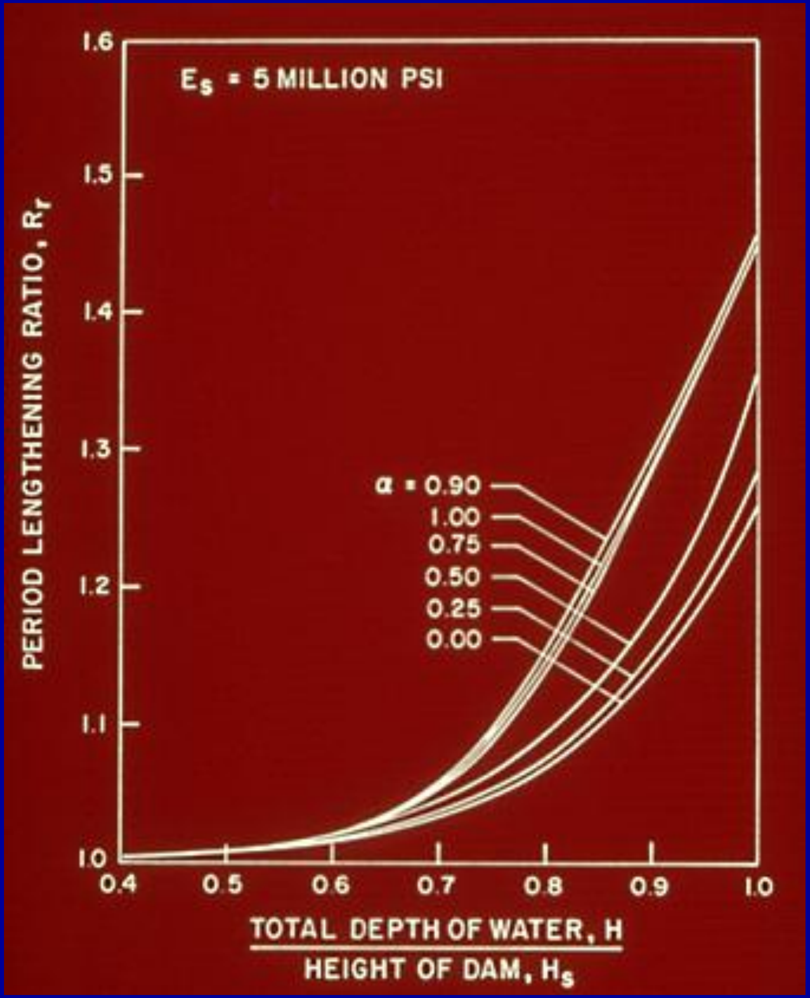
Standard Fundamental Period and Mode Shape of Vibration for Dam Design



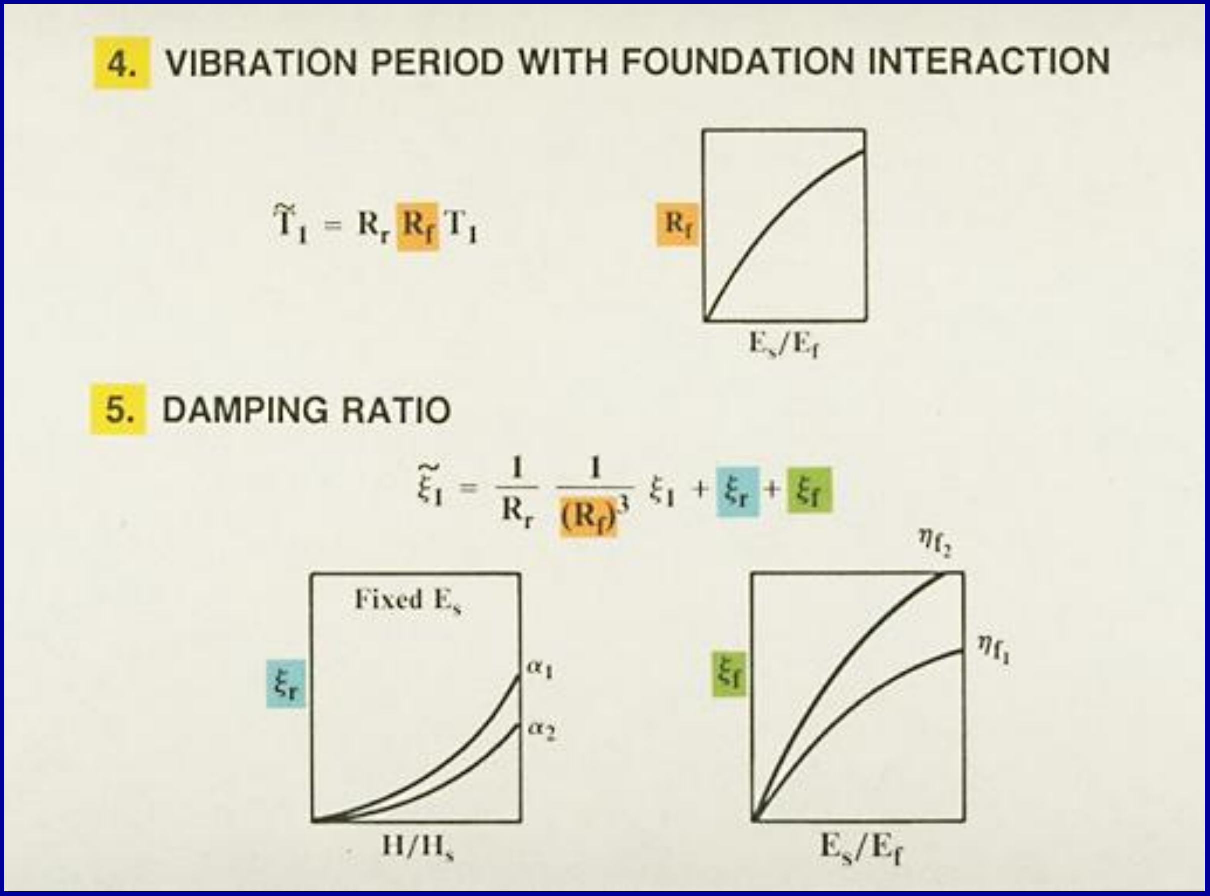
Lateral Earthquake Forces
Fundamental Vibration Mode



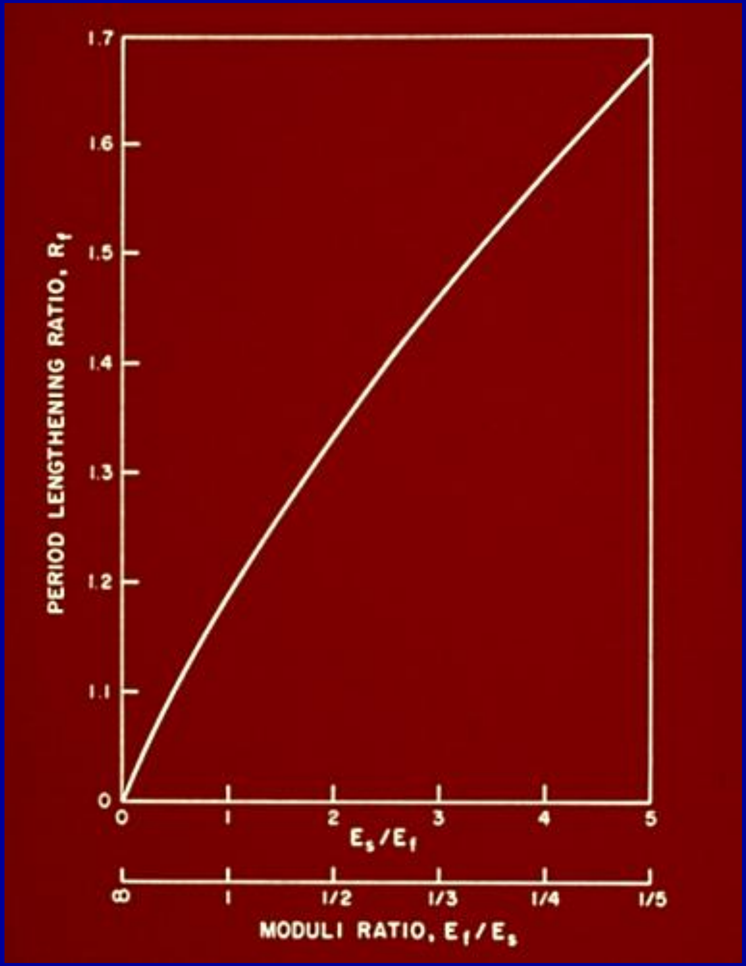
Hydrodynamic Effects
Period Lengthening Ratio, R_r



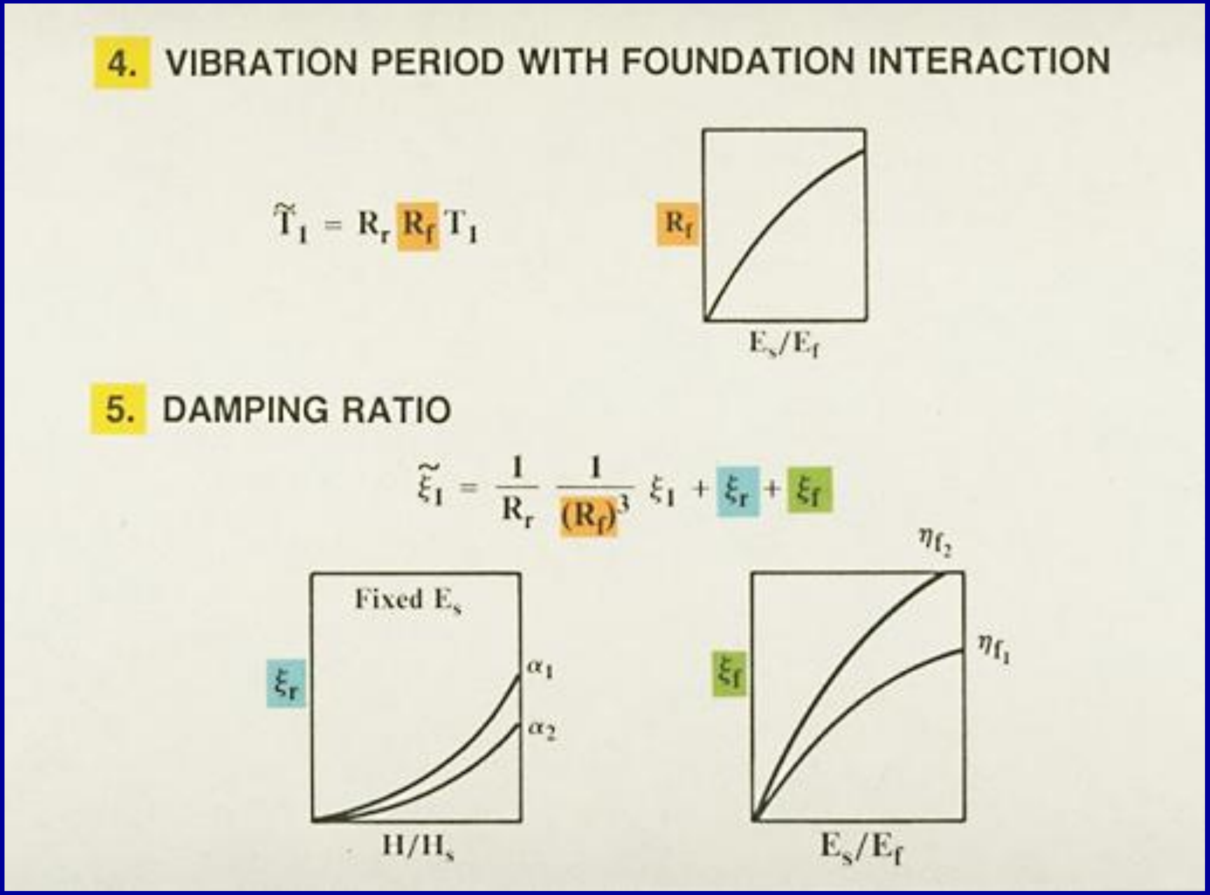
Lateral Earthquake Forces
Fundamental Vibration Mode



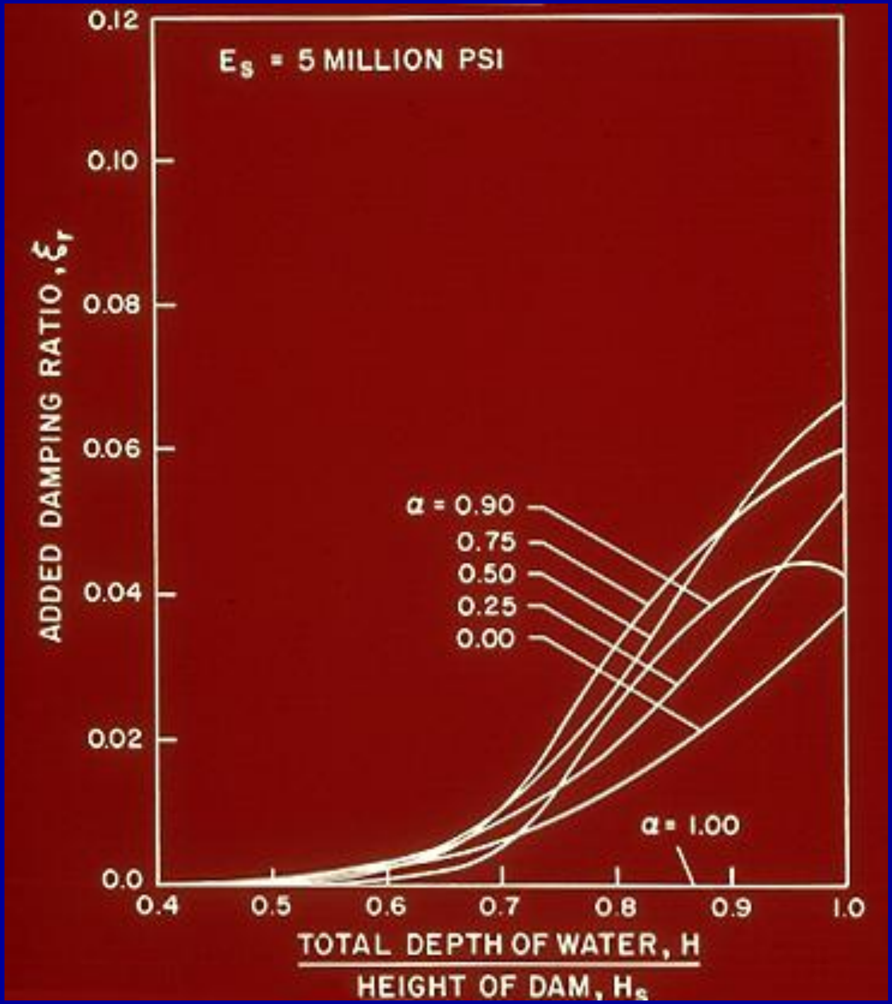
Dam-Foundation Rock Interaction
Period Lengthening Ratio, R_f



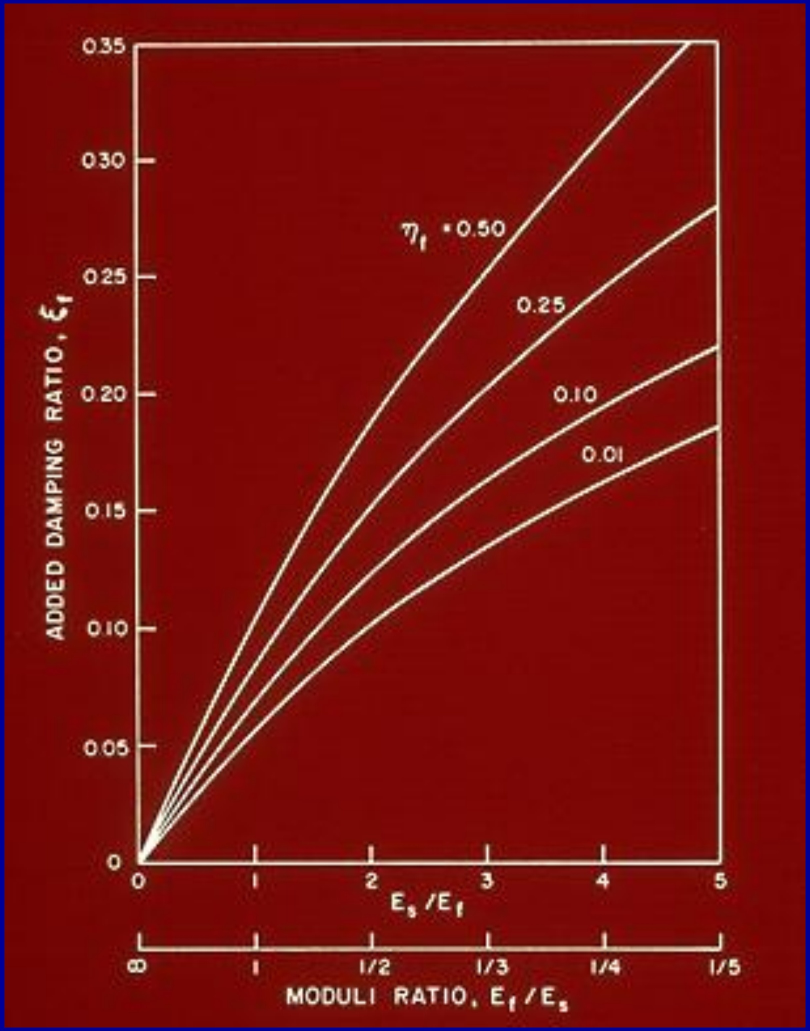
Lateral Earthquake Forces Fundamental Vibration Mode



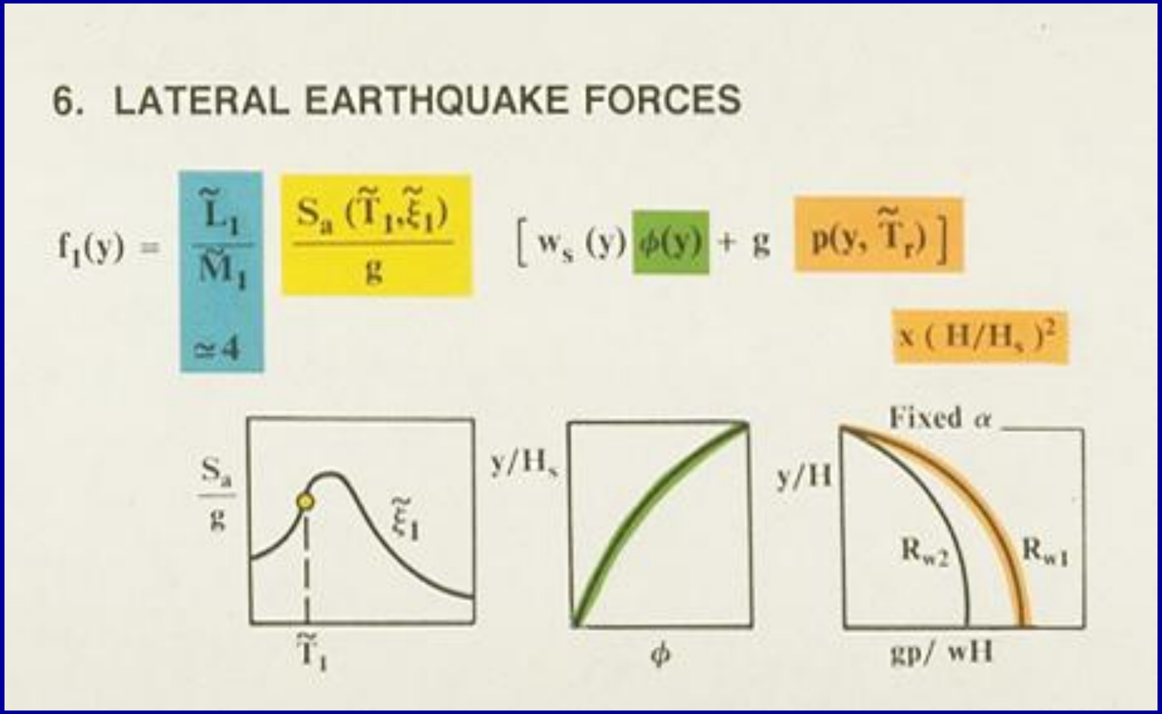
Hydrodynamic Effects
Added Damping Ratio, ξ_r



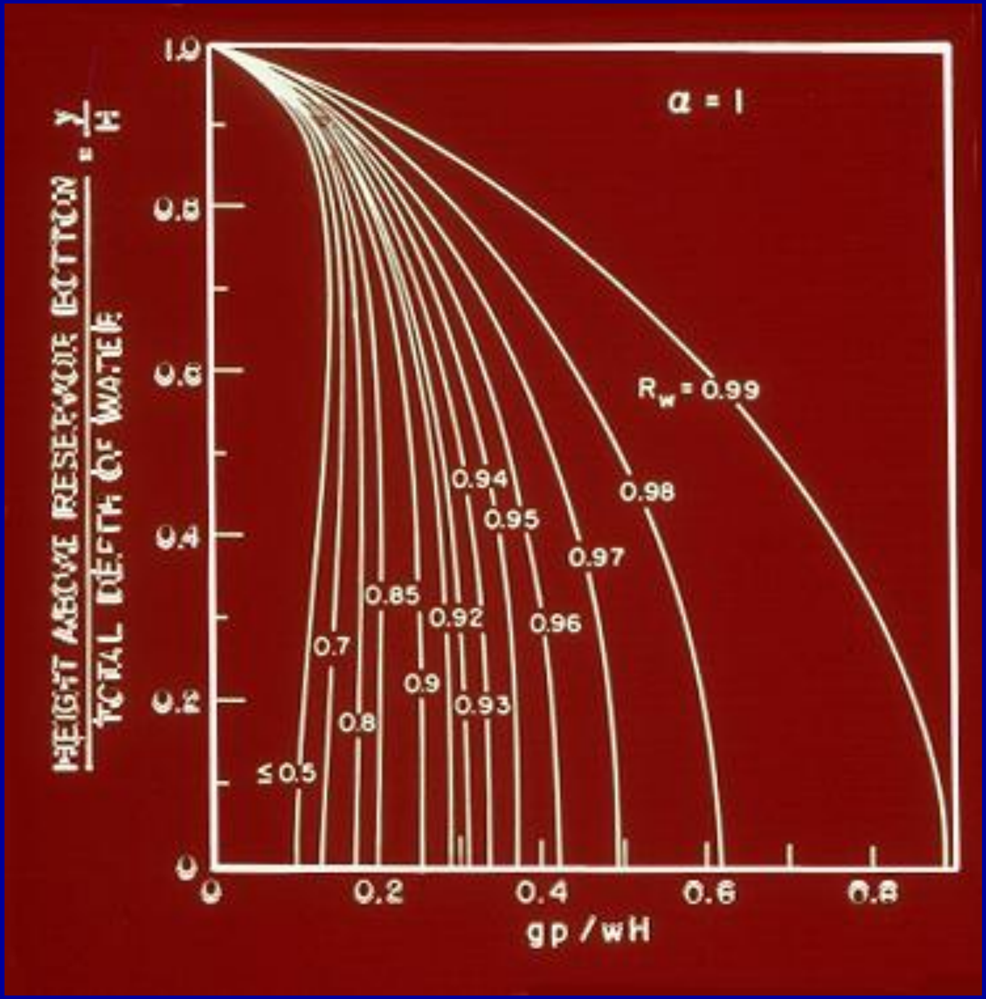
Dam-Foundation Rock Interaction
Added Damping Ratio, ξ_f



Fundamental Vibration Mode



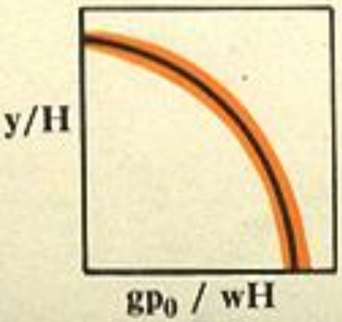
Hydrodynamic Pressure Function, p(y)



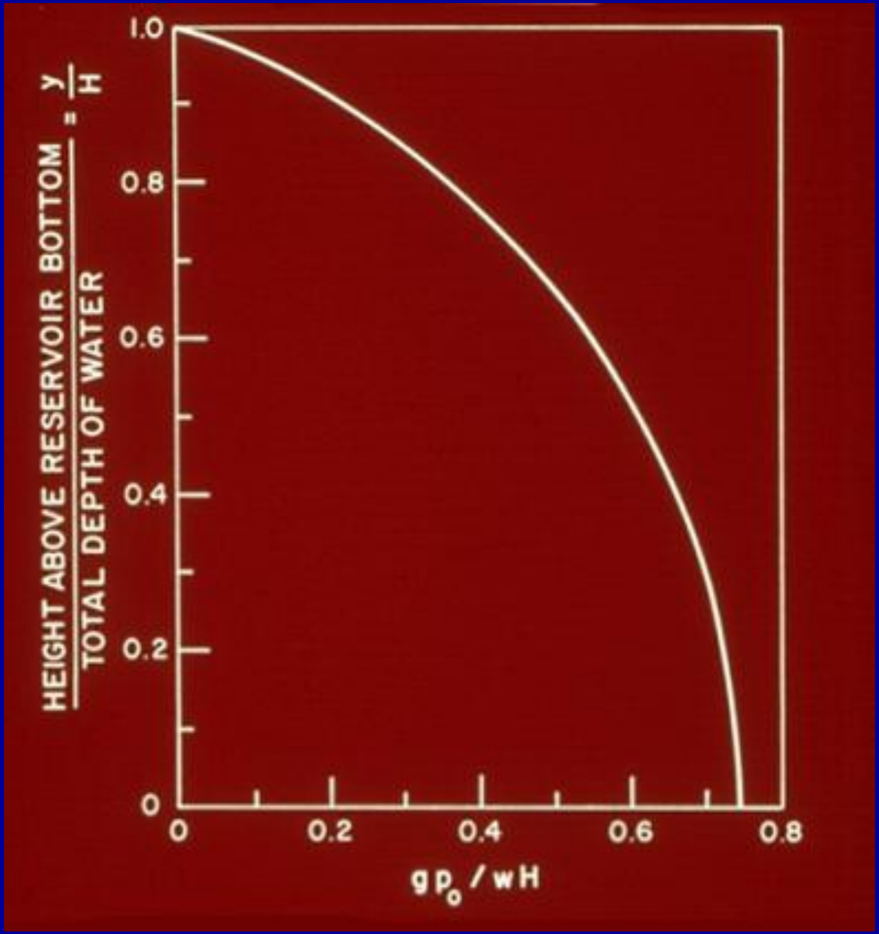
Lateral Earthquake Forces
Higher Vibration Modes

$$f_{sc}(y) = \frac{1}{g}\left\{ w_s(y)\left[1 - \frac{L_1}{M_1}\phi(y)\right] + \left[g\, p_0(y) - \frac{B_1}{M_1} w_s(y)\,\phi(y)\right]\right\} a_g$$

$$0.20\,\frac{F_{st}}{g}\left(\frac{H}{H_s}\right)^2$$



Hydrodynamic Pressure Function, $p_o(y)$



Critical Stresses

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Dynamic Response

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Total Response

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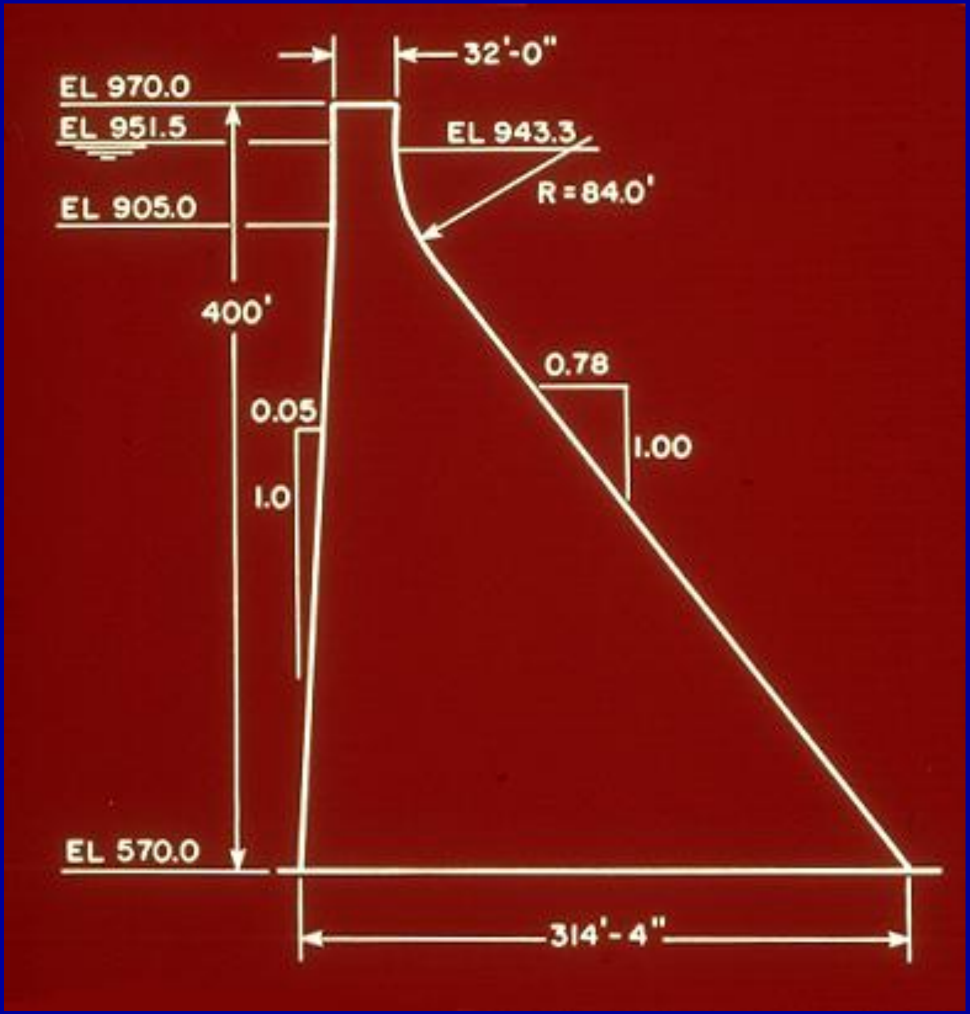
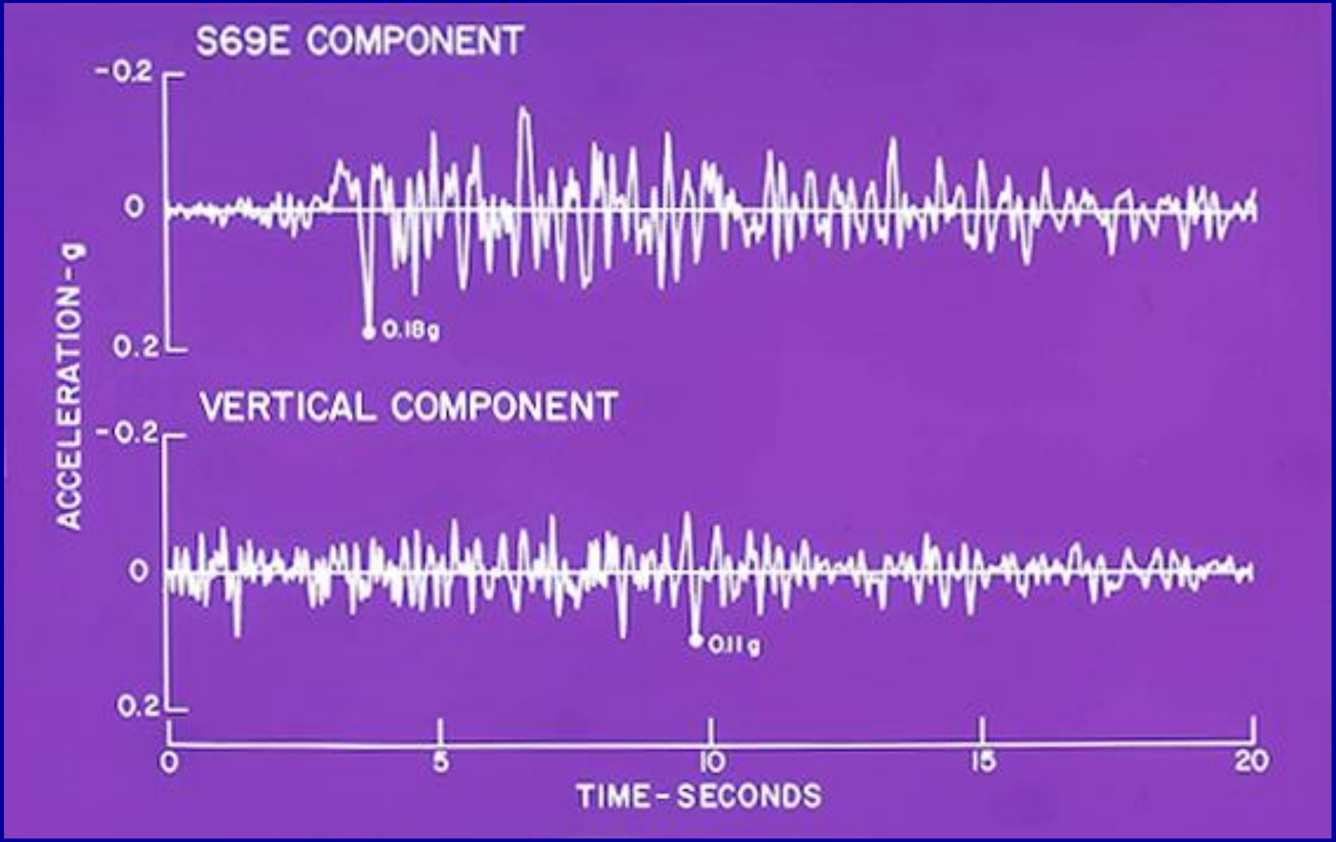
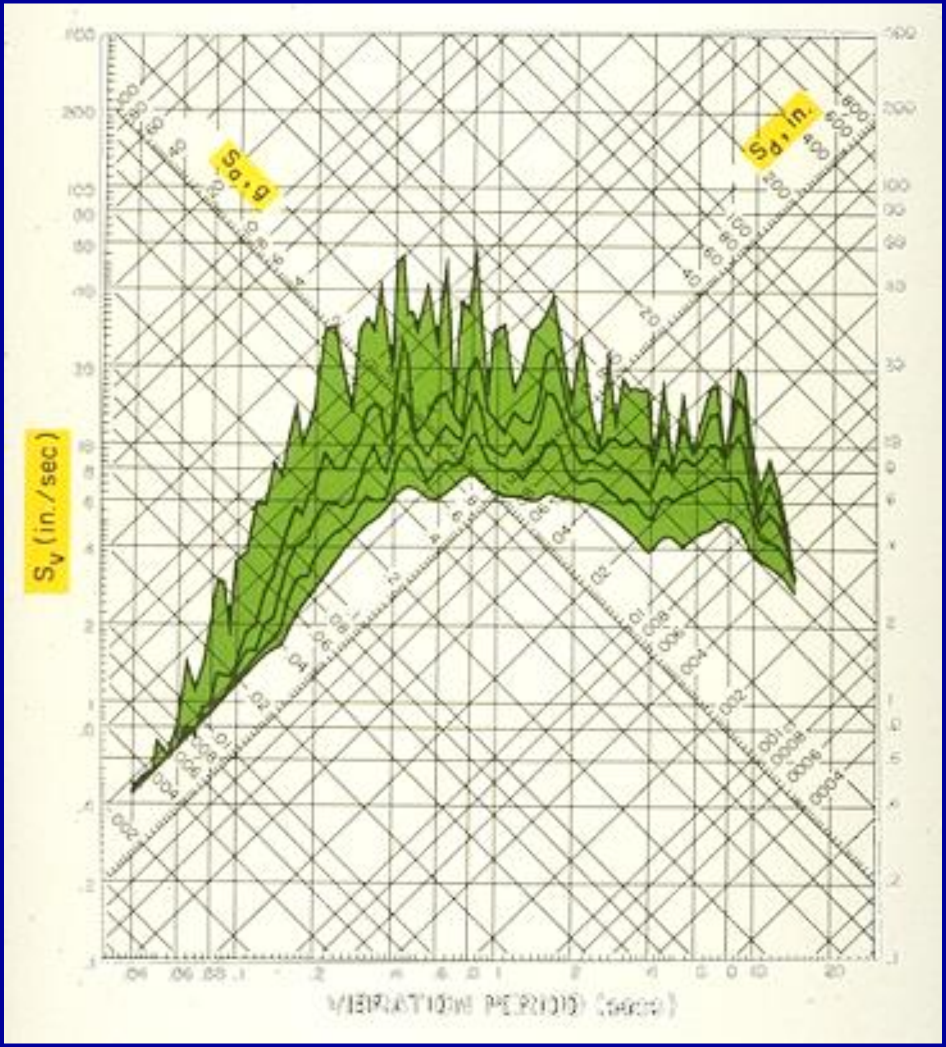
Pine Flat Dam: Tallest Non-Overflow Monolith



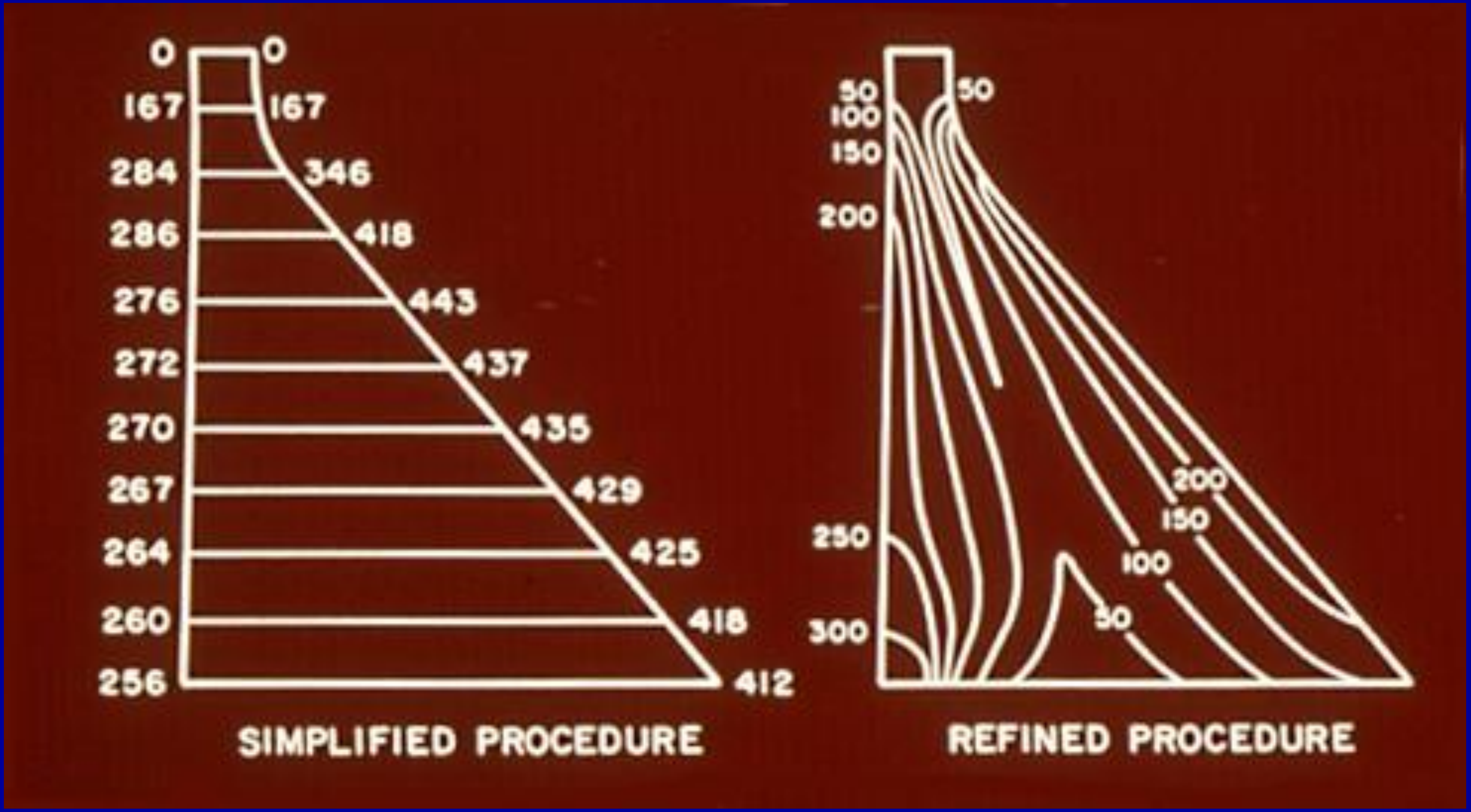
Taft Ground Motion, 1952



Response Spectrum – Taft Ground Motion



Evaluation of Simplified Procedure Flexible Foundation/Full Reservoir



Seismic Design & Safety Evaluation

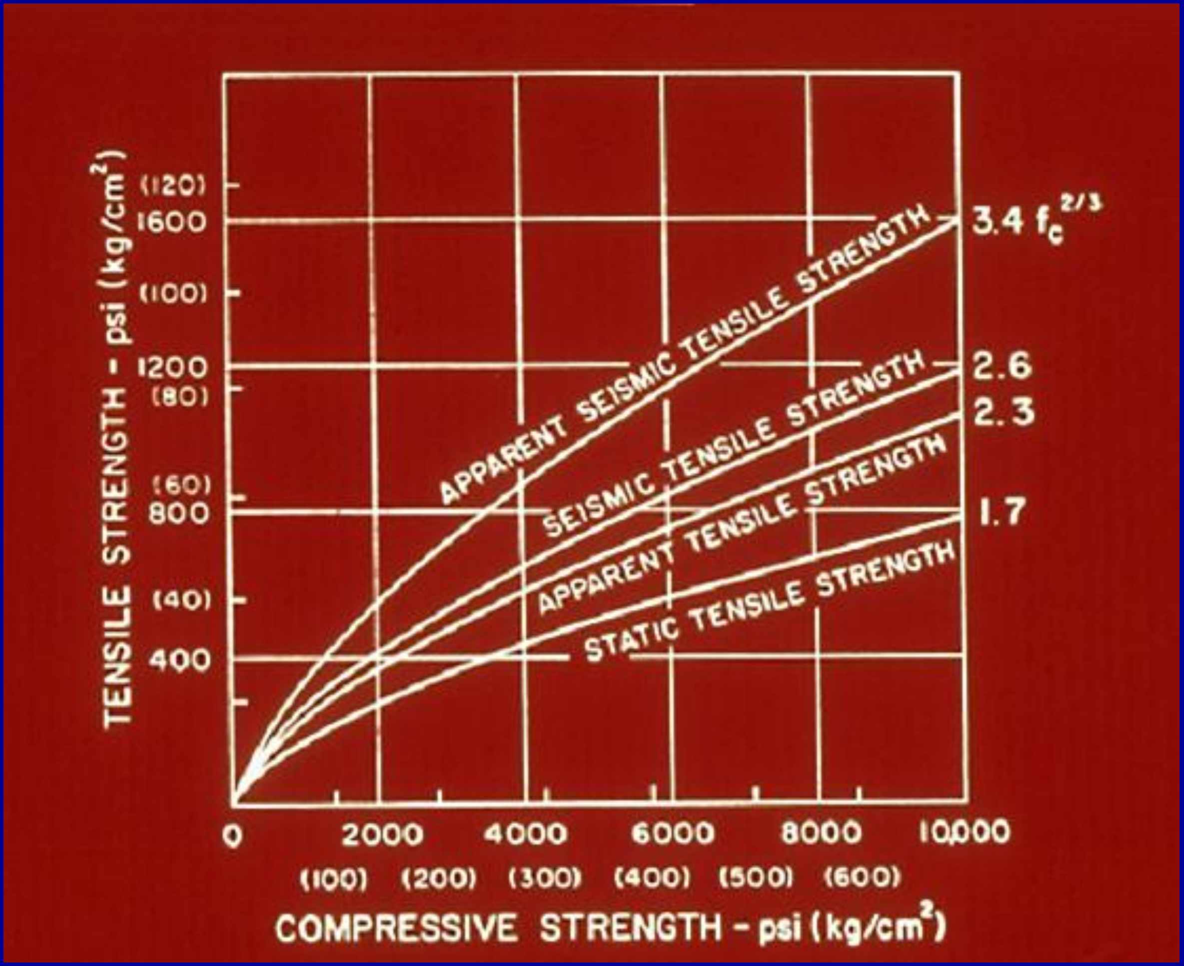
Seismic Design and Safety Evaluation

- Selection of earthquake motion and design spectrum

- Linear analysis of dynamic response of dam
  - Stage 1: simplified analysis
  - Stage 2: refined analysis

- Prediction of dam performance
  - tensile stresses < tensile concrete strength
    - NO DAMAGE
  - tensile stresses > tensile concrete strength
    - ESTIMATION OF DAMAGE

Tensile Strength of Concrete



$$f_t = 2.6 f_c^{2/3}$$

Koyna Dam

Pacoima Dam

Lower Crystal Springs Dam

Application to Design of New Dams

Richard B. Russel Dam, USA (1980s)

170 ft high

Balambano Dam, Indonesia (1997)

Roller-compacted concrete, 90 m high

Olivenhain Dam, California (2003)

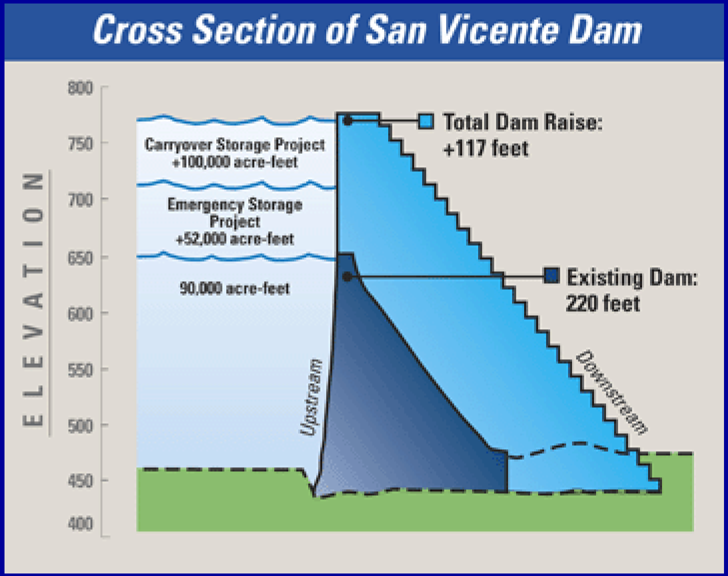
Roller-compacted concrete, 315 ft high

San Vicente Dam, California (2009)

Current height: 220 ft

Raised height: 337 ft

Roller-compacted concrete for dam raise

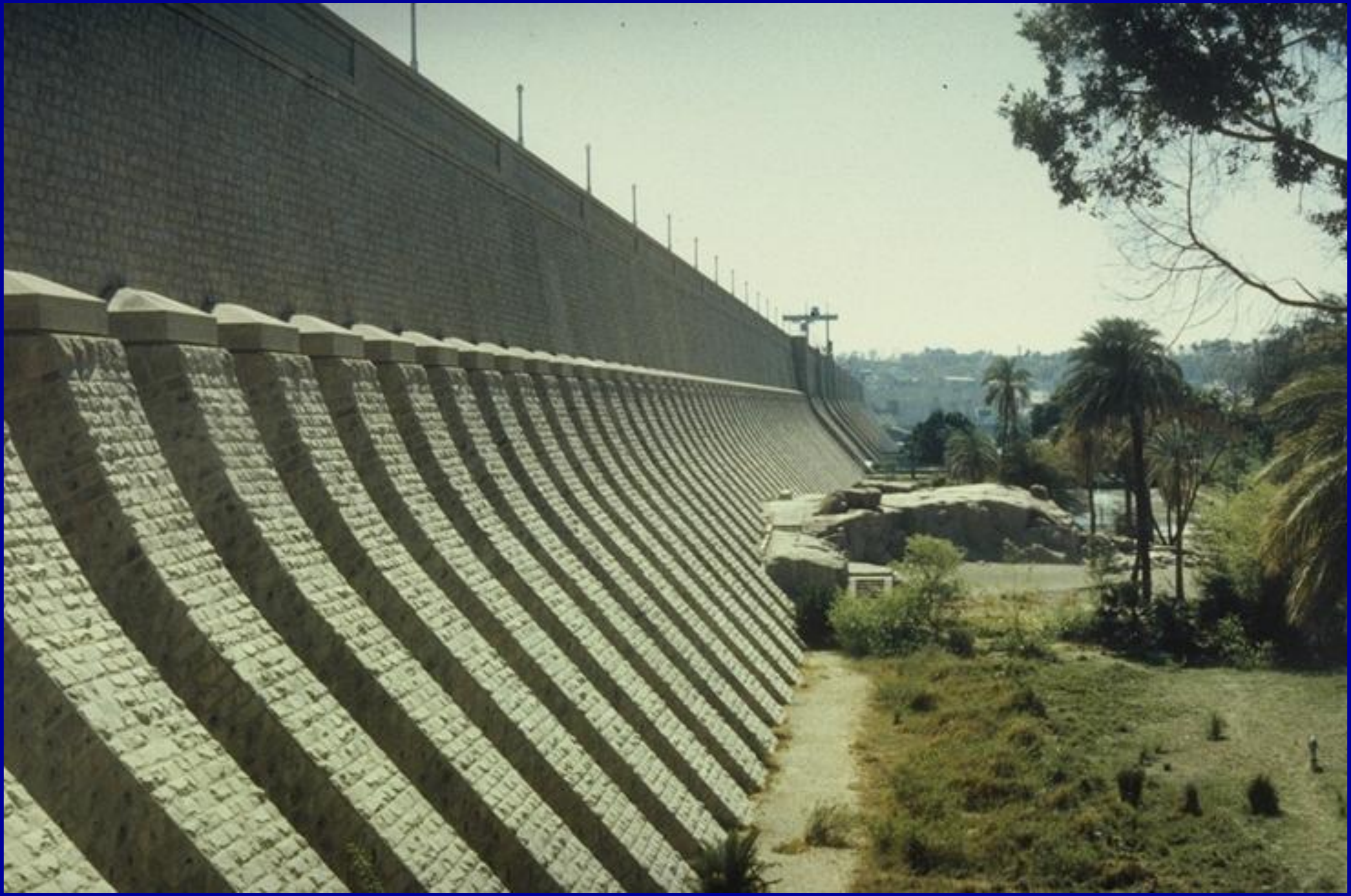


Applications to Evaluation and Remediation of Existing Dams

Thermalito Diversion Dam, California, USA

Folsom Dam, California
340 ft high

Old Aswan Dam, Egypt



Seven Mile Dam, Canada
215 ft high

Seismic remediation:
fifty-two 92-strand post-tensioned anchors

Gatun Spillway, Panama Canal
107 ft high

Madden Dam, Panama Canal