# Infrastructure Engineering and Management Research Thrust Area

## Earthquake Engineering Program

*D. E. Yule*

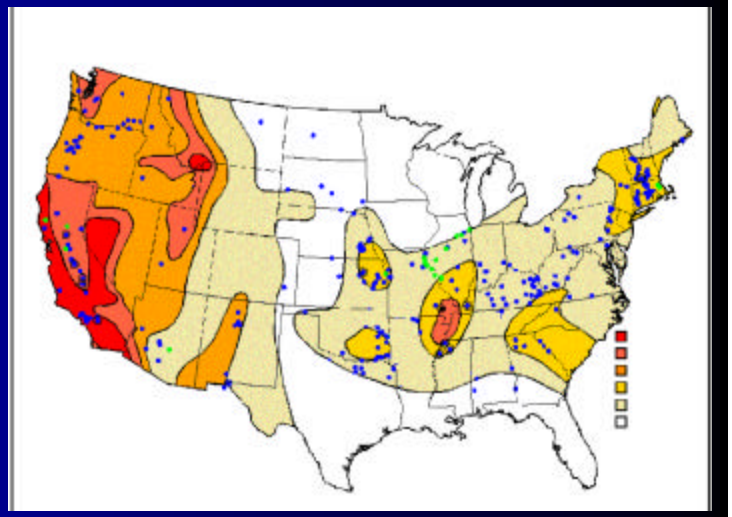
US Army Corps of Engineers

Engineering Research and Development Center

# Earthquake Engineering Research Program

## Problem

- Corps has 200 dams and 73 intake towers in areas with significant seismic hazards
- Most dams were constructed when earthquake engineering was in its infancy
- Using current technology, most of these would be judged seismically inadequate
- Replacement costs of these structures could reach $20 billion



*Seismic zone map showing SMIP project sites*

## Purpose

- To improve our ability to predict the performance of a dam under seismic loads, and to improve our ability to design and construct cost-effective remediation

## Major Thrusts

- Engineering geology / seismology
- Geotechnical earthquake engineering
- Structural earthquake engineering

*Mormon Island Dam, CA remediation*

## Target Structures

- Embankment dams
- Concrete dams
- Intake tower / outlet works

*Sardis Dam, MS remediation*

# Importance

- EQEN is ***only*** federal funded program focused on seismic safety of dams

- Coordination & Leveraging
  - National Earthquake Hazard Reduction Program (FEMA,USGS)
  - NSF - MCEER , PEER, MAEC and universities
  - FHWA Highway Seismic Research Program
  - US Bureau of Reclamation, BC Hydro
  - UJNR US-Japan Panel on Wind and Seismic Effects,
  - **Districts (reimbursable work)**

# EQEN - Embankment Dams

**Ground Motions**

Geology / Seismology

Engrg Ground Motion Analysis System

**Site Characterization**

Vs Database
Geophysical Methods
Penetration Testing

**Performance Assessment**

Newmark Analyses Behavior of Liquefying Soils
Failure Mechanisms & Damage Assessment
Liquefaction at Depth

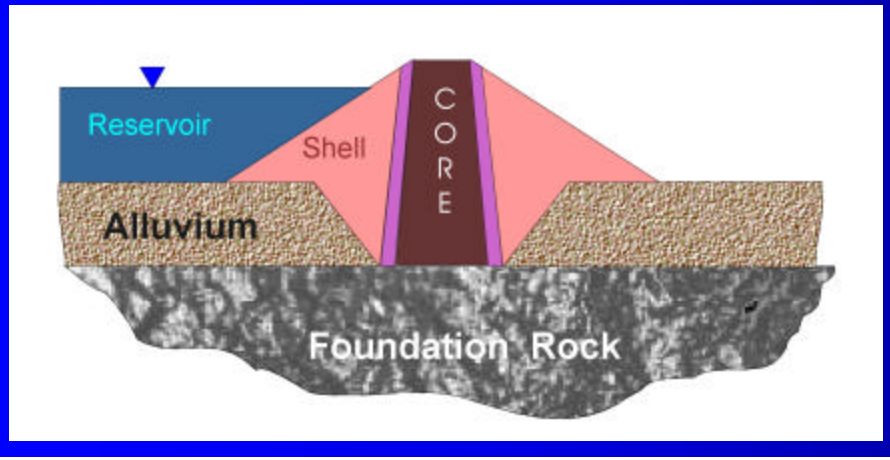
**Primary Analysis Tool**

Large Deformation Analysis of Embankment Dams

**Assessment & Remediation**

EQEN Phase II

Seismic Evaluation and Rehabilitation Program




*Products*

# EQEN - Concrete Dams and Outlet Works

Ground Motions

Intake Towers

Outlet Works

Quantify Ductility

Subbottom Absorption

Conventional Concrete Dams

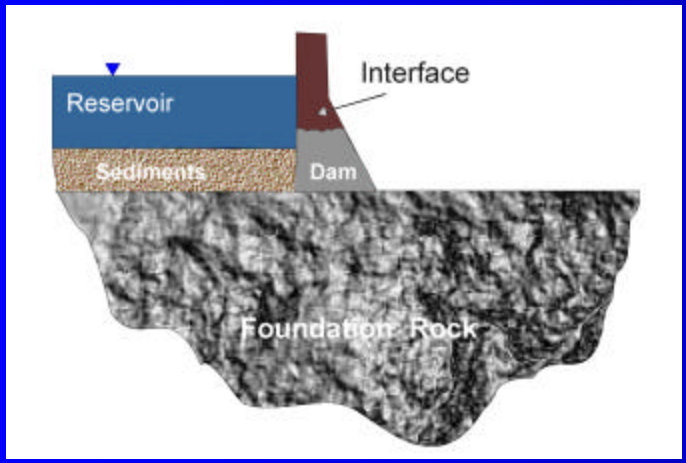
Retaining Walls

Primary Analysis Tool

Time - History
Non - Linear Analysis

Moment / Shear / Thrust

Post - Processors




*Products*

# Earthquake Engineering Research Program

## Accomplishments and Breakthroughs

**Seismic dam safety becomes a priority**

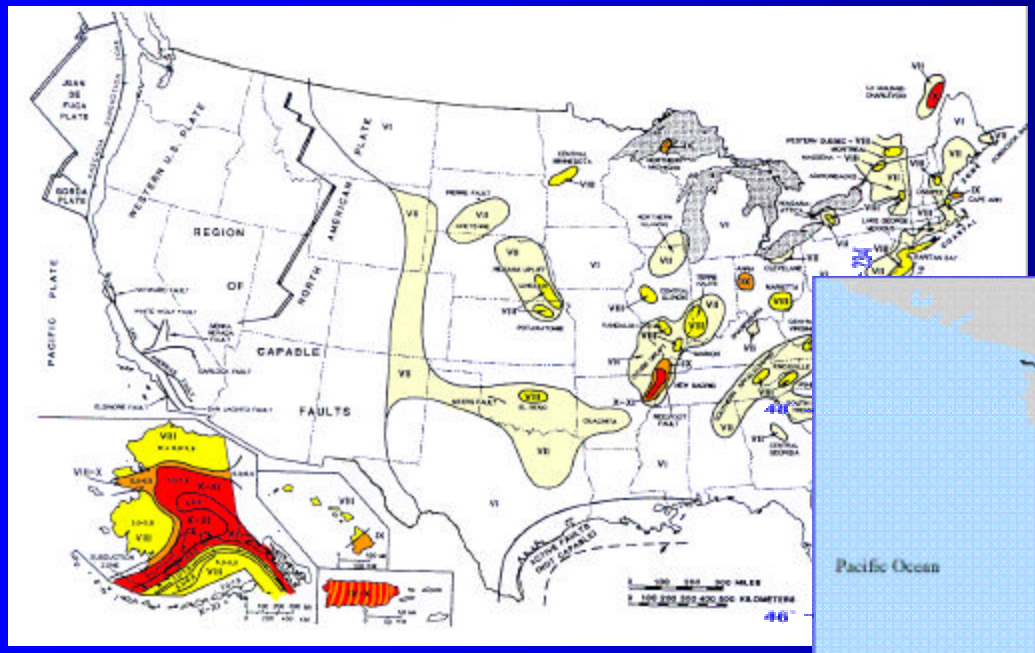
***Near failure of Lower San Fernando Dam***
***San Fernando Earthquake - 1971***

*Mormon Island Dam, CA remediation*

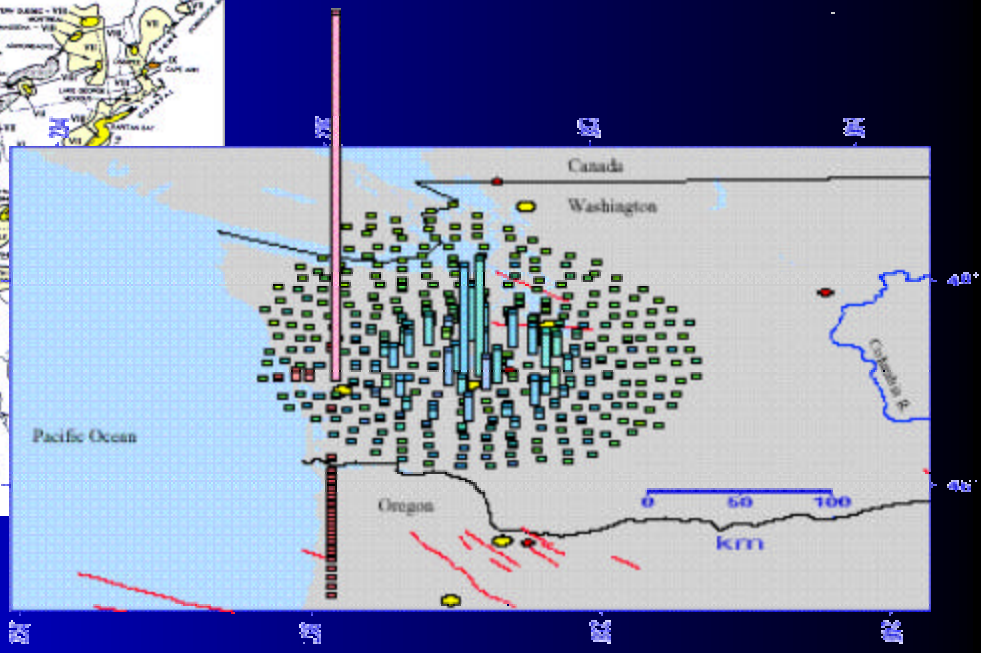
*Sardis Dam, MS remediation*

# Earthquake Engineering Research Program

- **Geological - Seismological Evaluations**
  Incorporated latest knowledge into methods for geological-seismological evaluations of earthquake hazards enabling accurate site-specific ground motions for potential earthquakes affecting Corps projects




*Seismic source zones for U.S.*



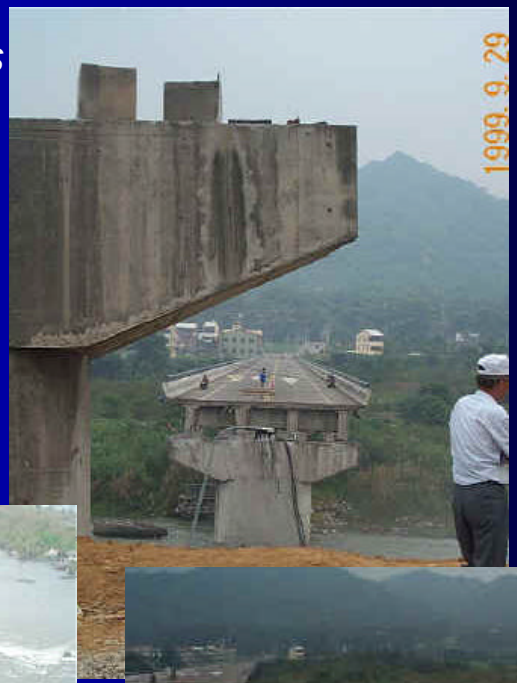

*Azimuth Decomposition of Seismic Hazard.*

**Continuing transition of geologic & seismologic research into engineering**

# Earthquake Engineering Research Program

- **Geological – Seismological- Geotechnical Evaluations: Earthquake Reconnaissance**

*Taiwan Earthquake Photos*



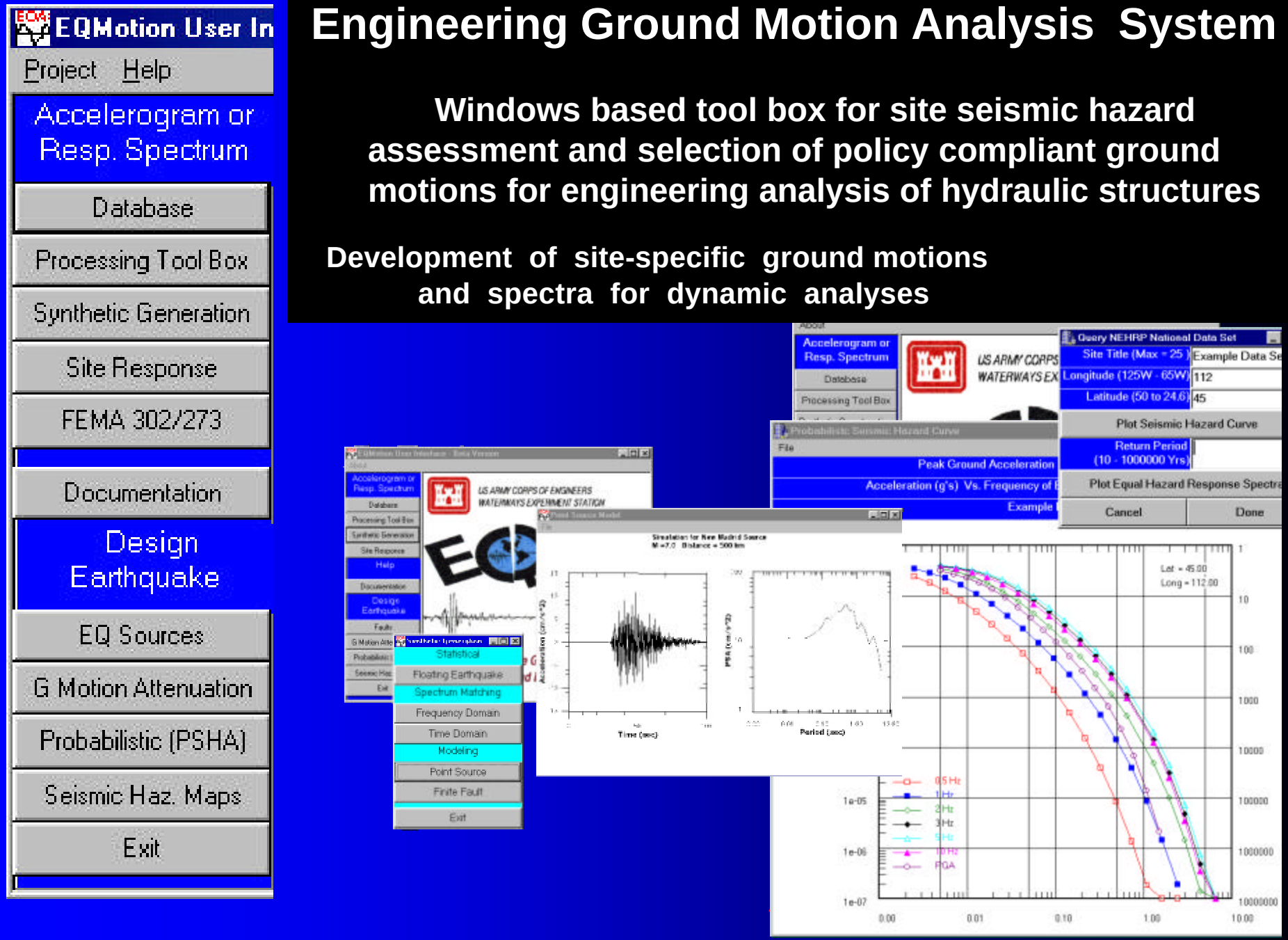



**Continuing transition of geologic & seismologic research into engineering**

# Engineering Ground Motion Analysis System

**Windows based tool box for site seismic hazard assessment and selection of policy compliant ground motions for engineering analysis of hydraulic structures**

**Development of site-specific ground motions and spectra for dynamic analyses**

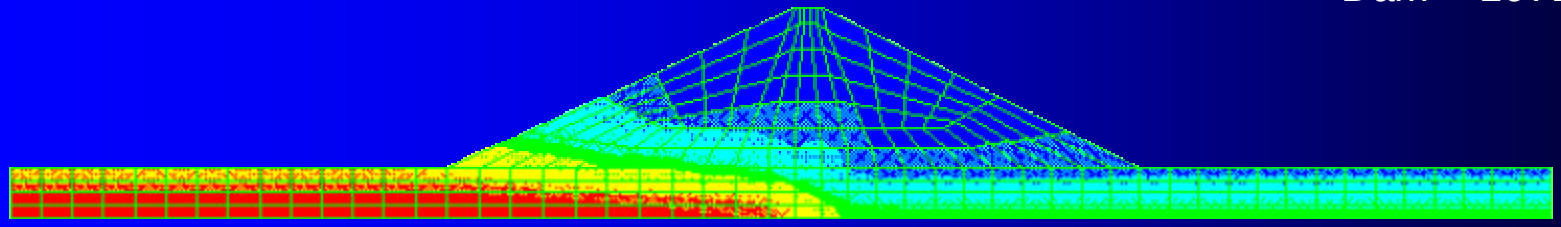


# Earthquake Engineering Research Program
# Embankment Dams

## Research Thrust Areas

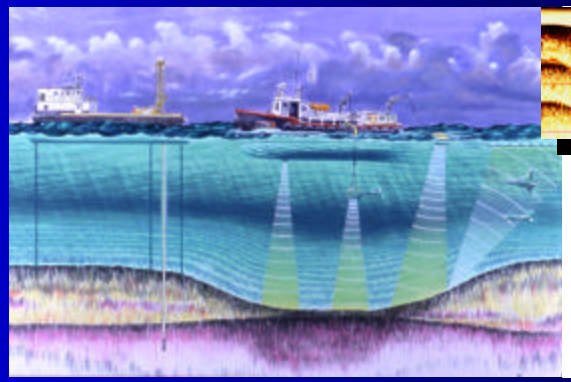
- **Site Characterization**
- **Liquefaction**
- **Large Deformation Analysis**

*Slide in Lower San Fernando Dam - 1971*

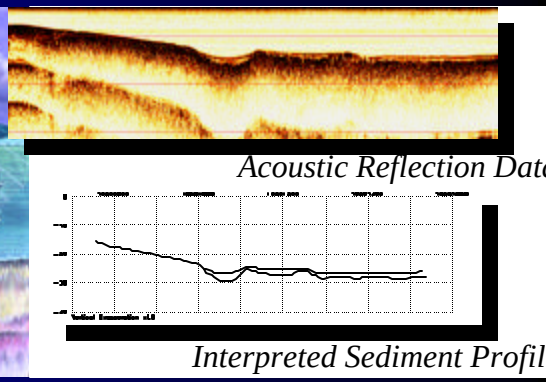


# Earthquake Engineering Research Program

- **Geophysical Methods for Site Characterization**
  **Waterborne Geophysics**
  - Subbottom material identification, distribution, and volume
  - Side scan image mosaics



*Subbottom Profiling System*



*Acoustic Reflection Dat*

*Interpreted Sediment Profil*

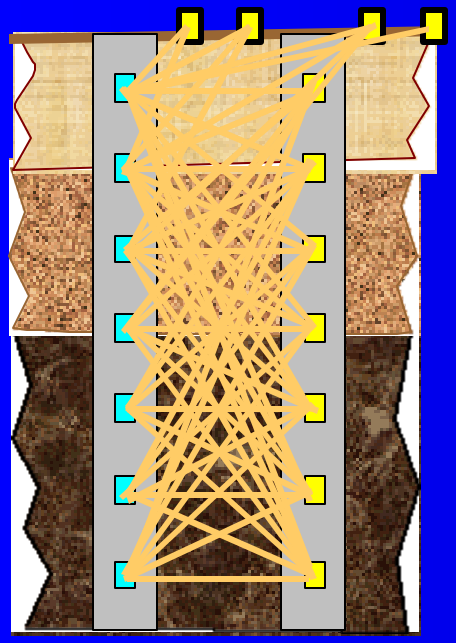
*Arkabutla data*

**Advanced Characterization**
**Detailed Imaging**

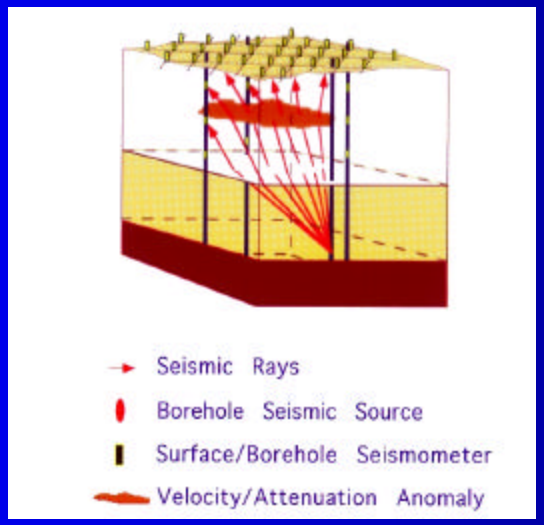
*Side scan sonar of Arkabutla control structure*

# Earthquake Engineering Research Program

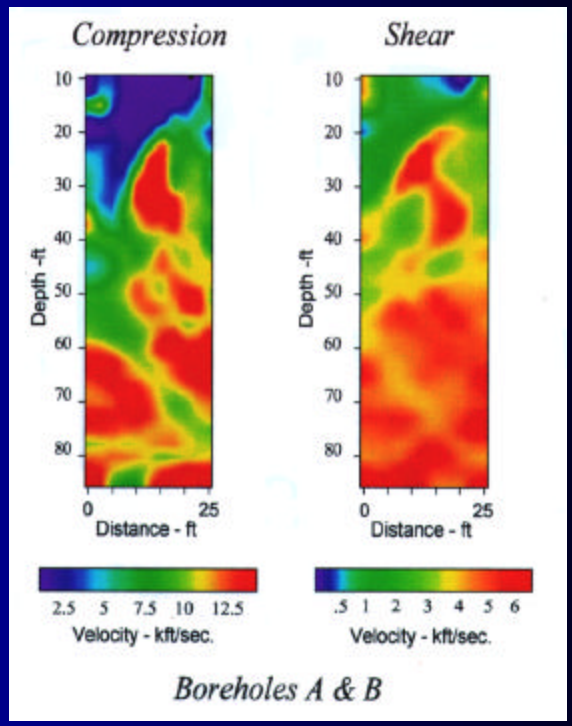
- **Geophysical Methods for Site Characterization**
  **Land based methods**
  - **Advanced Data Content - Improved Analysis**
  - **Increased Coverage - Less Cost**



*2-D*

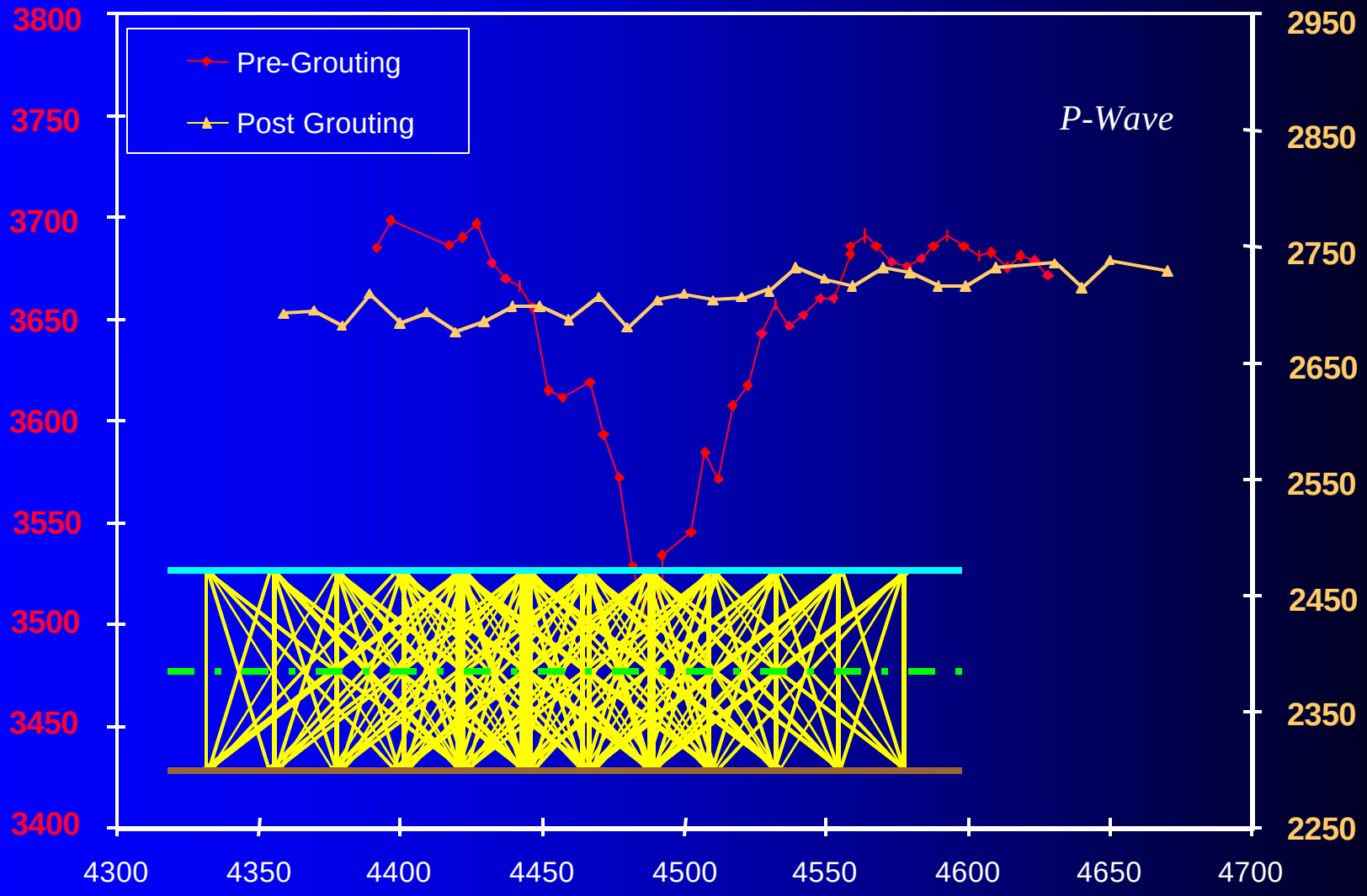



*3-D*




*Success Dam, CA*
*borehole tomography*

# Through-the-Dam Tomography

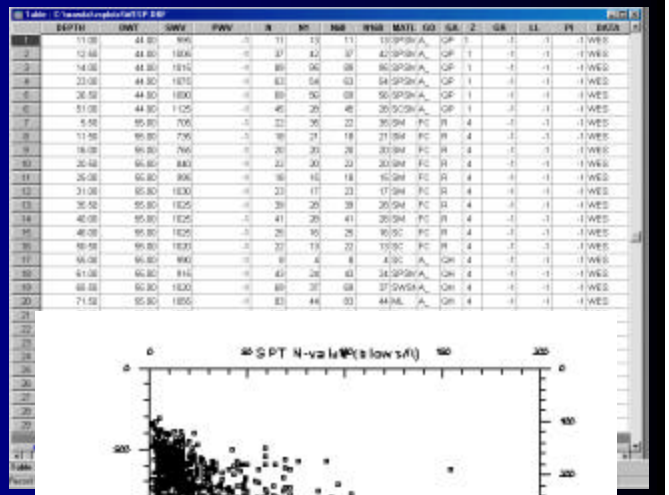


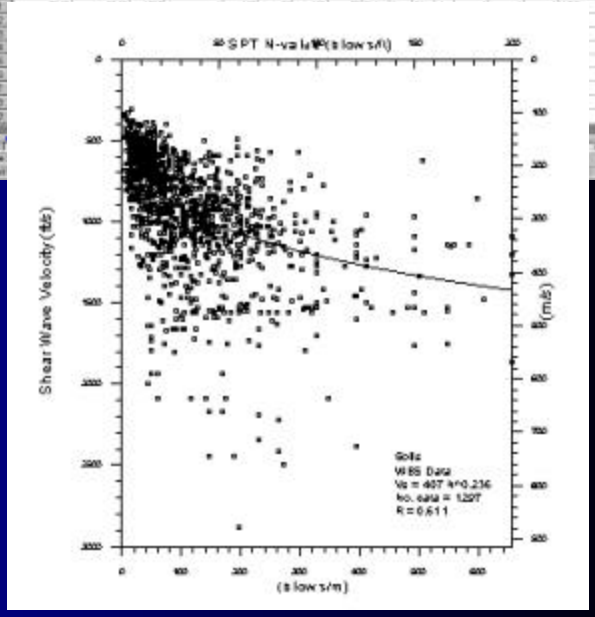
# Earthquake Engineering Research Program

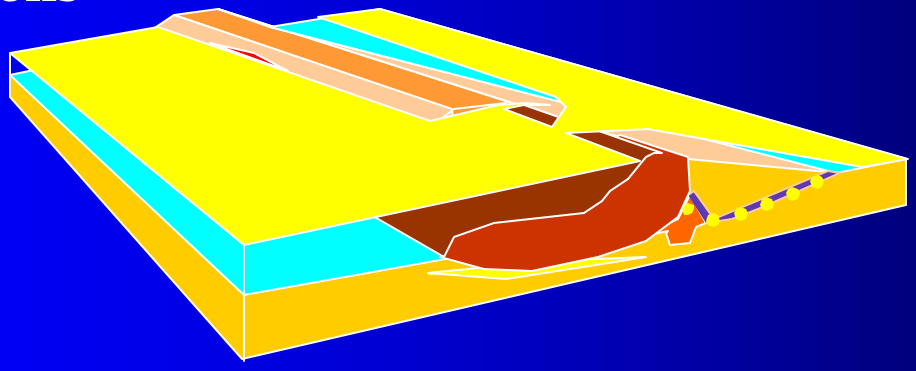
- **Shear Wave Velocity Database -** developed to support screening analysis

- **Newmark Sliding Block Analysis** – validated by compilation and investigation of case histories

- **Criteria for identifying liquefiable fine-grained soils**

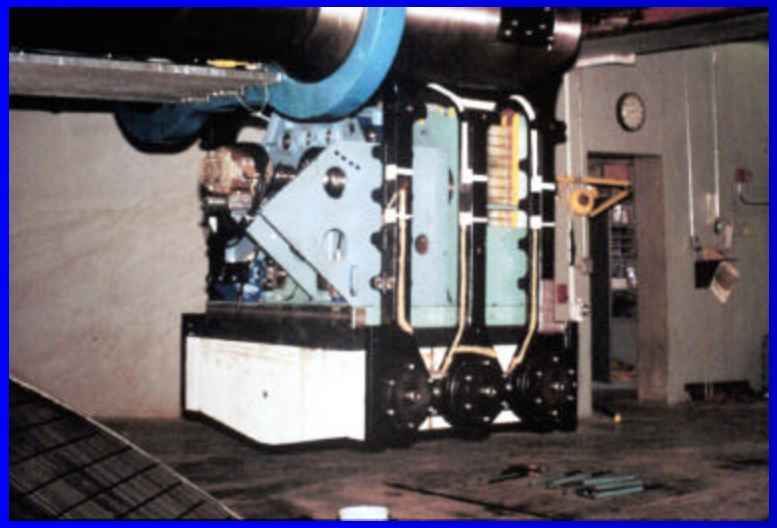




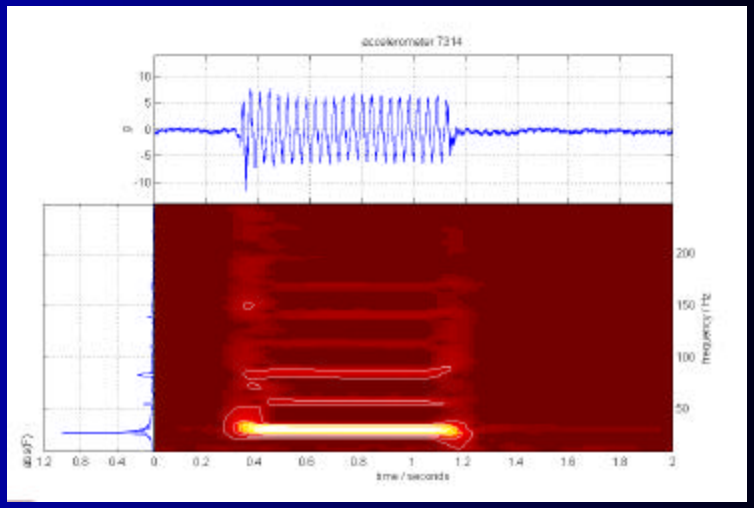



# Earthquake Engineering Research Program

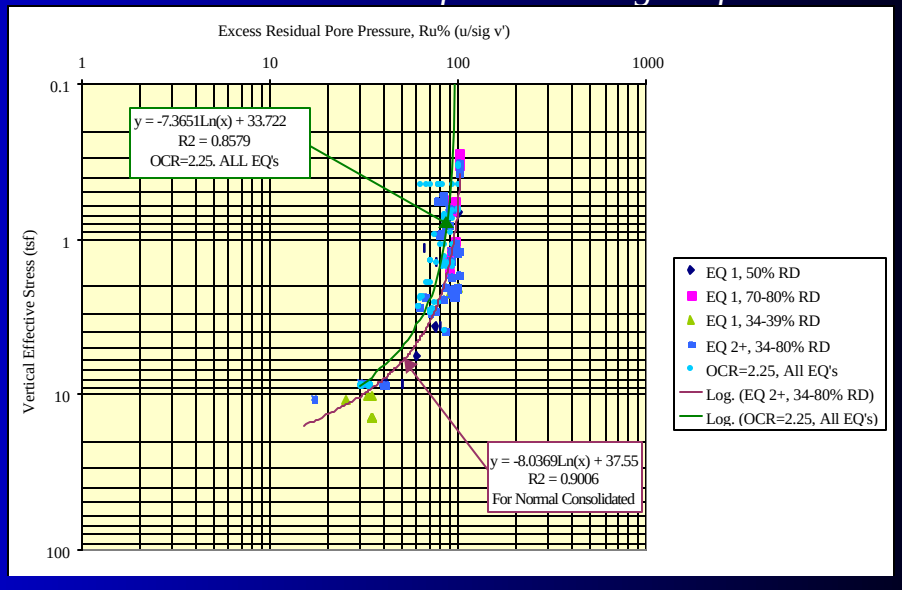
- **Research into the behavior of liquefying soils**



*Earthquake shaker mounted on centrifuge arm*




*Wavelet analysis of soil response to earthquake loading response*

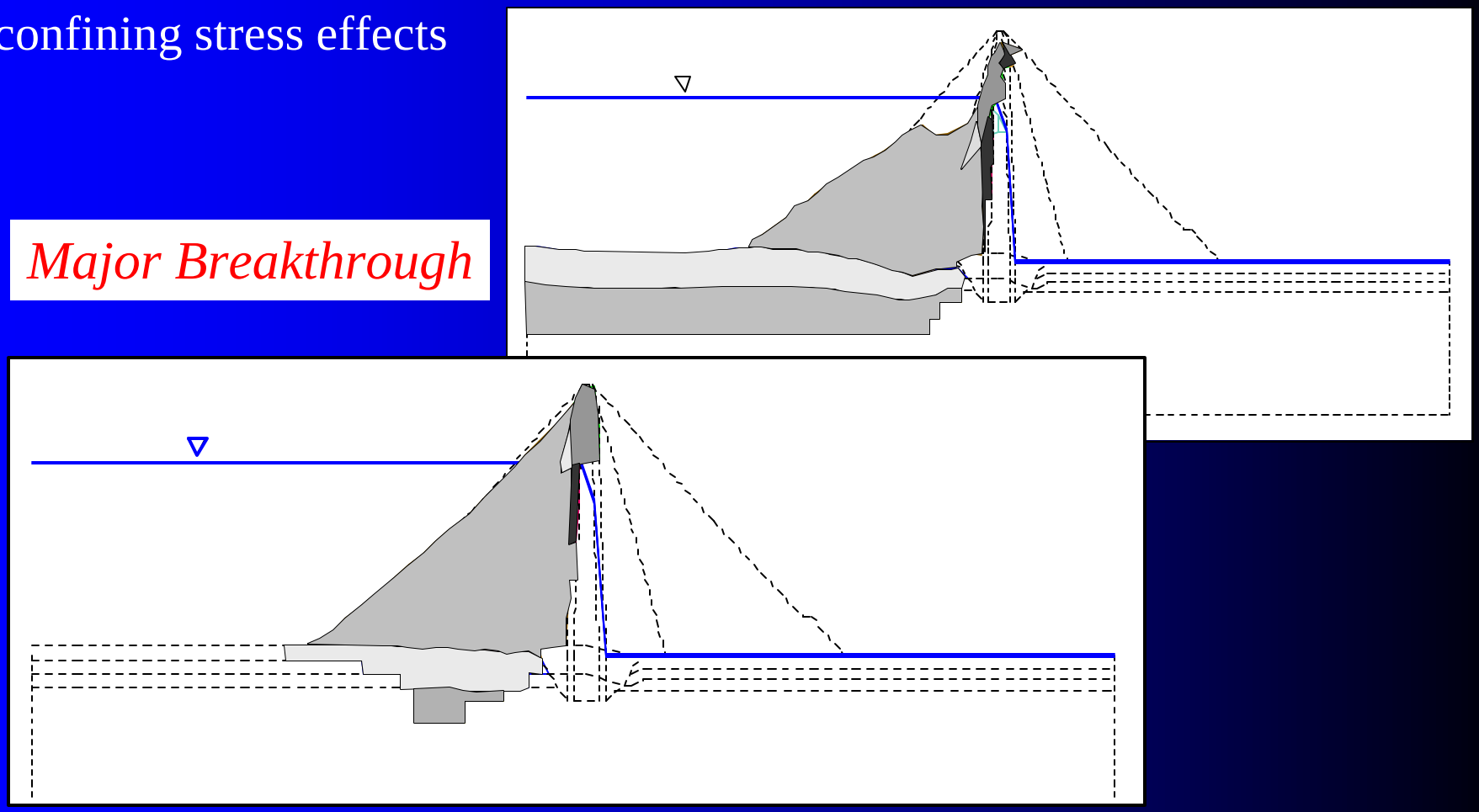



*Dynamic Induced Residual Excess Pore Pressure Limit*

# Earthquake Engineering Research Program

- **Liquefaction:** Improve state-of-the-practice for determining confining stress effects

*Major Breakthrough*



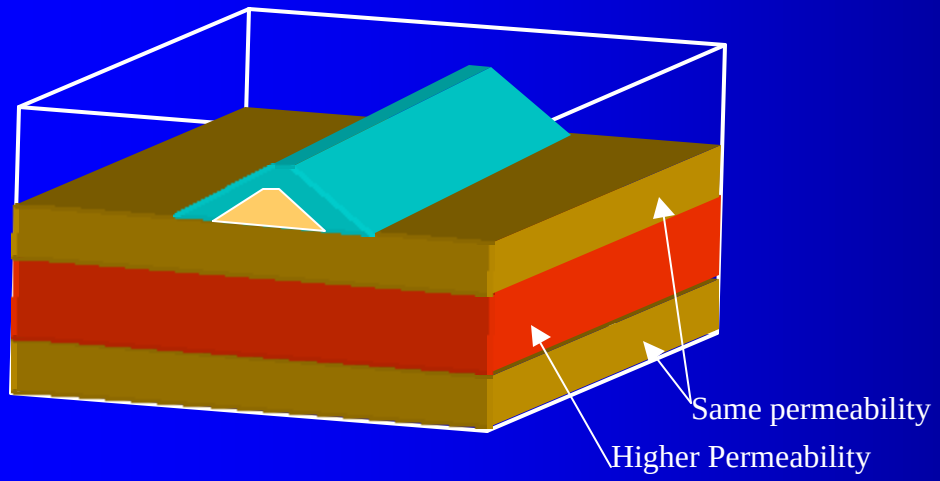
***Effect of current findings on limiting depth of liquefaction, Success Dam, CA***

# Earthquake Engineering Research Program

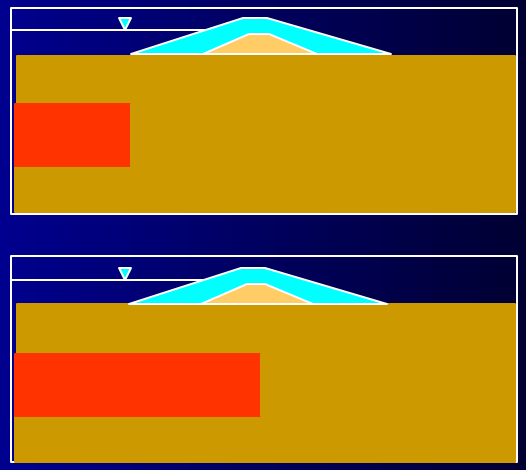
- **Failure Mechanisms and Damage:** Improve state-of-the-practice for determining performance of dams in response to liquefaction of soils

*Slide in Lower San Fernando Dam - 1971*

***Centrifuge (physical) modeling***



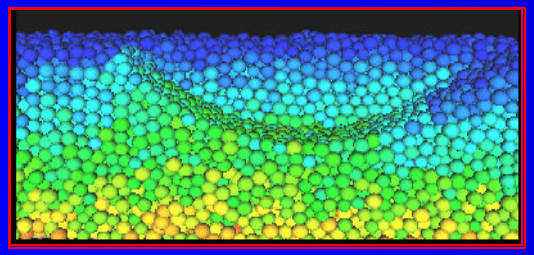

*Effect of layer permeability*



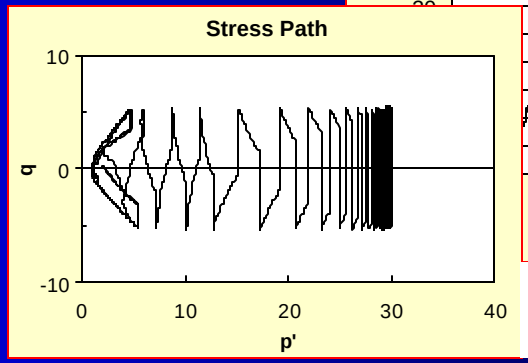
*Extent of liquefiable layer*

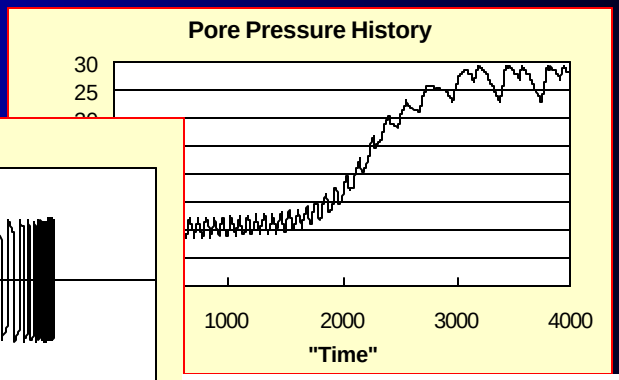
# Earthquake Engineering Research Program

- **Seismic Stability and Deformations of Earth Structures and Foundations:** numerical modeling to improve the estimation of post-earthquake deformation.

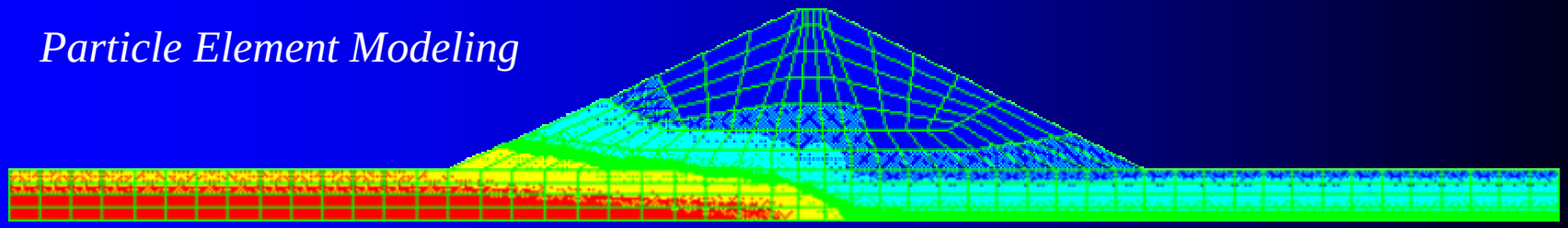


*Particle Element Modeling*




Coupled with Stress



*Idealized dam initial pore water pressure*

# Infrastructure Engineering and Management Research Thrust Area

## Earthquake Engineering Program

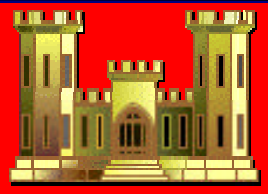
*D. E. Yule*

*End of Presentation*

*Questions*

US Army Corps of Engineers

Engineering Research and Development Center



# EQEN Program
# Structural Aspects

*Dr. Robert L. Hall*

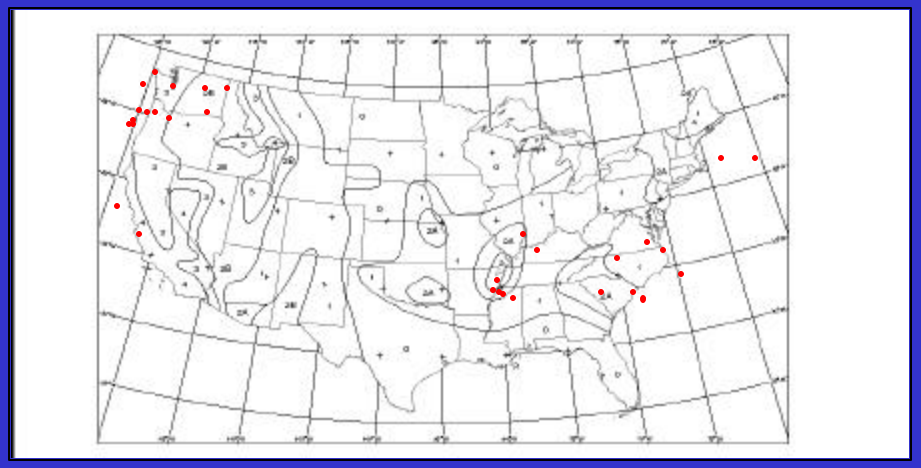
- Concrete Dams
  - Numerical & Physical Modeling
  - Back Analysis of Performance of Dams -Taiwan
  - Database Development
- Outlet Works
- Retaining Walls

US Army Corps of Engineers

Engineer Research and Development Center

# Earthquake Engineering: Concrete Dams

The accurate evaluation of the seismic performance of concrete dams requires the development of numerical procedures that account effectively for the most critical factors controlling the response.

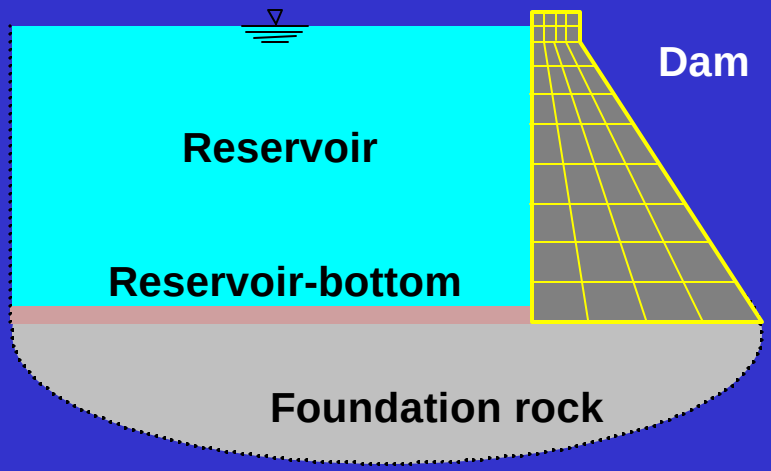


## Objective

Development, implementation and validation of numerical procedures for dynamic analysis of concrete dams subjected to seismic excitation.

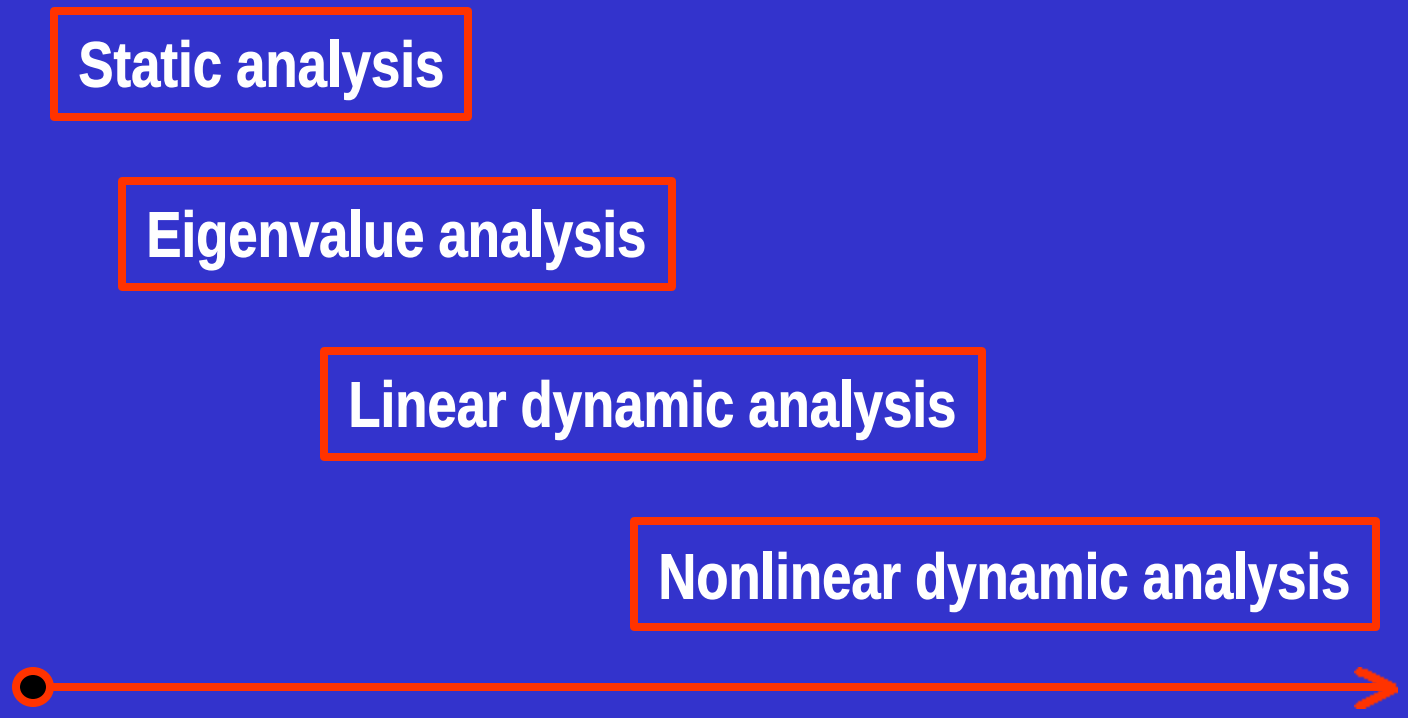
# *Problem*

- The prediction of the seismic performance of concrete dams constitutes a challenging problem governed by
  - Three-dimensional geometry
  - Spatial variability of seismic input
  - Intensity and frequency characteristics
  - Material constitutive behavior
  - Presence of lift and contraction joints
  - Interaction phenomena

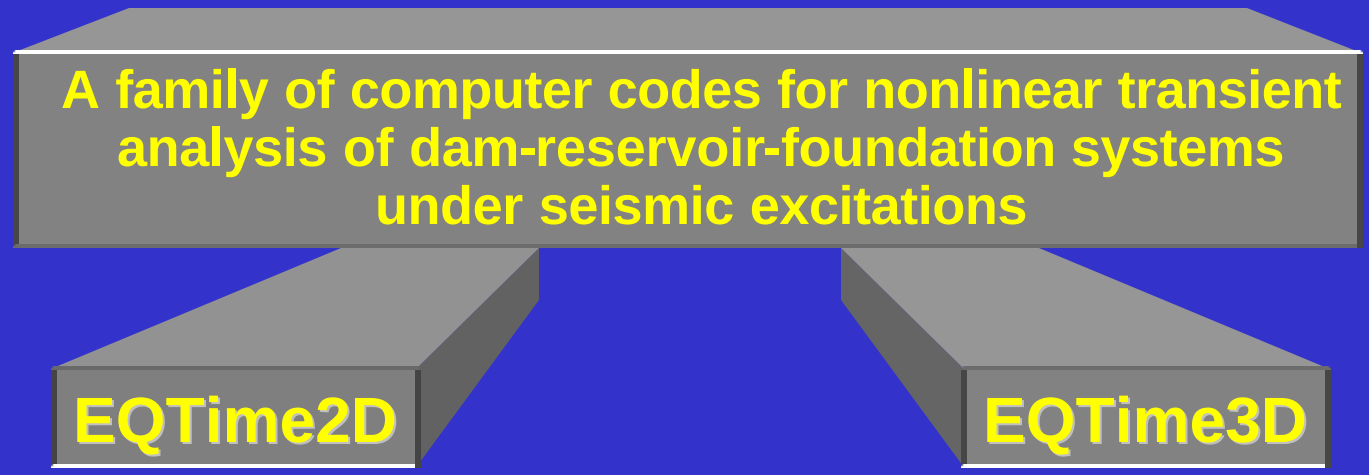


# *Problem (cont.)*

- **Different approaches can be used to generate a "solution" to the problem, ranging in complexity and modeling capabilities.**

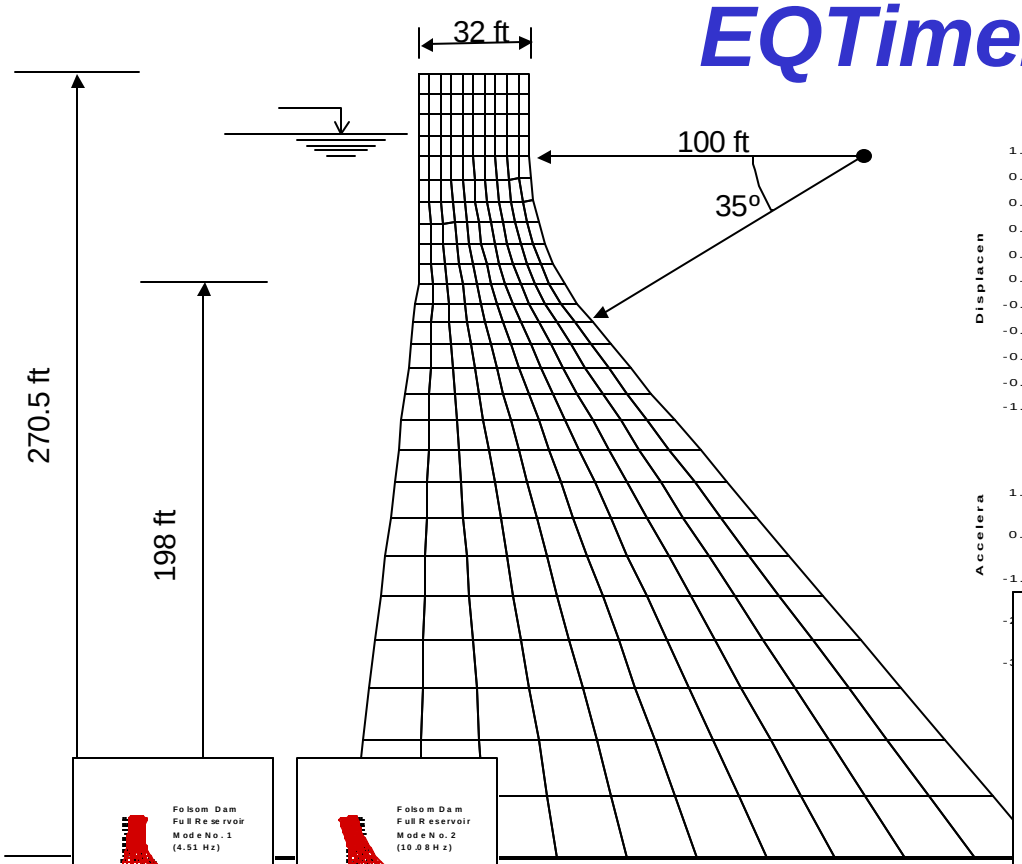


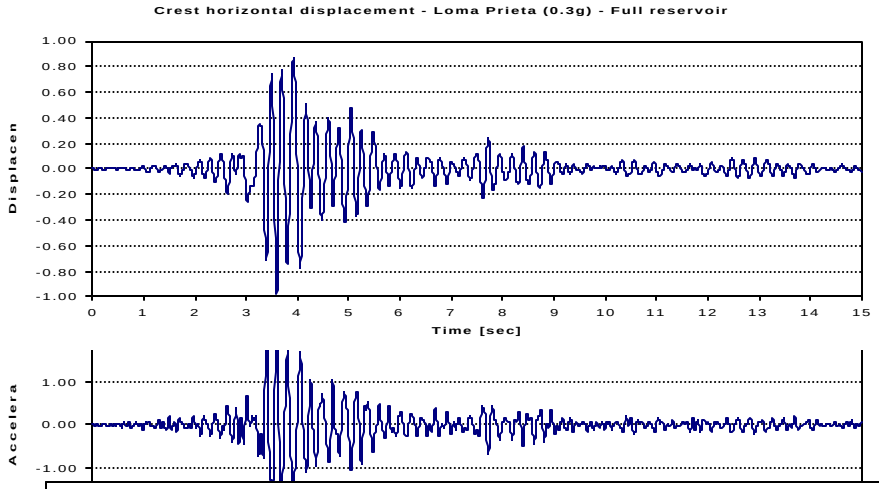
# *Products*




- 2D model
- Platform for evaluation of models and solution strategies
- 3D model
- Final analysis tool

# EQTime2D: Folsom Dam, CA

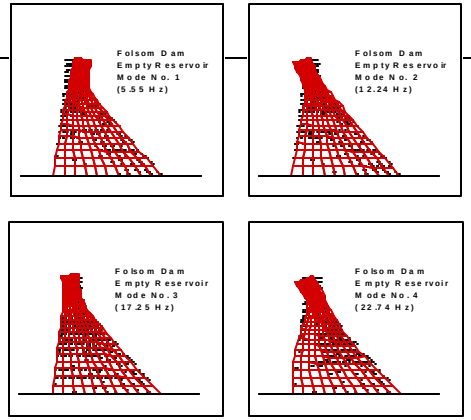


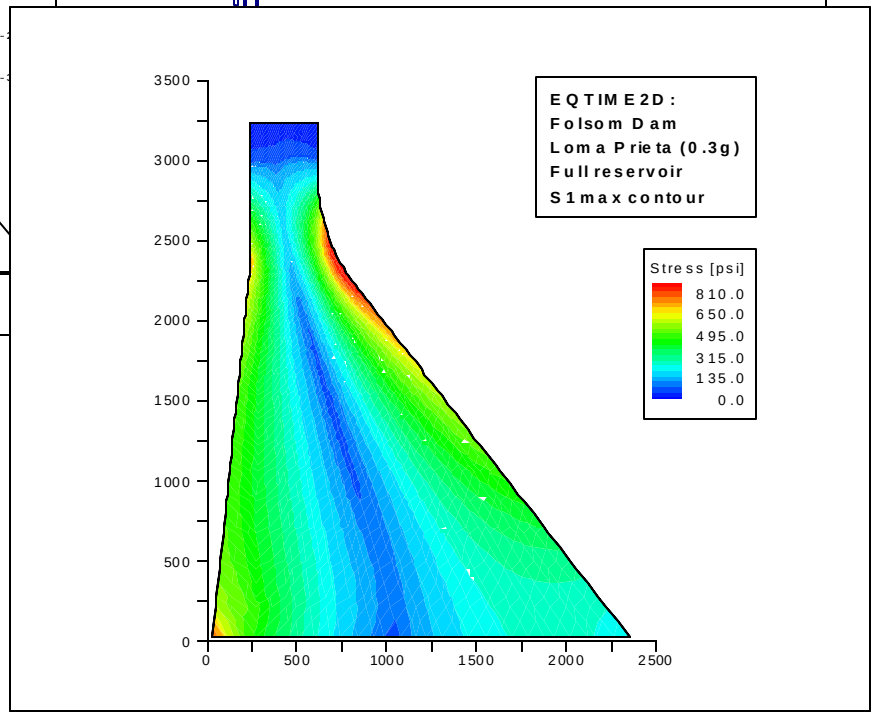




**Mode shapes (full reservoir)**




**Mode shapes (empty reservoir)**




**Maximum principal stress contour (Loma Prieta)**

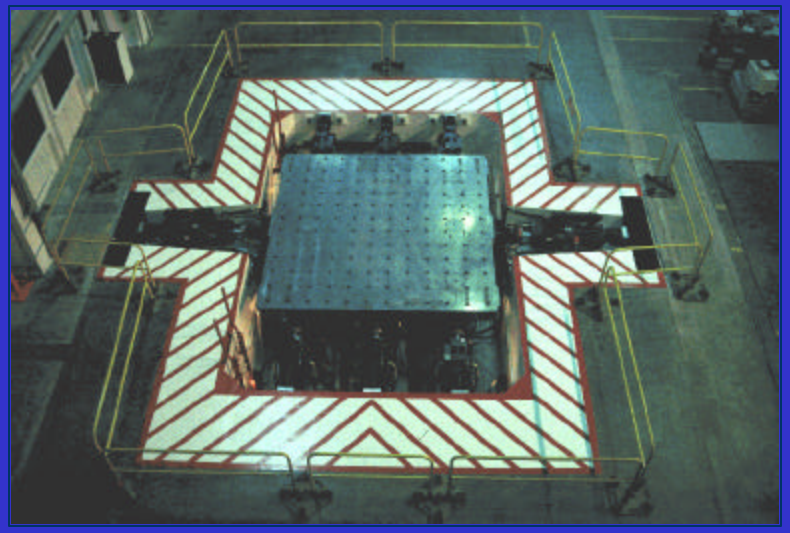
# *Validation - Dongjiand Dam, China*

## Database Development

- **Experimental Performance of Dams**
- **Actual Performance of Dams**

# *Shake Table Experiments*

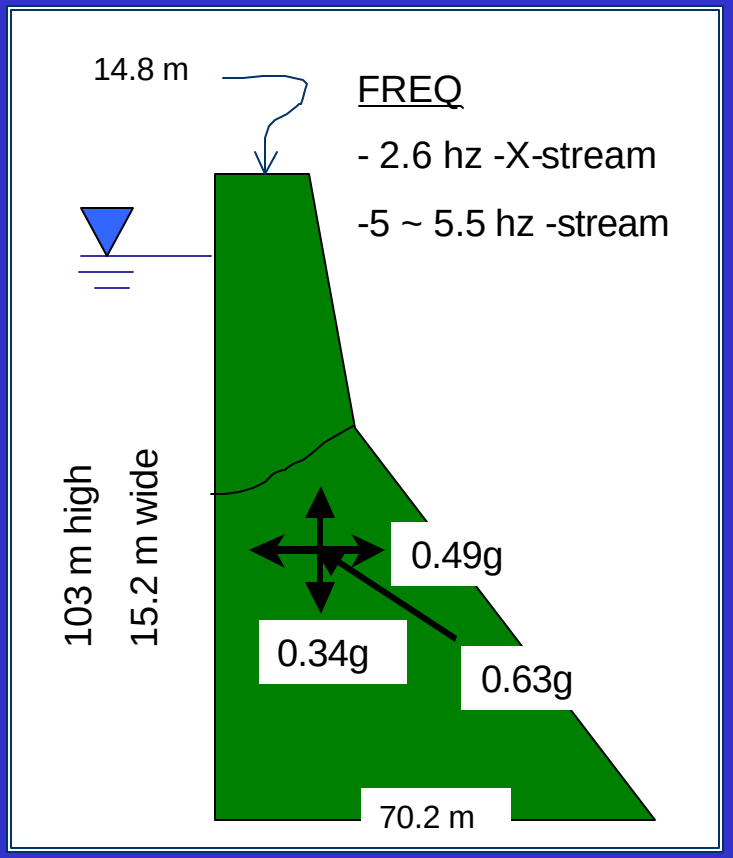
- **To simulate the dynamic behavior of a monolith of Koyna Dam (earthquake-induced cracking pattern).**
- **To observe and identify response characteristics and failure mechanisms under various types of excitation signals.**
- **To provide data for validation and calibration of analytical models.**

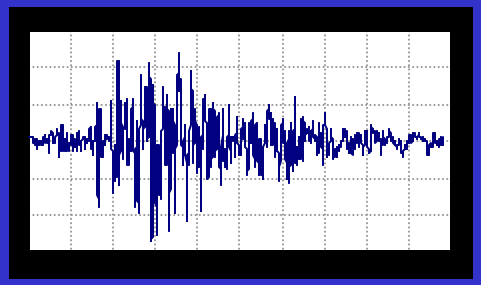


***CERL Shake Table***

# *Why Koyna Dam?*

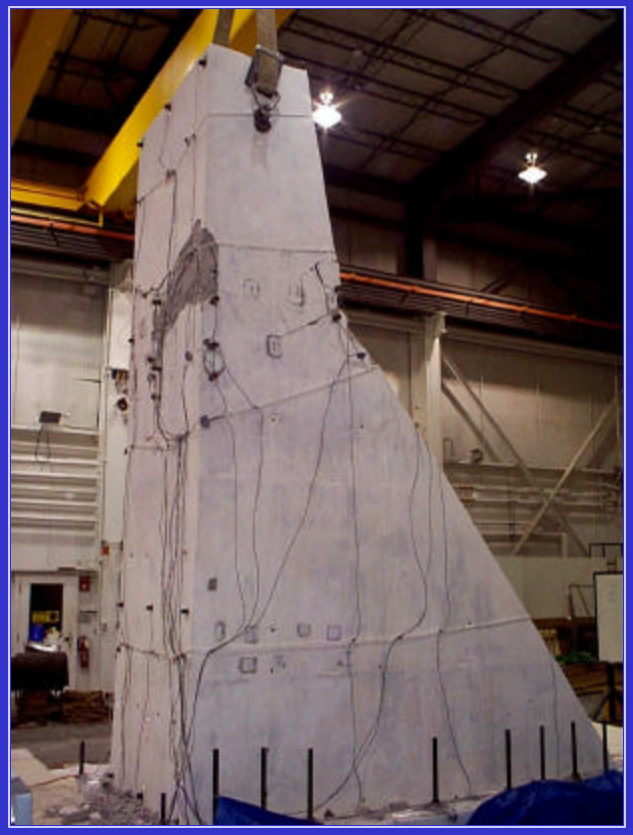
- **Post-earthquake field data are available**
- **Gravity dam subjected to significant structural damage due to seismic ground motion (Koyna earthquake, 1967).**
- **Previous laboratory results are available:**
  - **University of California, Berkeley (1980).**
  - **Bureau of Reclamation (1999).**

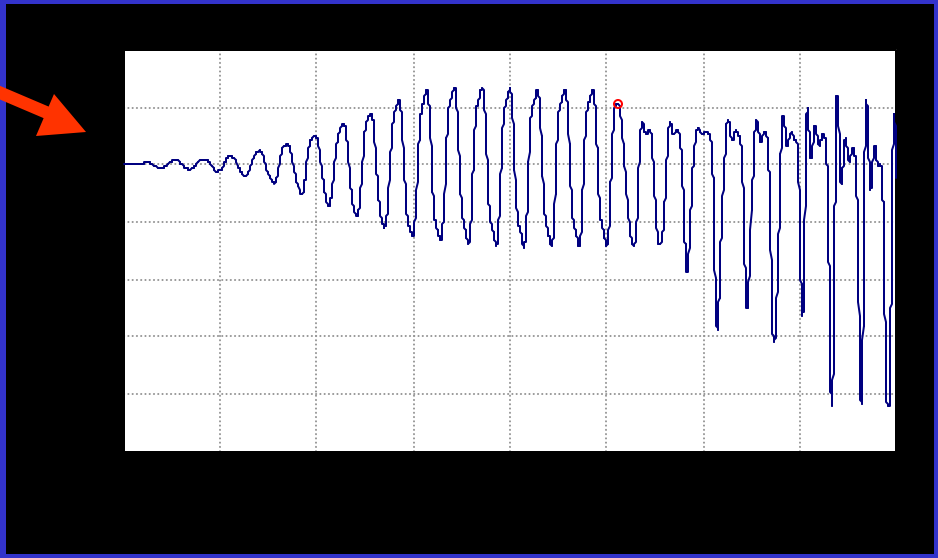


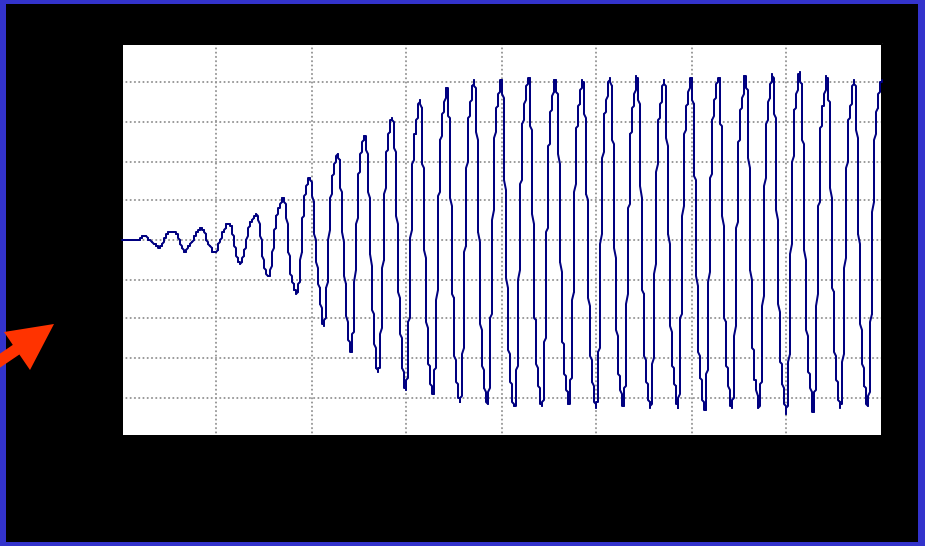



# *Shake Table Results (Strain Gage Data)*

- ~.**0.16** Sin(2π(**14**)t)



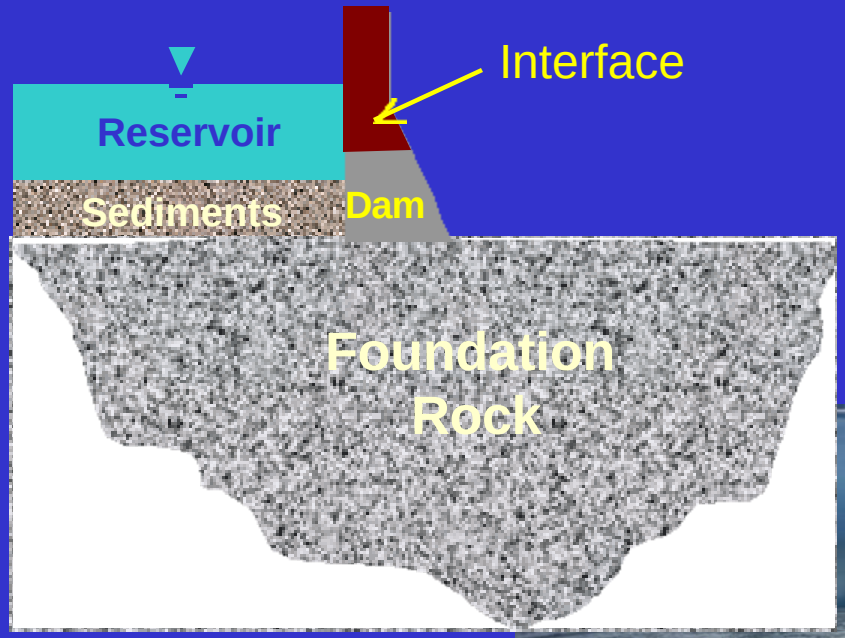


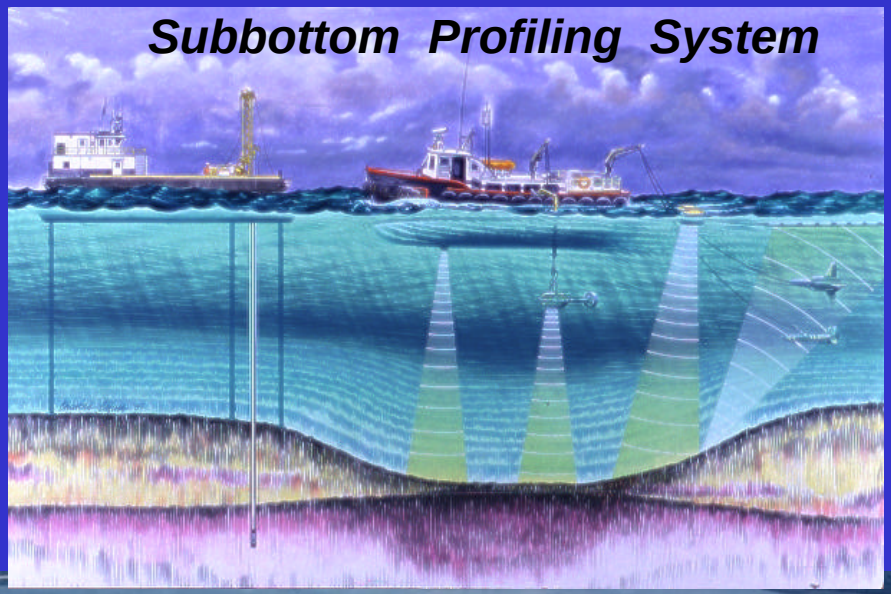


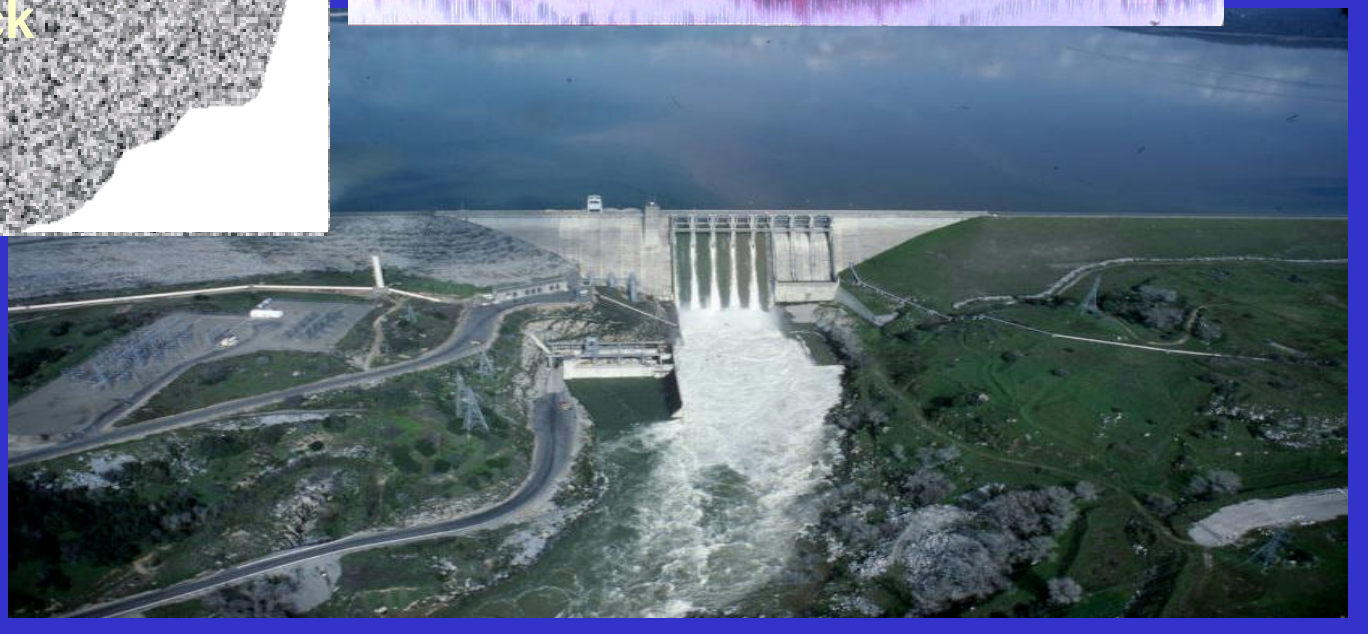
- ~.**0.12** Sin(2π(**14**)t)

# *Breakthrough in Concrete Dam Research – Subbottom Absorption*

- **2-D Time Domain Model**
- **Guidance**



# *Back Analysis of Taiwan Dams*

**Performance of Dams During Large Earthquakes**

**Nice to learn in another's backyard**

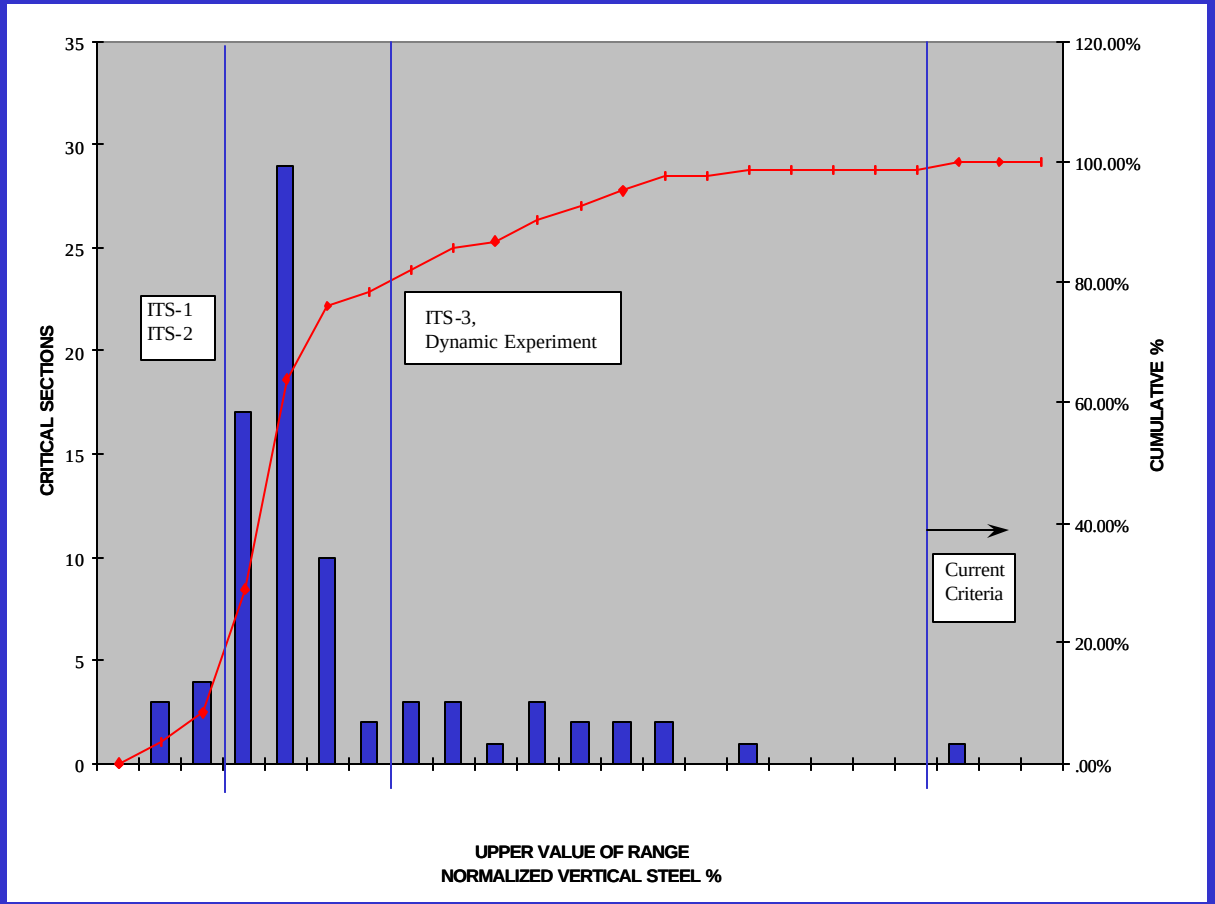
# *Potential Savings*

- **72 Towers have been identified as being located is seismic zone 2 or above, almost all are very lightly reinforced.**
- **The cost of retrofitting an existing tower has been estimated to be between $5 million and $100 million.**
- **Proper estimation of ductile capacity has a large potential payoff.**

Gathright Tower, VA

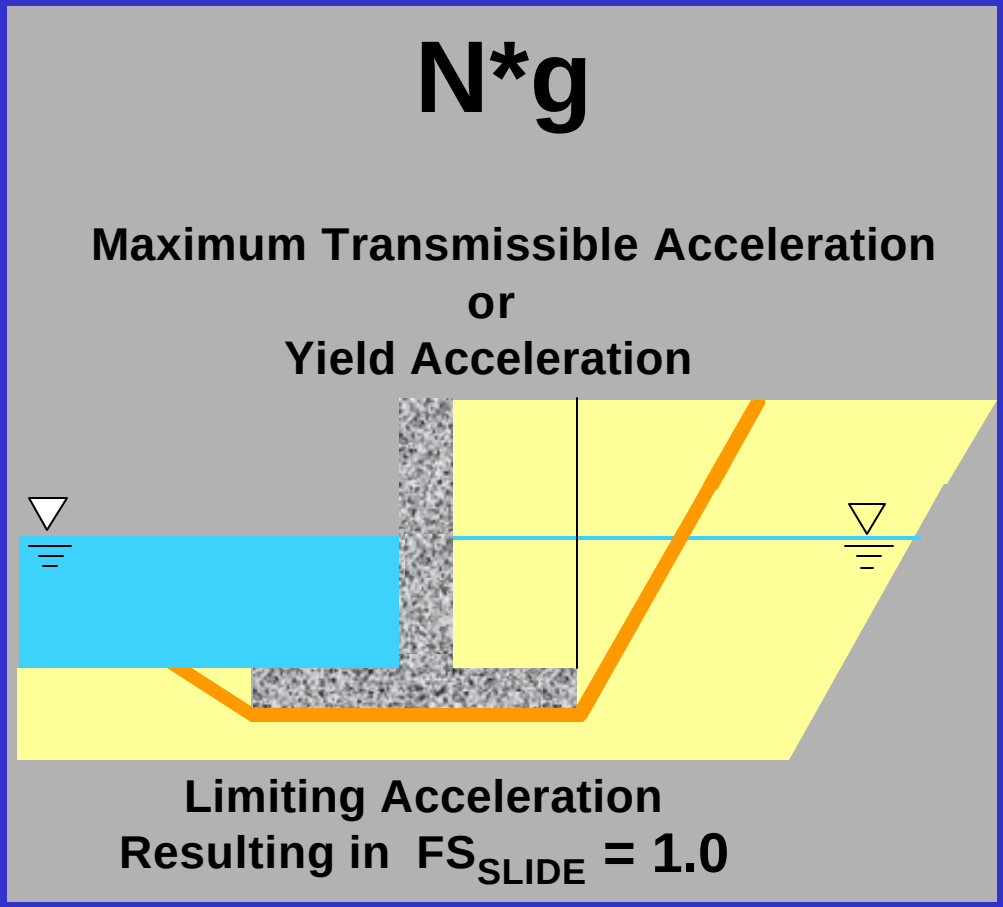
# Inventory of Existing Towers

- Used to design Intake Tower Substructure (ITS) experimentation.
- ITS experimentation was conducted and demonstrated significant ductility in a single crack failure mode.
- Based on experimentation, the Displacement Based Analysis technique was selected as a promising analysis method.



# *Seismic Design of Cantilever Retaining Walls*

- **Development of CSLIP Computer Program**




**CSLIP – windows based program for computing seismically-induced deformations in retaining walls, for performance based designs**

# Technical Reports

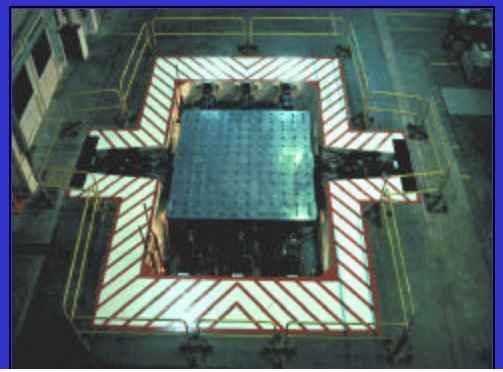
- Roller-Compacted Concrete Dams
- Measurements of Reservoir Bottom Absorption
- Uplift Pressures for Concrete Dams
- Dynamic Response of Intake Towers
- General Ductility of Gate Piers
- Experimental Study of Dongjiang dam for Dam-Water-Foundation Interaction
- Measurement and Prediction of Dam-Water-Foundation Interaction at Longyangxia dam
- Experimental Study of 1/20th Scale of Koyna Dam
- Guidance for Including Effects of Reservoir Bottom Absorption

# Summary Of Accomplishments

- EC 1110-2-6050 Response Spectra and Seismic Analysis for Concrete Hydraulic Structures
- EC 1110-2-6051 Time-History Analysis of Concrete Hydraulic Structures
- EC 1110-2-285 Structural Analysis and Design of Intake Structures for Outlet Works
- EQ-Time 2D
- Internet Based Data Base

# Earthquake Engineering Research Program
## Concrete Dams - Summary

- Hydrodynamic loads on concrete dams – field procedures
- Roller-compacted concrete – seismic properties and construction procedures
- Nonlinear analysis code for cracking
- Nonlinear analysis for monolith to monolith interaction
- Nonlinear analysis for sliding on lift joints
- Comprehensive code for reservoir-foundation-structure analysis
- Software to translate FEM output into moments, shears, and thrusts
- Software to interpret time history analysis results



*CERL Triaxial Earthquake Shock Simulator*

*Folsom Dam, CA*

# Infrastructure Engineering and Management Research Thrust Area

## Earthquake Engineering Program

*End of Presentation*

*Questions*

**US Army Corps of Engineers**

**Engineering Research and Development Center**