EQEN Program Accomplishments

Dr. Robert L. Hall
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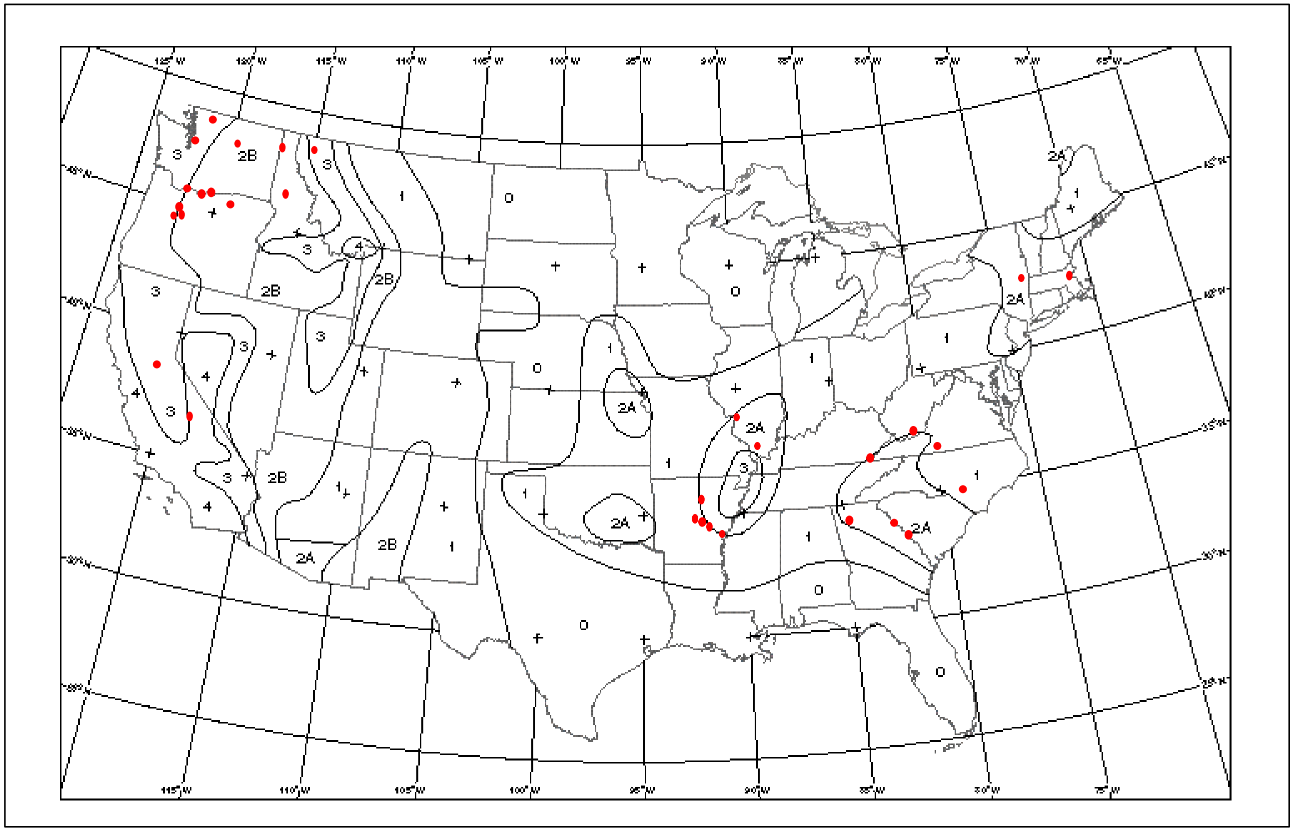
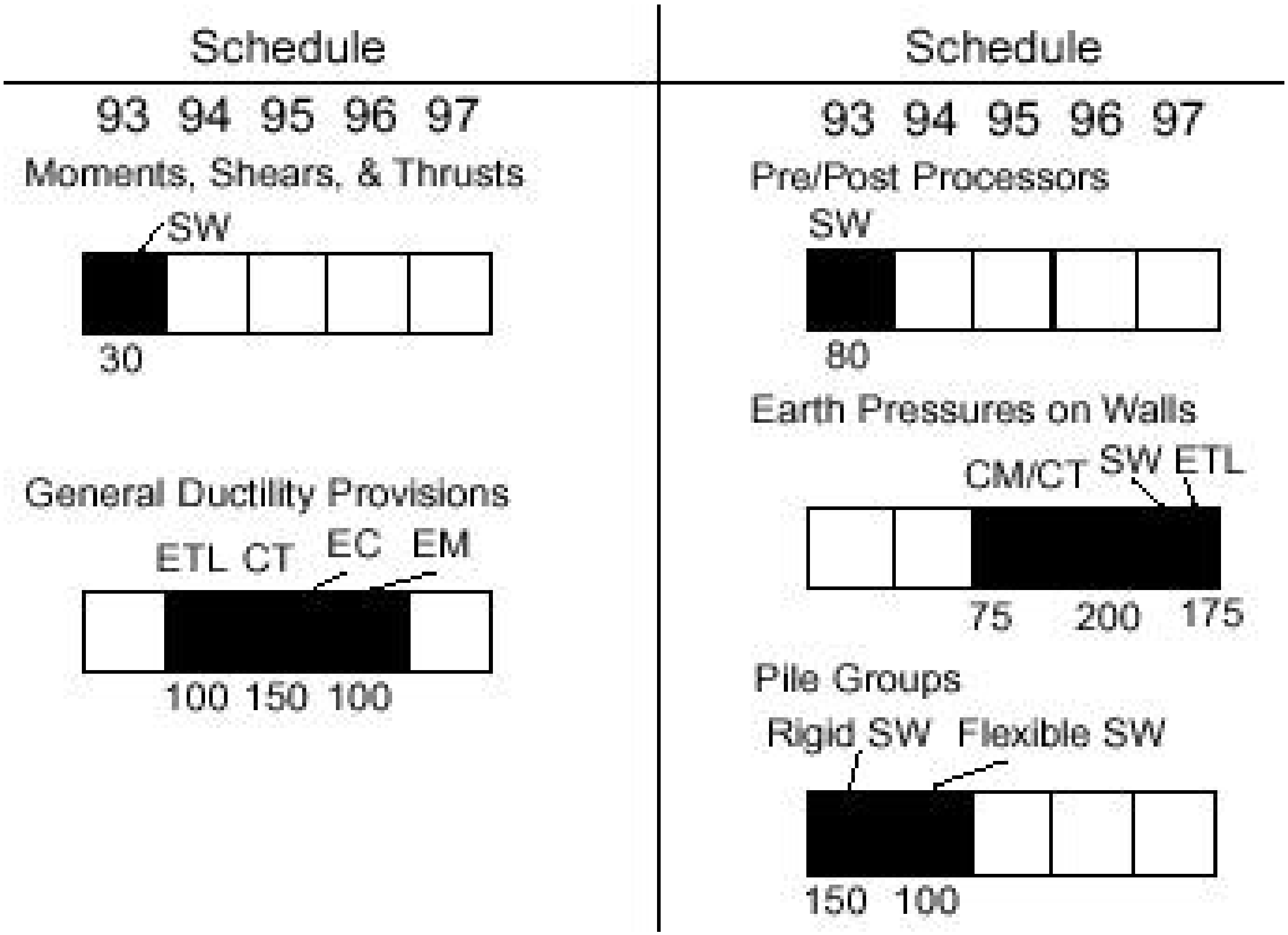


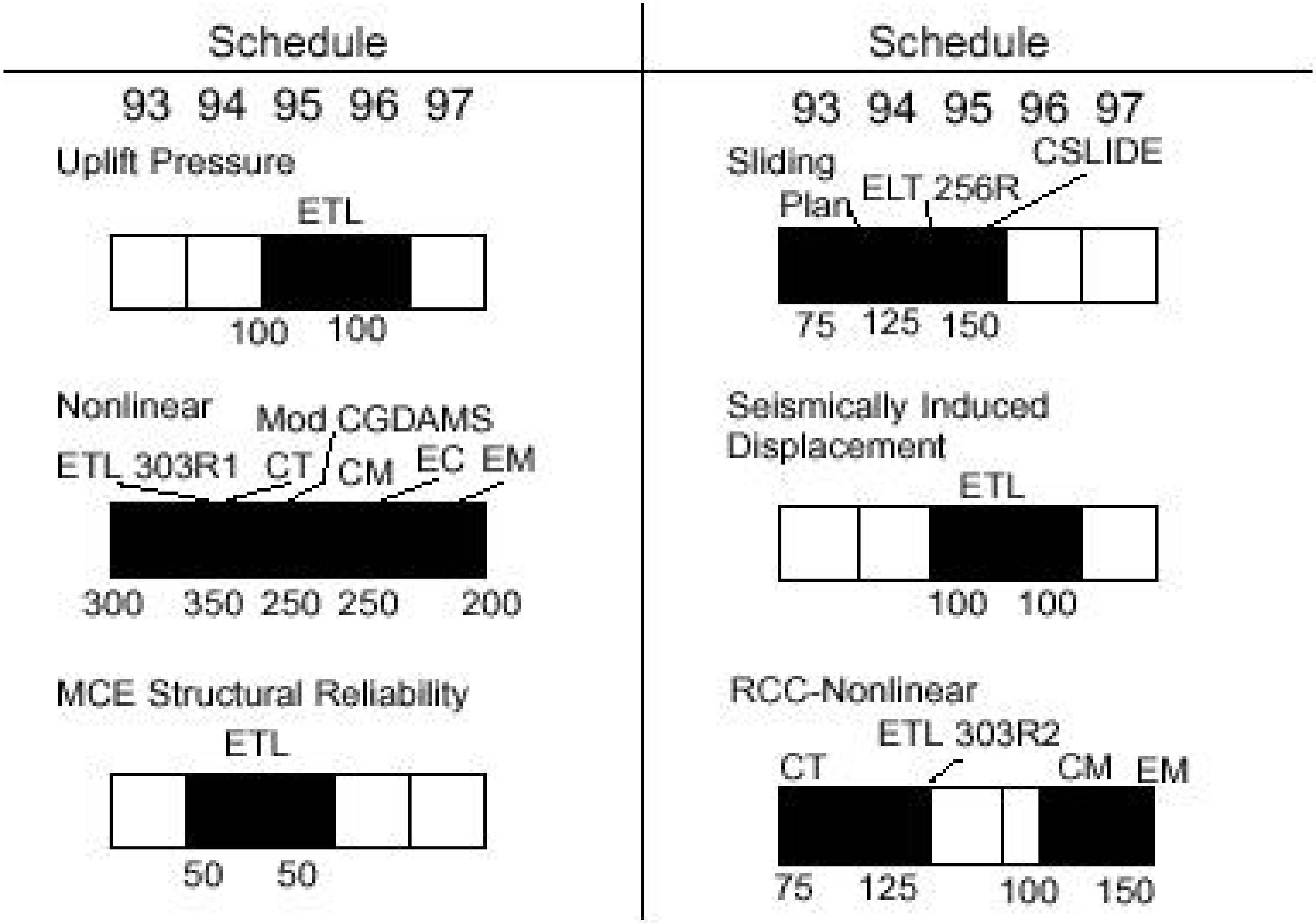
1994 UBC Seismic Zones

31 Concrete Dams in Zones 2A,2B, and 3

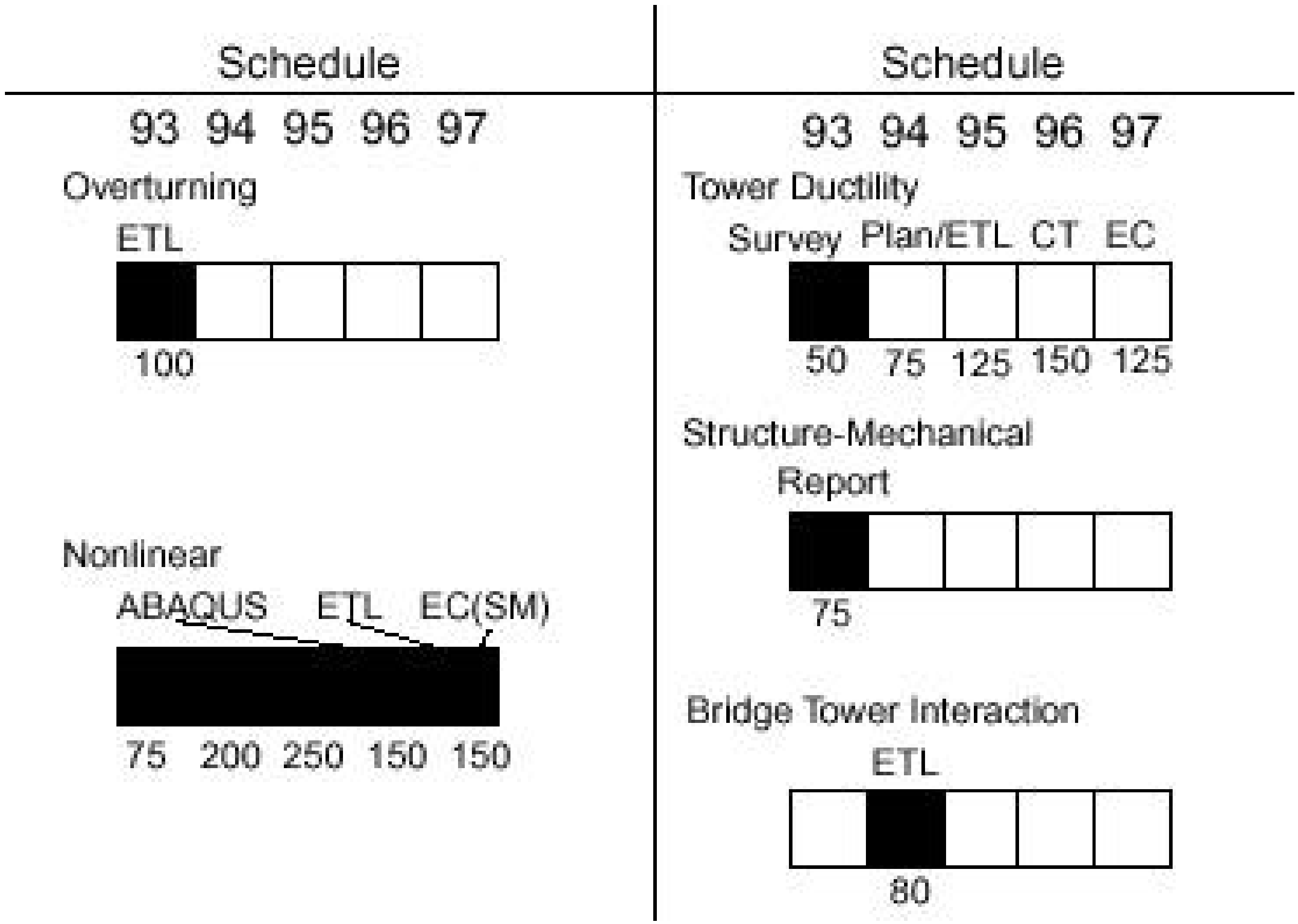
Earthquake Analysis Tools for Structures



Seismic Response to Concrete Dams



Seismic Response of Outlet Works



Introduction

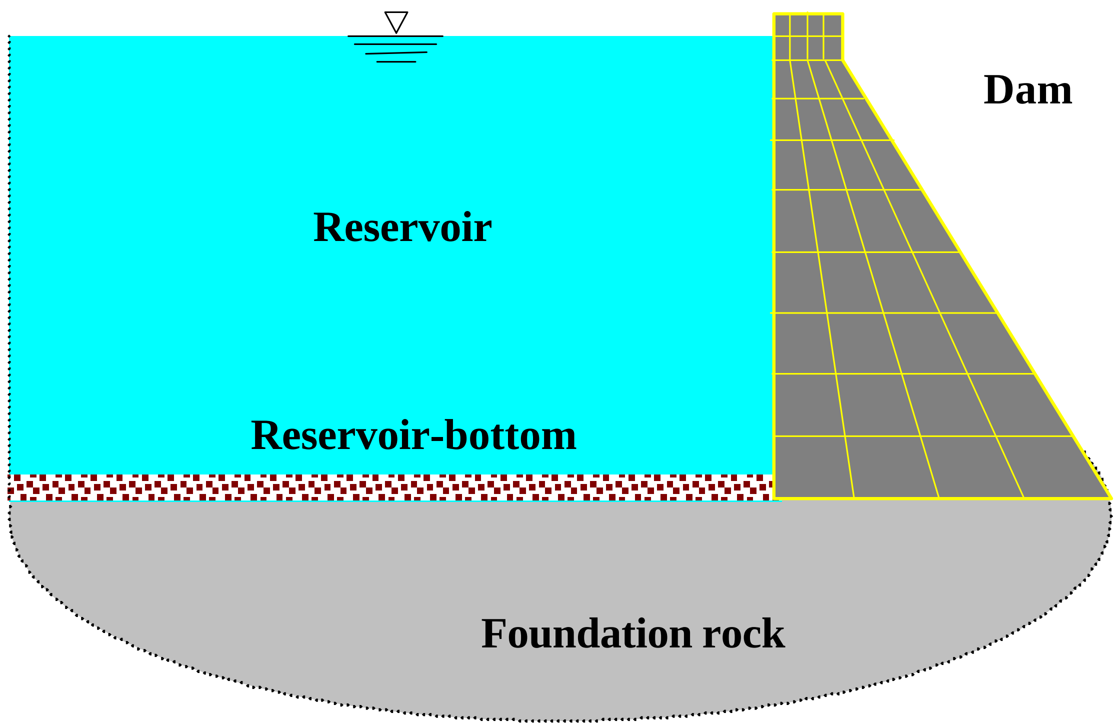
The accurate evaluation of the seismic performance of concrete dams requires the development of numerical procedures that account effectively for the most critical factors controlling the response.

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

Objective

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



Products

A family of computer codes for nonlinear transient analysis of dam-reservoir-foundation systems under seismic excitations

EQTime2D

- **2D model**
- **Platform for evaluation of models and solution strategies**

EQTime3D

- **3D model**
- **Final analysis tool**

- The multi-purpose modular platform has been completed with the following features:
  - Eigenvalue, static (incremental) and dynamic analysis options.
  - Implicit integration with full and modified Newton-Raphson iterations.
  - Static initialization with gravity and hydrostatic loading.
  - Proportional damping model (tangent).
  - Consistent hydrodynamic mass matrix.
  - Smeared crack model (crack control options: free and fixed crack evolution).

EQTime2D (Cont.)

- **A first version of the Theory Manual has been completed, describing the theoretical aspects behind the program analysis options.**
- **Extensive output options have been added:**
  - **Node/element user defined lists.**
  - **Time histories (selected response quantities).**
  - **Mode shapes (linear case).**
  - **Stress contour envelopes.**
  - **Excess stress index.**

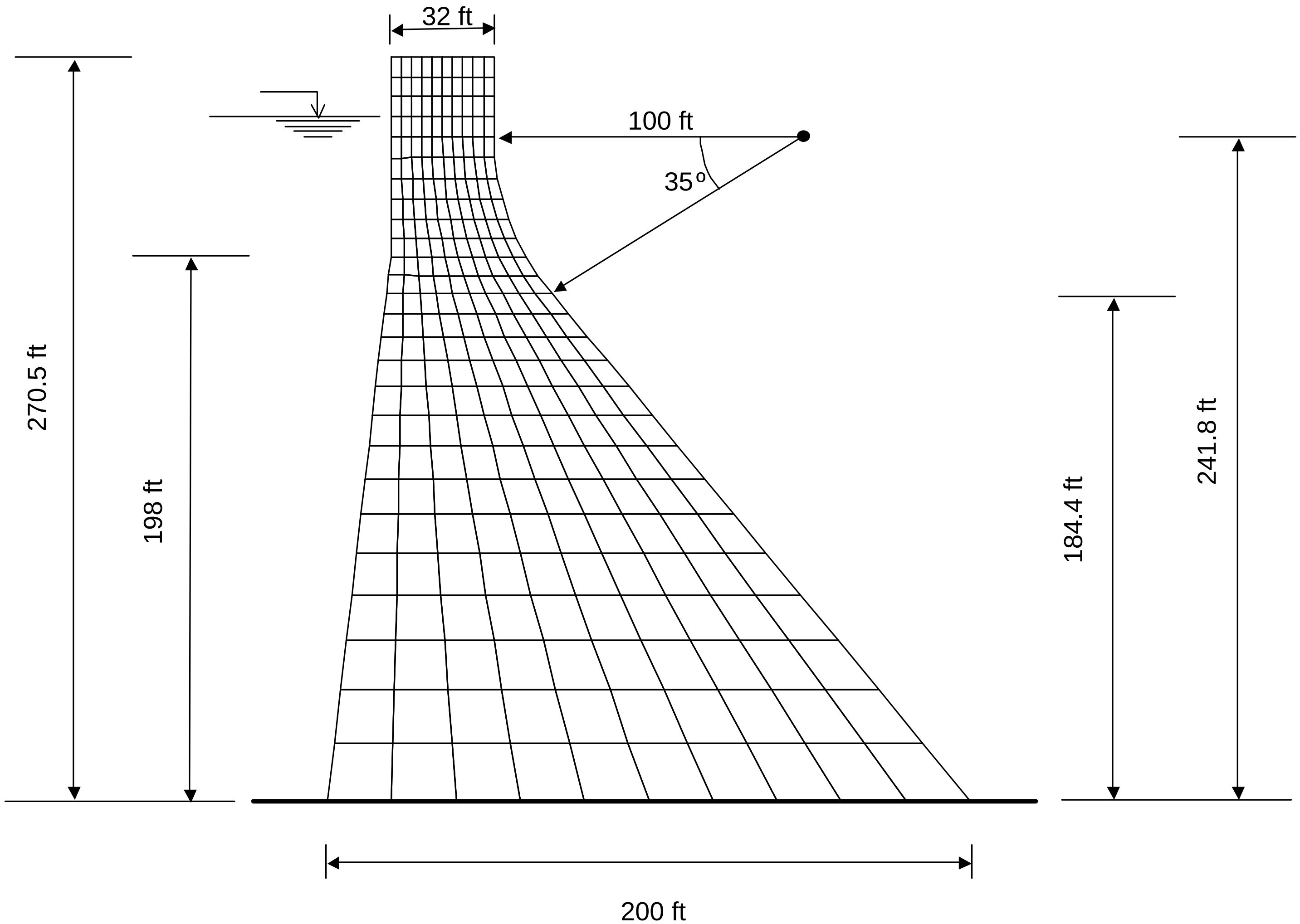
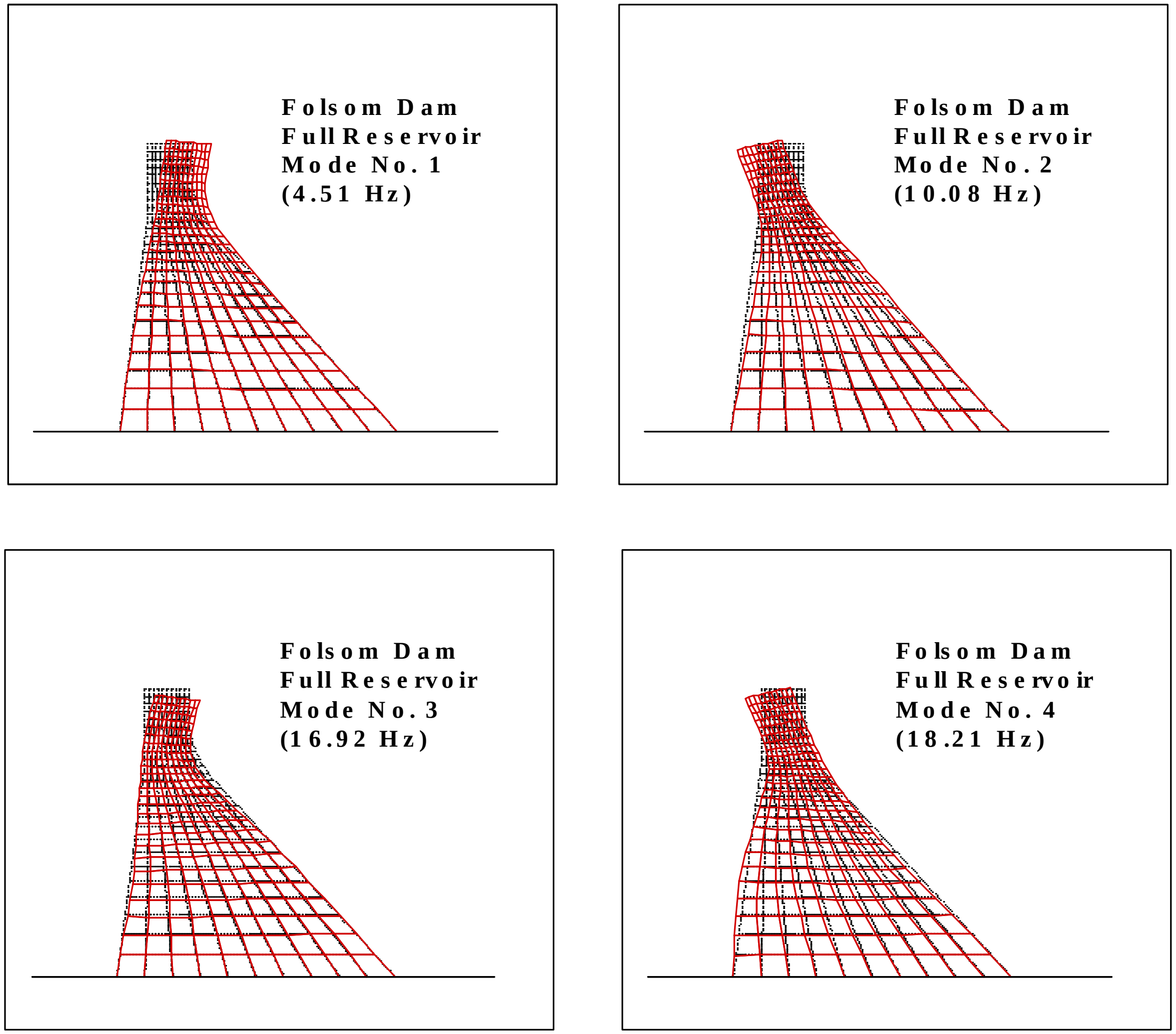


Figure 6.3-3. Section geometry and finite-element model.

EQTime2D



Mode shapes (full reservoir).

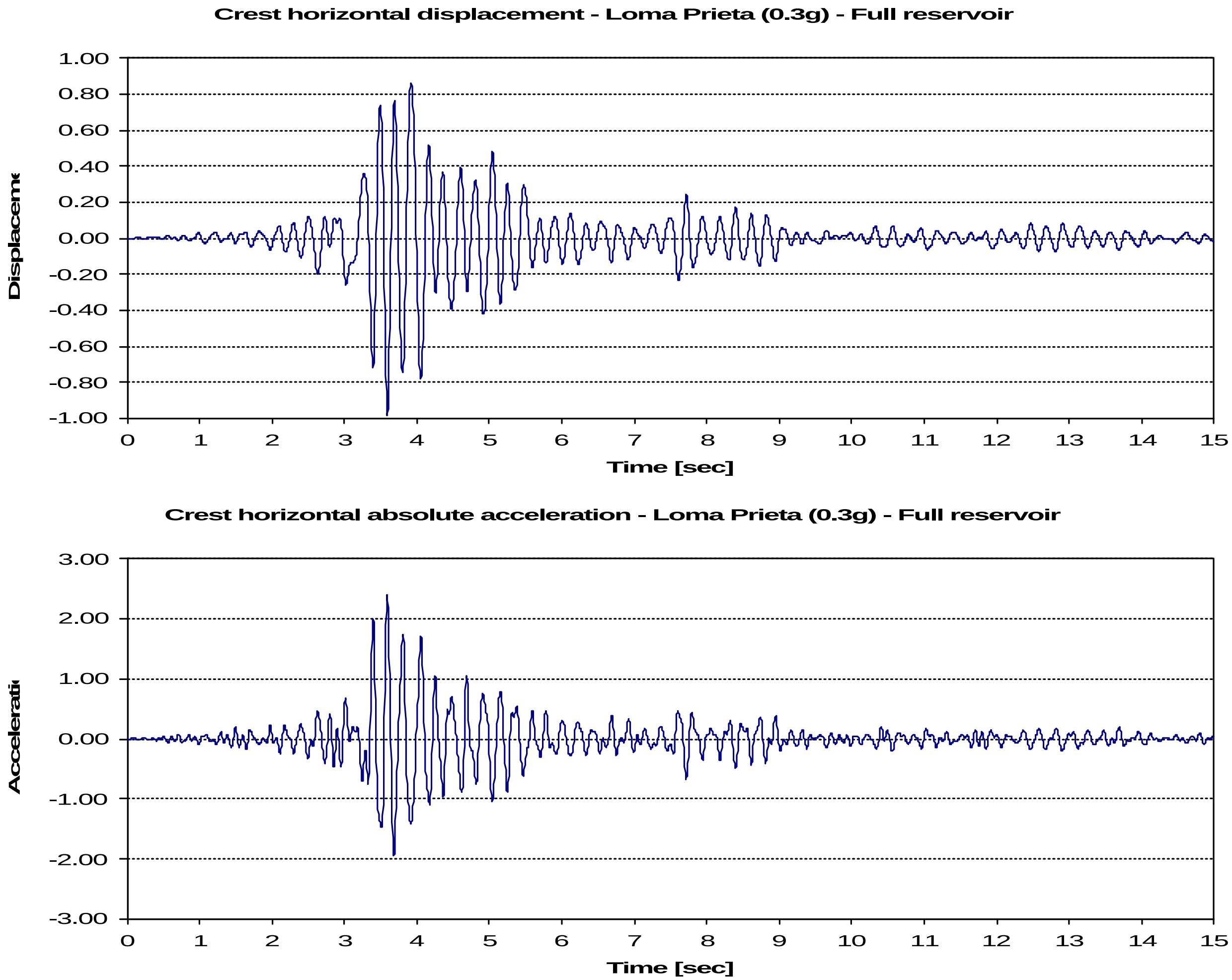
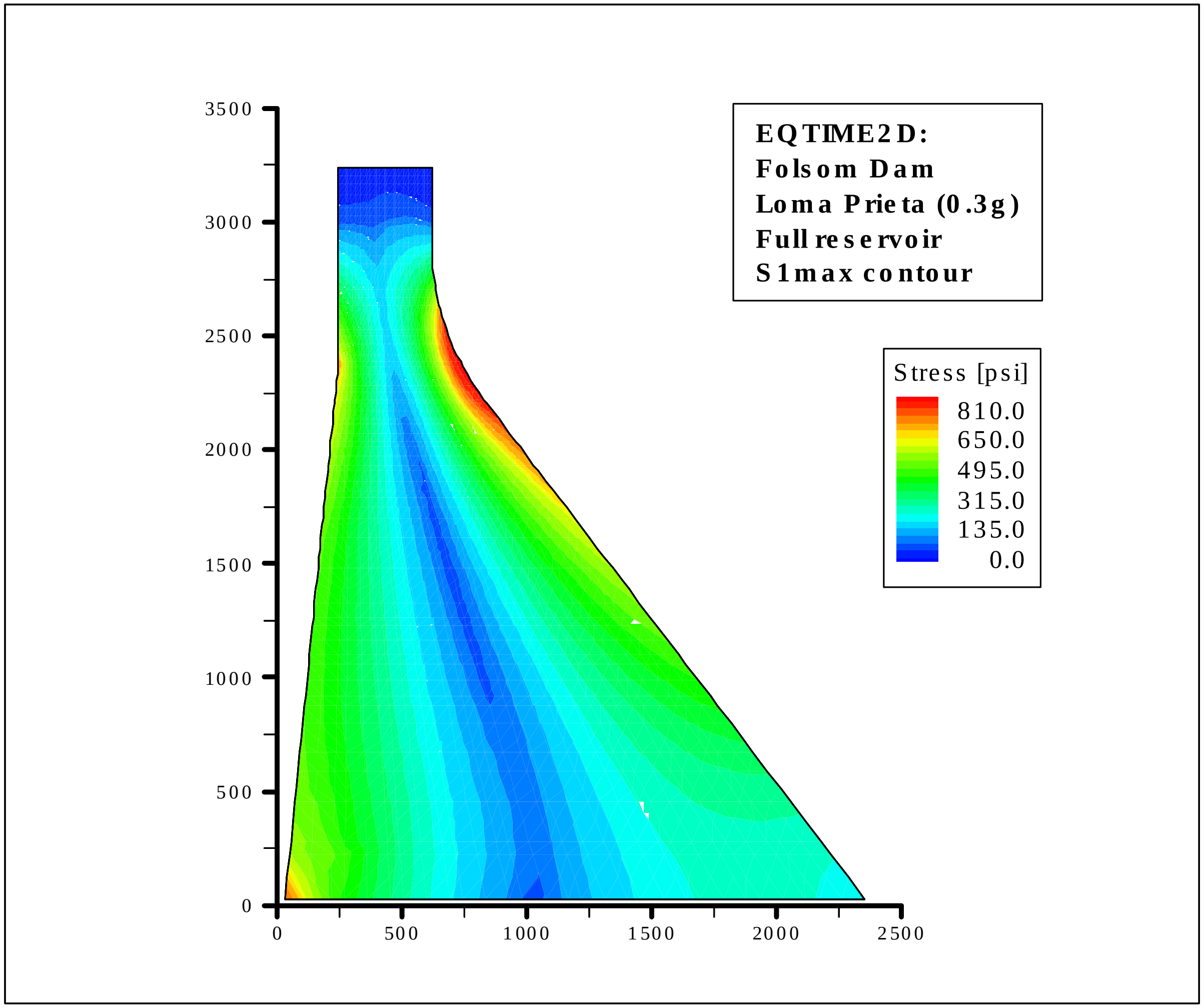


Figure 6.3-7. Crest relative displacement and crest absolute acceleration (Loma Prieta).

EQTime2D

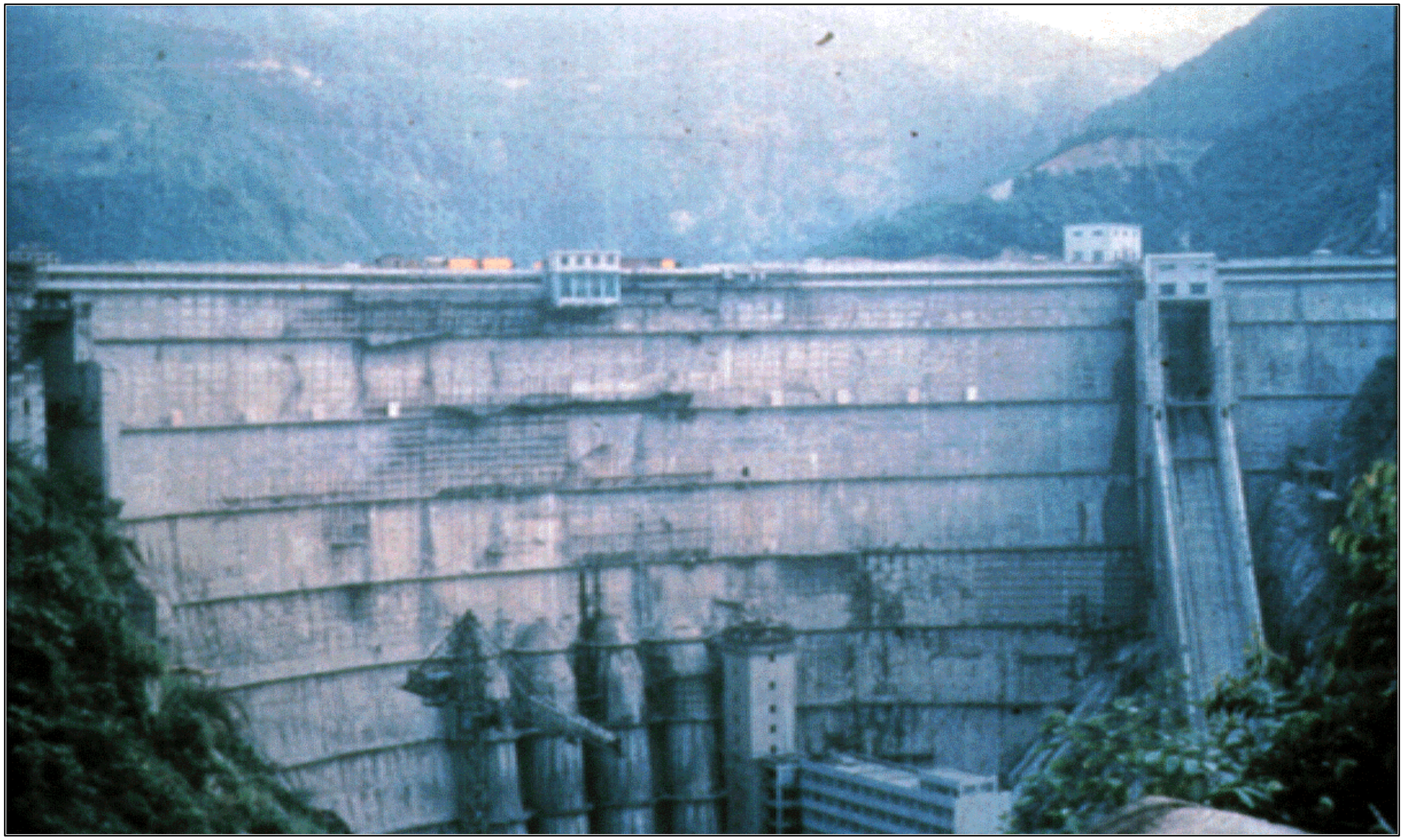


Maximum principal stress contour (Loma Prieta).

Validation - Dongjiand Dam, China

Data Base Development

- Experimental Performance of Dams
- Actual Performance of Dams

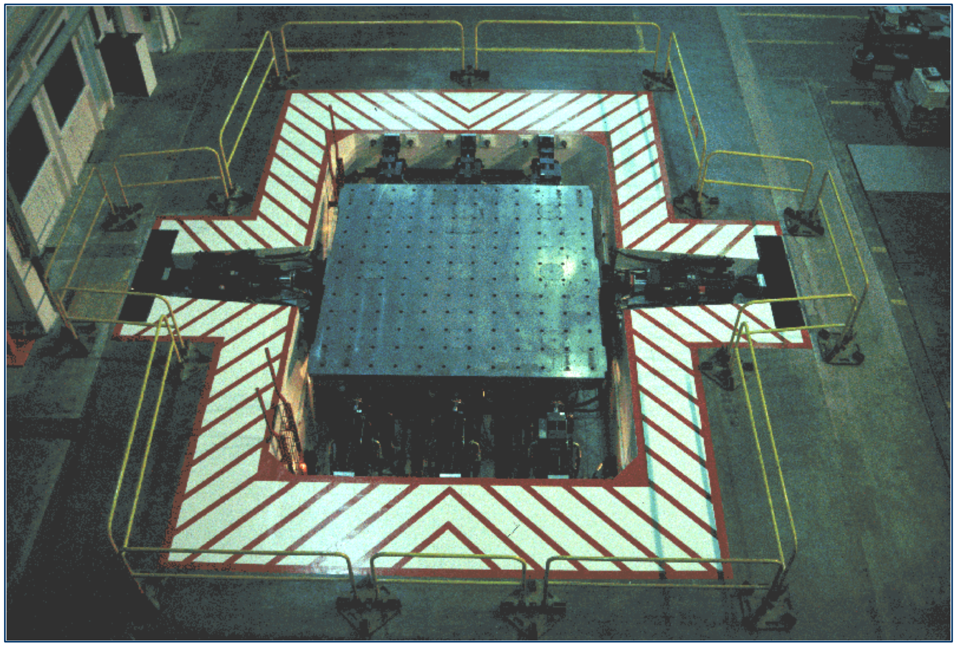


Validation - Longyangxia Dam, China

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.**

Shake Table at CERL



TESS

PERFORMANCE ENVELOPE PLOTS AND SPECIFICATIONS

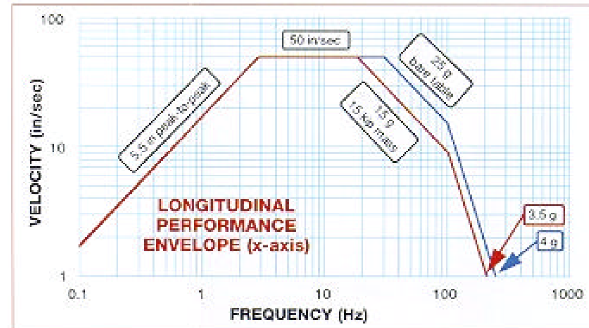
TABLE DIMENSIONS
12 ft x 12 ft; note that models exceeding these dimensions can be mounted and tested

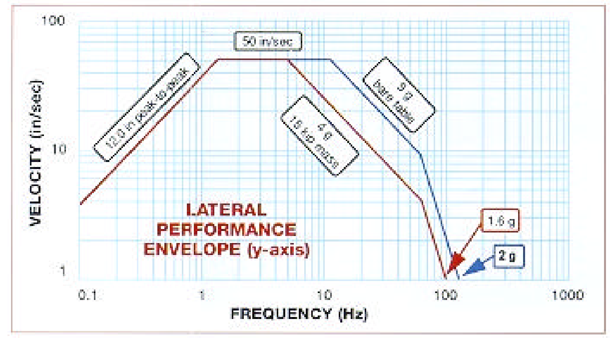
HORIZONTAL FORCE
x-axis: 450,000 lb
y-axis: 150,000 lb

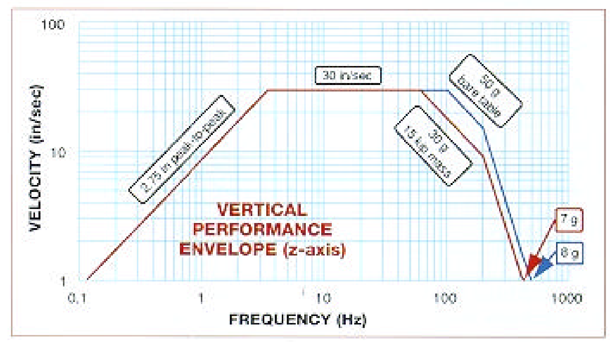
VERTICAL FORCE
z-axis: 810,000 lb

DISPLACEMENTS
x-axis: ±2.75 in.
y-axis: ±6.00 in.
z-axis: ±1.375 in.

DATA ACQUISITION SYSTEM
- 128-channel data acquisition system (future expandability to 512 channels)
- 50,000 samples per second throughput to disk
- sample-and-hold and anti-alias filter on each channel to prevent time-skewing and eliminate high-frequency noise and aliasing effects
- software incorporates all test-execution data, documentation, test data, and data management information into a common database for each test performed

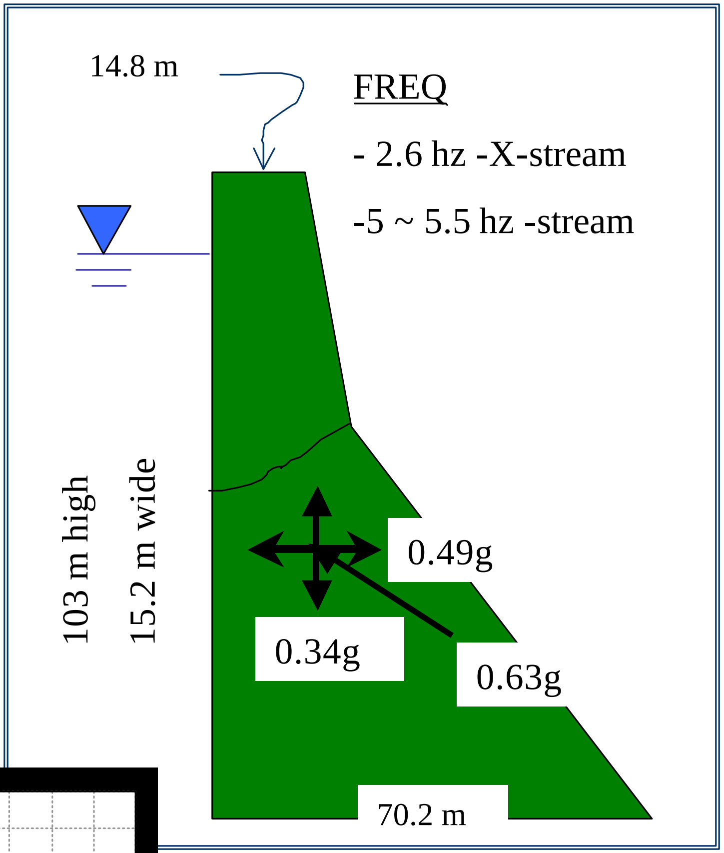


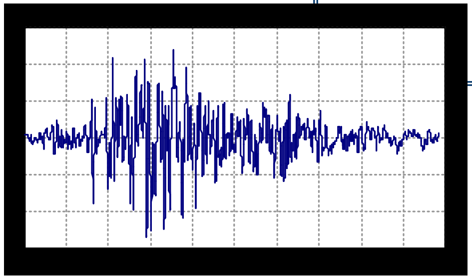




Why Koyna Dam?

- **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).**





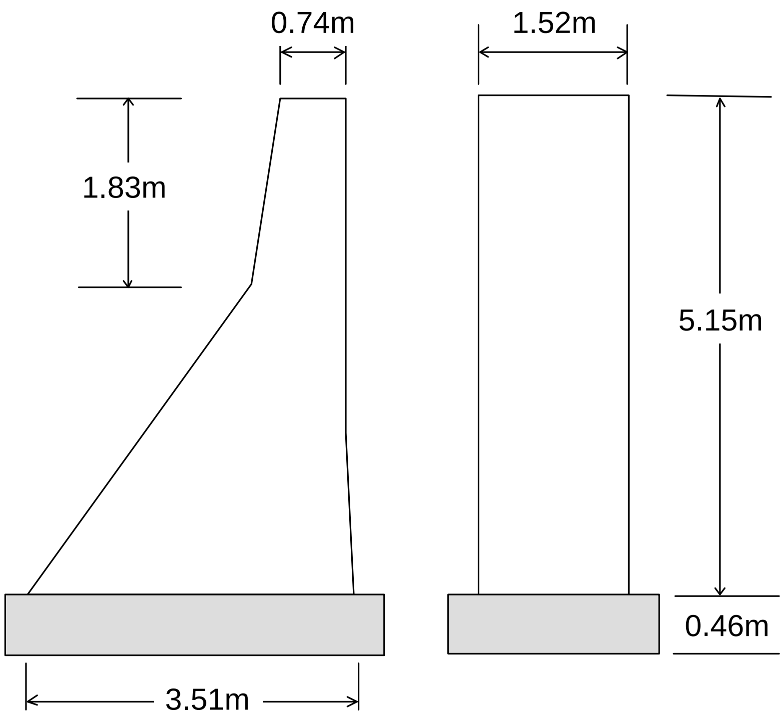
Model Design and Material Properties

Property	Prototype	Model
Unit weight	23.57 kN/m^3	23.57 kN/m^3
Modulus of elasticity	27.58 GPa	1.379 GPa
Compressive strength	27.58 MPa	1.379 MPa
Tensile strength	2.76 MPa	0.138 MPa
Poisson's ratio	0.20	0.20

- Very Fluid and Dense Mix

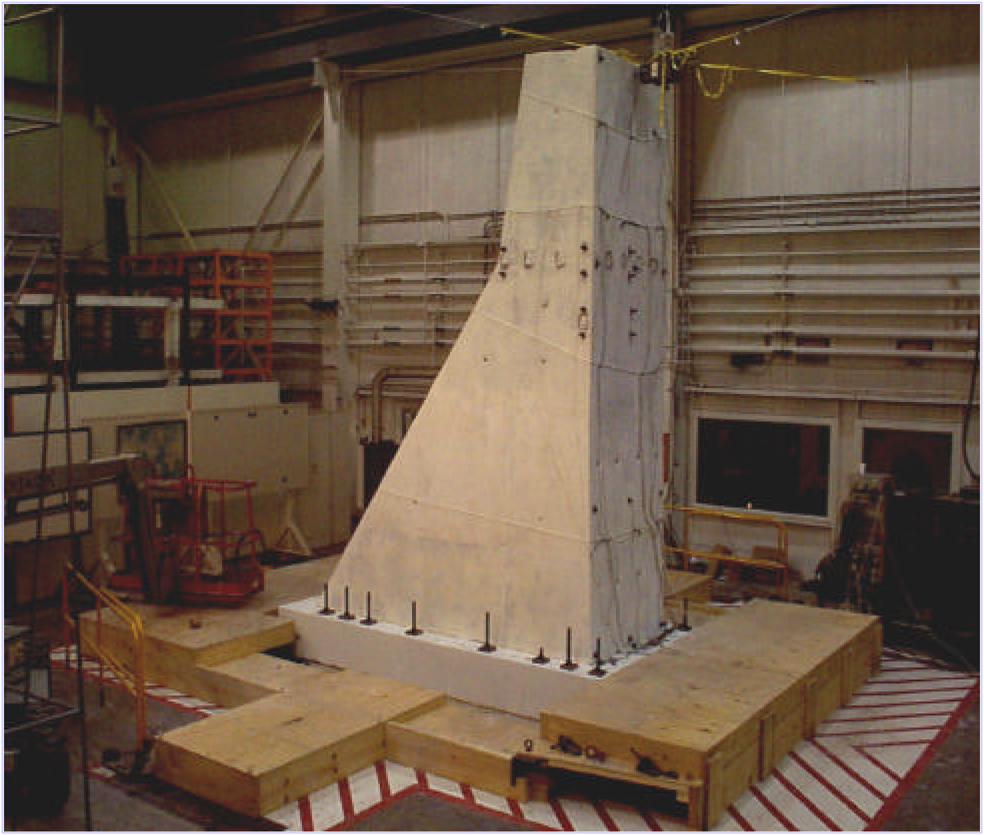
ERDC Model Material Property	@ Base of Model
Unit weight	23.28 kN/m^3
Modulus of elasticity	3.447 GPa
Compressive strength	4.60 MPa
Tensile strength	0.60 MPa

Model Configuration



- **1/20th Scale Model of Koyna Dam**
- **Scaled Material Properties, f'_c = 200 psi**
- **60 in. deep section (2 monoliths)**
- **Height = 203 in. (5.15 m)**
- **Base Width = 138 in. (3.51 m)**
- **Base Beam Thickness = 18 in.**

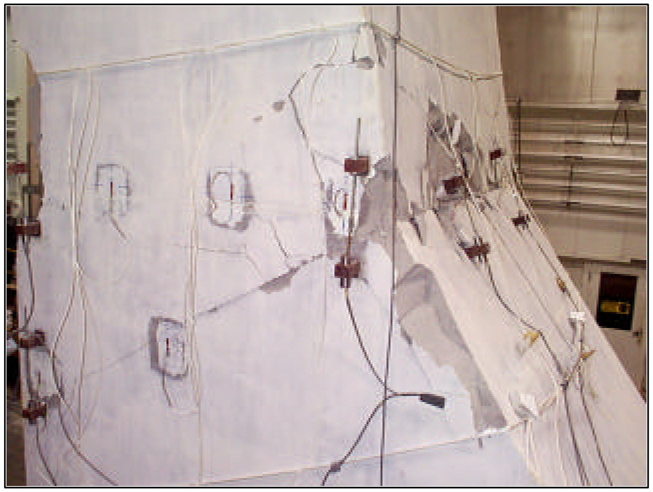
Surface Preparation & TESS Protection Frame

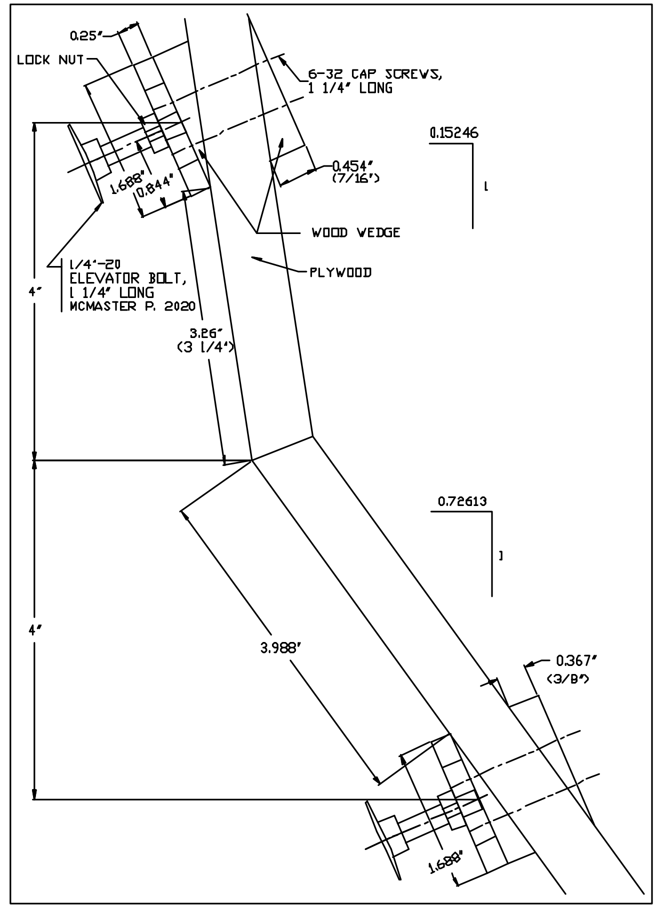


- **Model Surface kept Saturated**
- **Forms removed at 16 days**
- **Curing compound Applied**
- **Lime White-wash Applied**
- **TESS Protection Frame Constructed**

- **Very Fluid Material**
- **Damage to Shaketable Surface and Accelerometers**

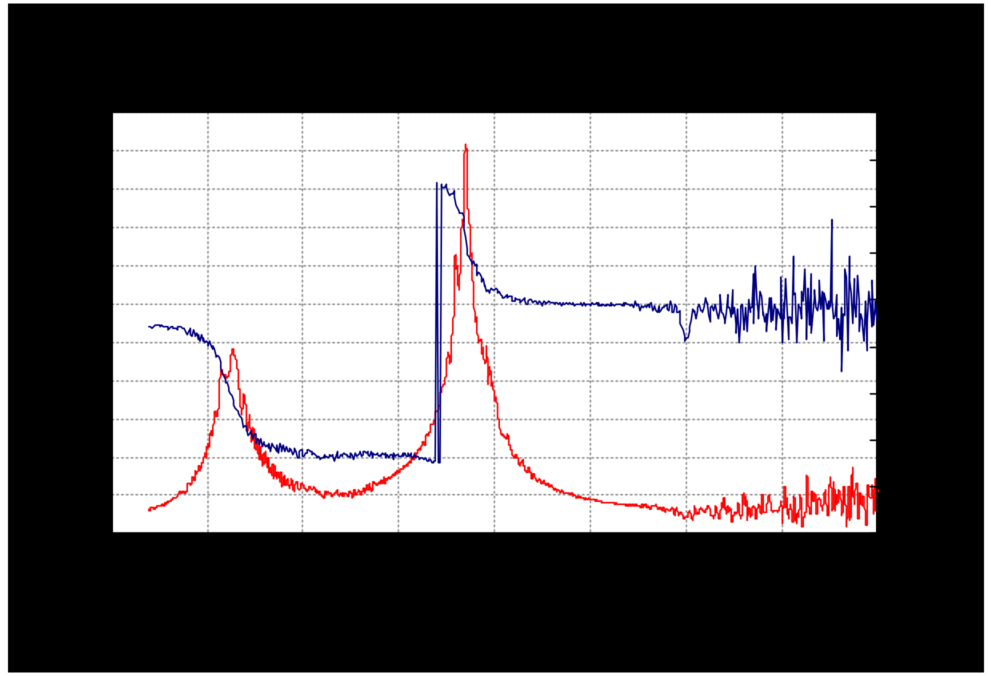
Instrumentation Details





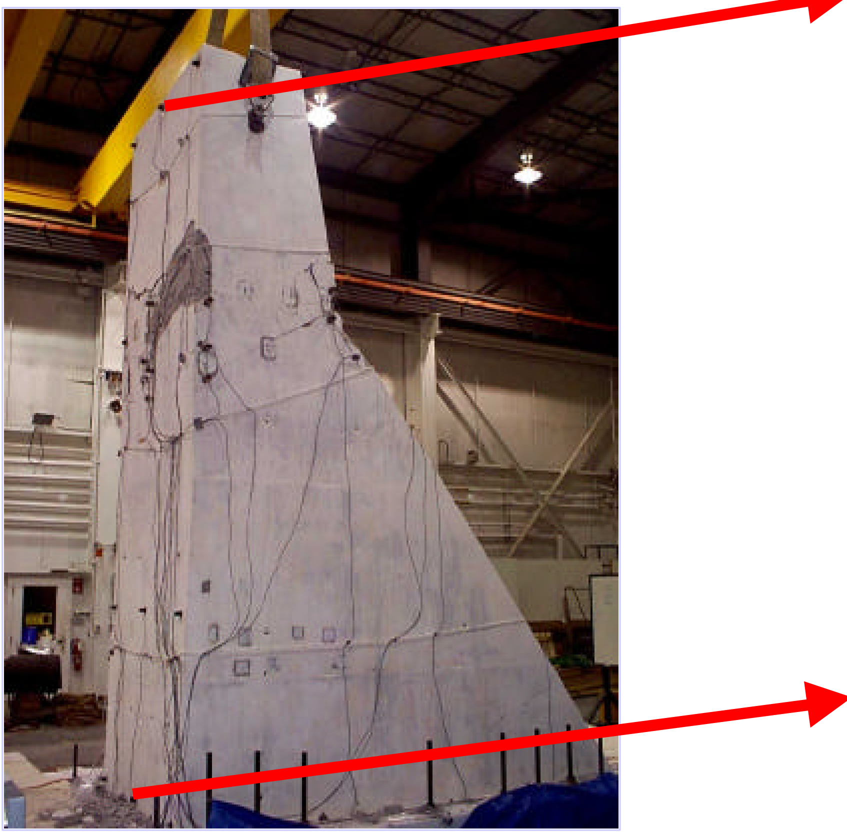
- **Instrumentation Plates Cast into the Model**
  - **Accelerometers**
  - **LVDTs**
- **Strain Gauges Difficult to Install**

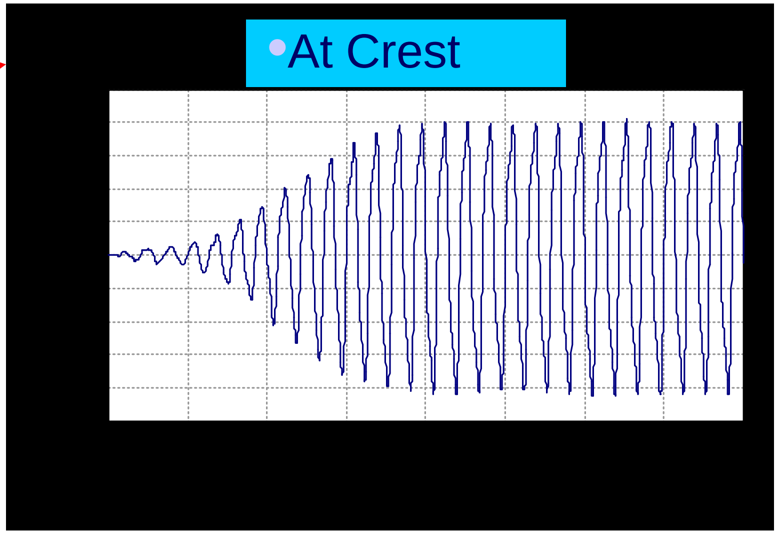
In-Plane Mode of Vibration

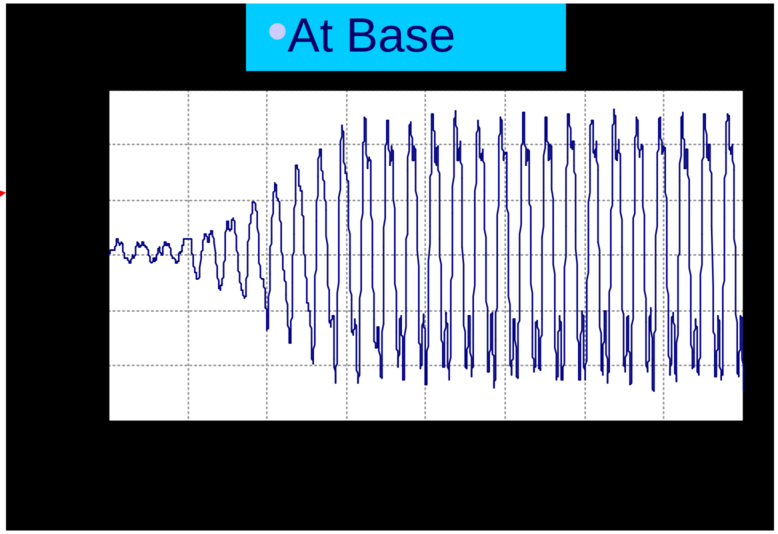


- **Ist Mode = 12.7 Hz** ***(x = 5.5%)***
- **2nd Mode = 37.0 Hz** ***(x = 2.5%)***

Shake Table Results (Accelerometer Response)



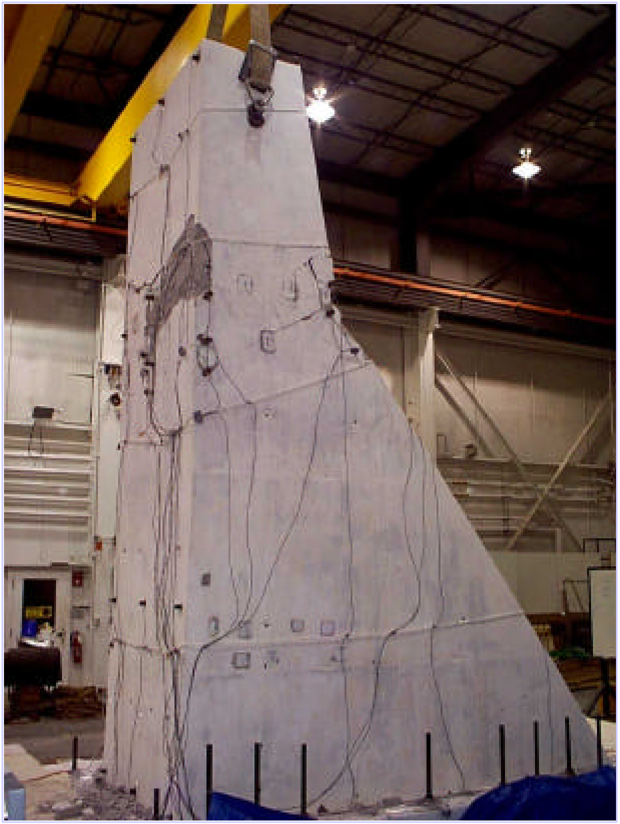


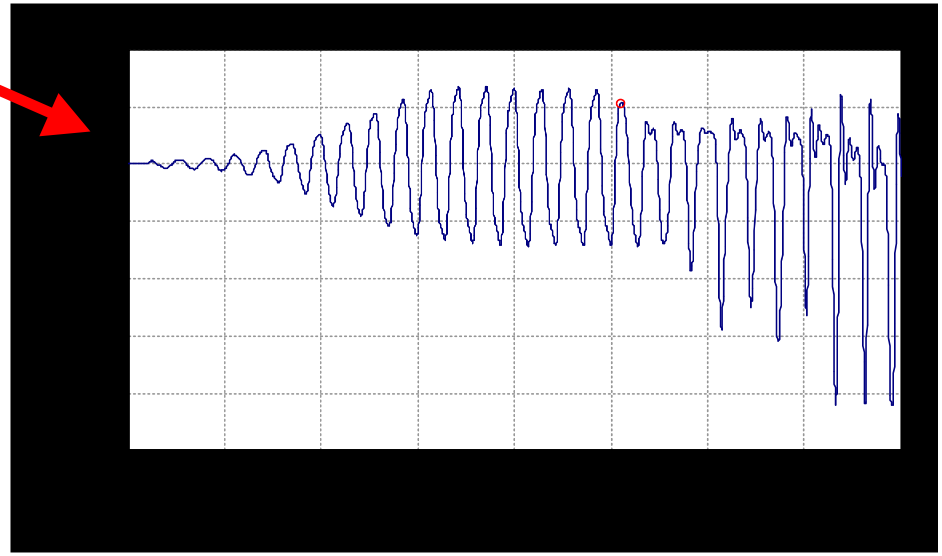


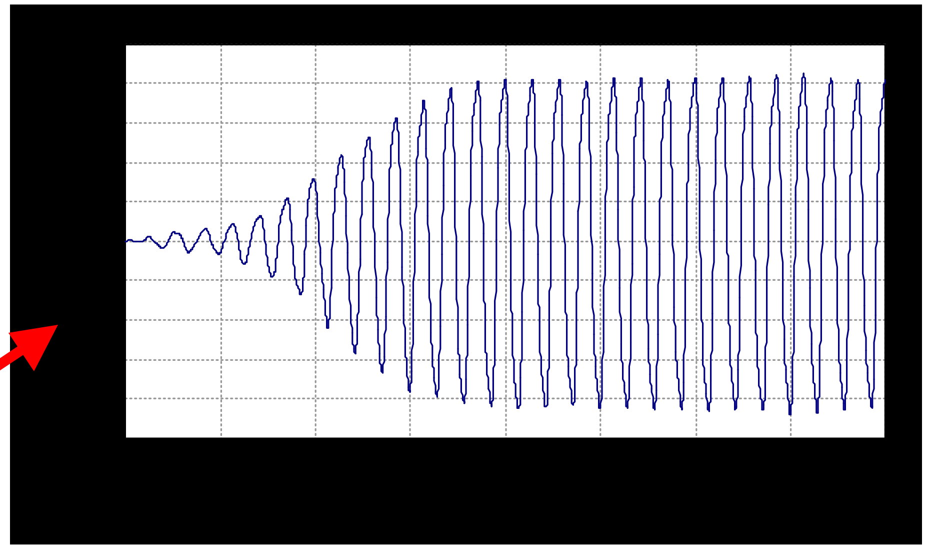
- **Sine Sweep test at 14 Hz**
- **Peak to Peak = 0.24g**

Shake Table Results (Strain Gage Data)

- ~.**0.16** Sin(2π(**14**)t)

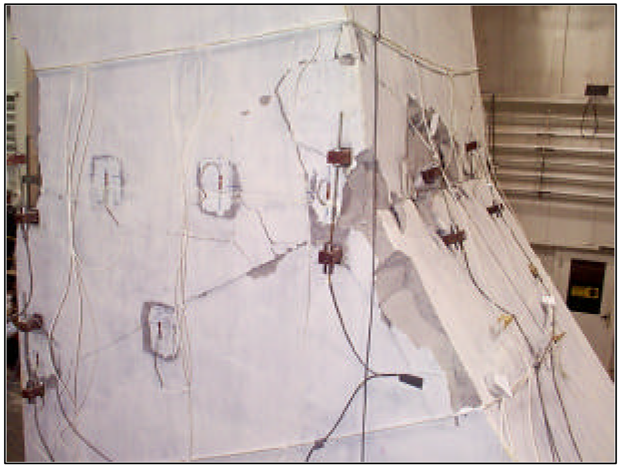


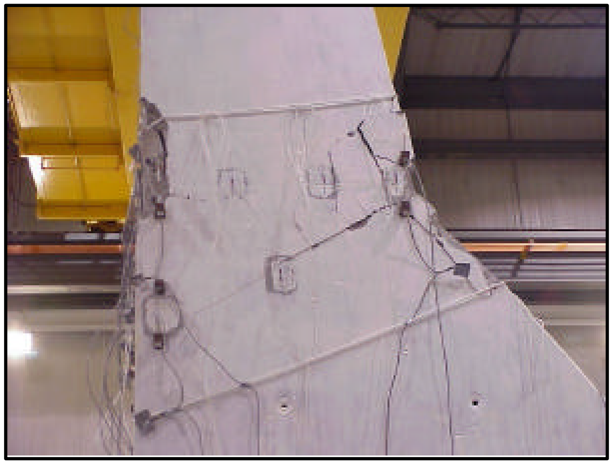




- ~.**0.12** Sin(2π(**14**)t)

Shake Table Results (Strain Gage Data)





Conventional Concrete Dams

- **Validated Nonlinear 2-D Numerical Procedures**
  - **Hydrodynamic Loads**
  - **Elastic Foundation**
  - **Reservoir Bottom Adsorption**
- **Guidance for Time History Analysis**
- **Material Properties for RCC Dams**
- **Time-History Tools**
- **Functional Data Base**

Subbottom Absorption

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

Proposed Morrow Point Dam Experiments

Objective:

- **Determine the measured and computational effects of radiation damping**
- **Ground Explosion Tests**
- **Acoustic Tests**
- **Dynamic Characteristics of Rock**

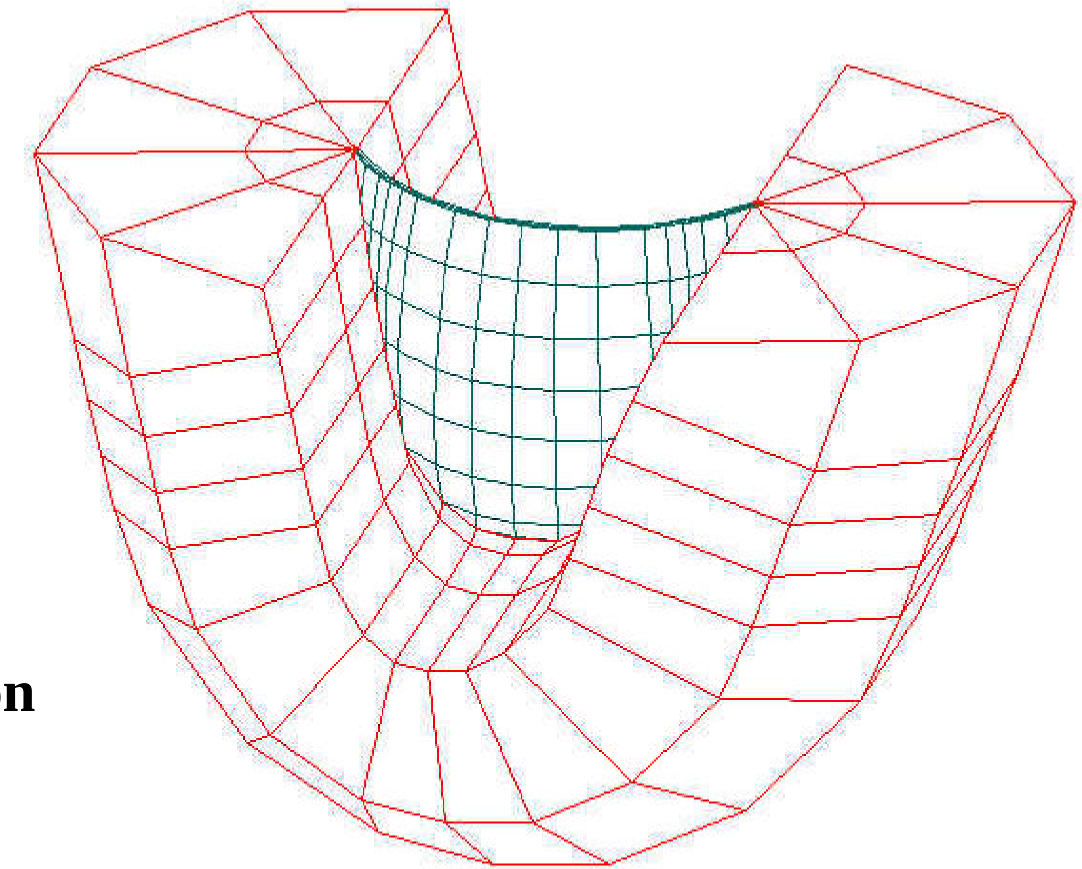
Morrow Point Dam

Joint Research :

- **Bureau of Reclamation**
- **Quest Structures**
- **Engineering Research and Development Center**

Funding:

- **National Science Foundation**
- **Bureau of Reclamation**
- **Engineering Research and Development Center**



FINITE ELEMENT MODEL OF MORROW POINT DAM

Back Analysis of Taiwan Dams

Team Members :

- **Yusof Ghanaat, Quest Structures**
- **Larry Nuss , U. S. Bureau Of Reclamation**
- **Tim Little, B. C. Hydro**
- **Robert Hall, ERDC**

Back Analysis of Taiwan Dams

Back Analysis of Taiwan Dams

Problem Statement

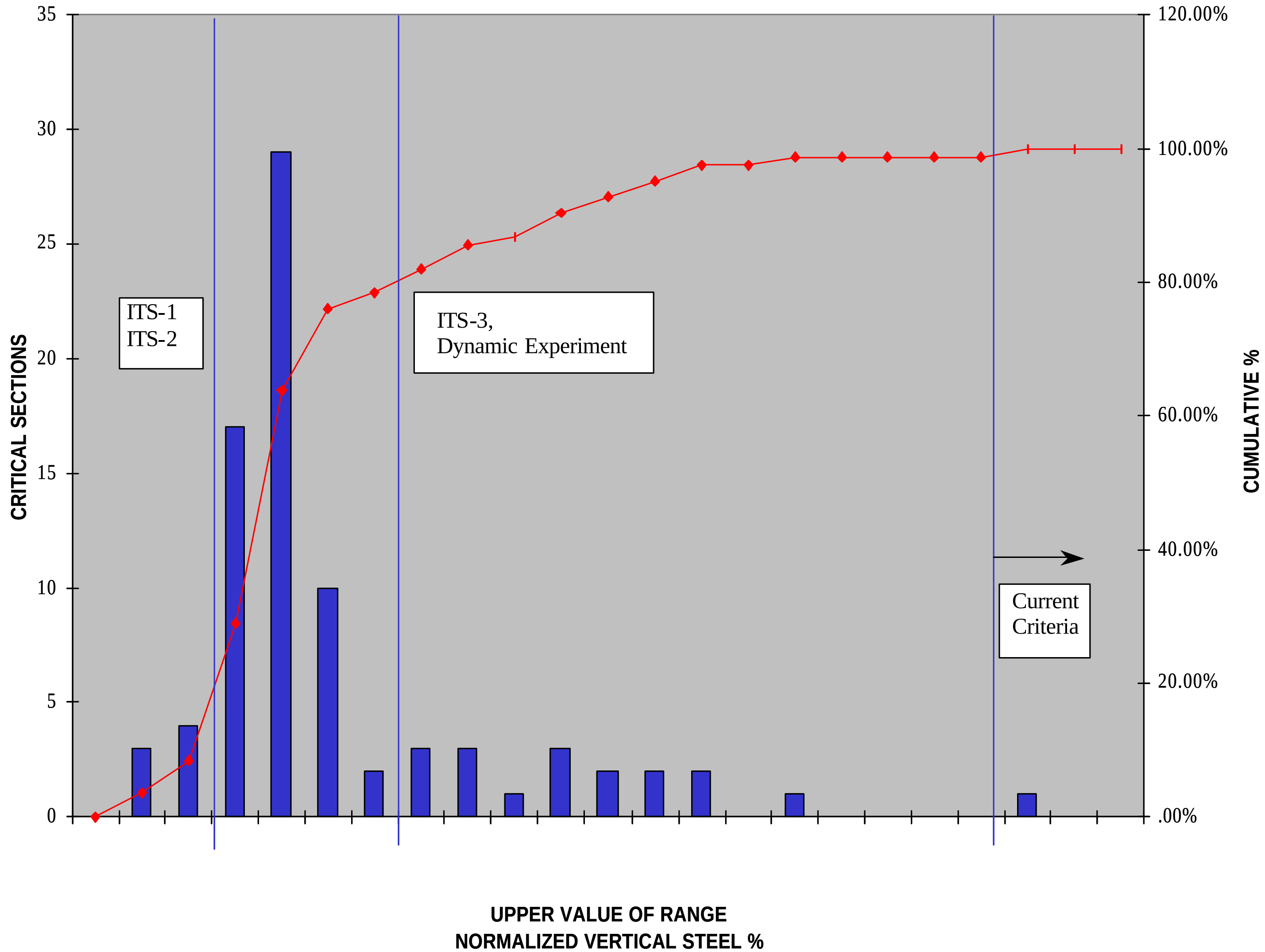
Existing Corps intake towers are lightly reinforced structures with unknown ductility and undetermined failure mechanisms.

Objectives

- **Determination of significant failure modes.**
- **Validation of analysis procedures accounting for ductility in these failure modes.**
- **Provision of design and retrofit guidance for intake towers incorporating analysis procedures.**

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.


35
30
25
20
15
10
5
0
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
.00%
CRITICAL SECTIONS
CUMULATIVE %
ITS-1
ITS-2
ITS-3,
Dynamic Experiment
Current
Criteria
UPPER VALUE OF RANGE
NORMALIZED VERTICAL STEEL %

Approach /Accomplishments

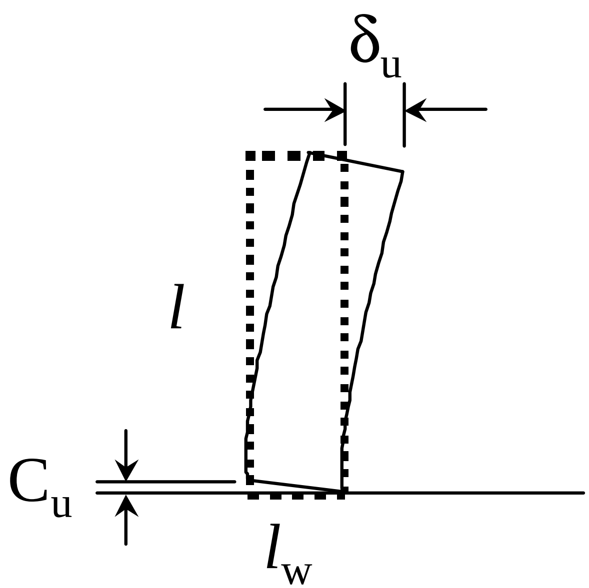
- **Analysis of inventory of existing towers was used to design Intake Tower Substructure (ITS) experimentation.**
- **ITS experimentation was conducted and demonstrated significant ductility in a single crack failure mode.**
- **Based on experimentation, the Displacement Based Analysis technique was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

Approach /Accomplishments

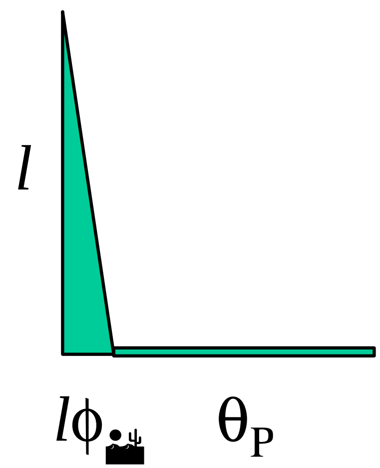
- **The Displacement Based Analysis technique must be modified to properly model localized response seen in the experimentation.**
- **The Strain Penetration experiments provided information needed for modification and a new model was developed.**
- **New model provides simple method of estimating deflection capacity, consistent with mechanics of the response of lightly reinforced structures.**

Response Model

Deflection



Rotation



$$d_u = \frac{f_E l^2}{3} + q_p l$$

$$q_p = \frac{C_u}{l_w}$$

$$f_E = \frac{M}{EI_g}$$

$$d_u = \frac{f_E l^2}{3} + \frac{C_u}{l_w} l$$

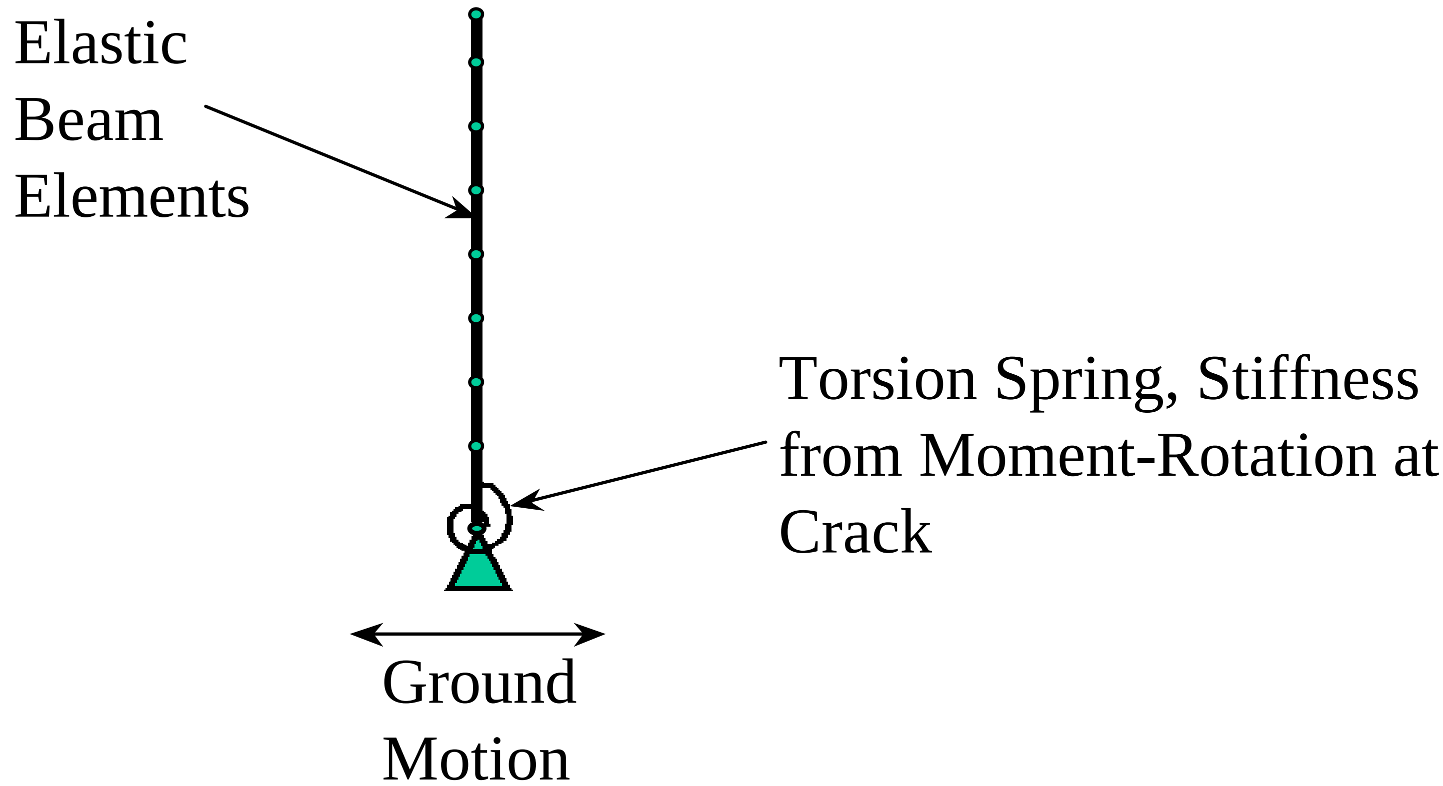
$$C_u = 0.1759 + 1.035e_r$$

Where:

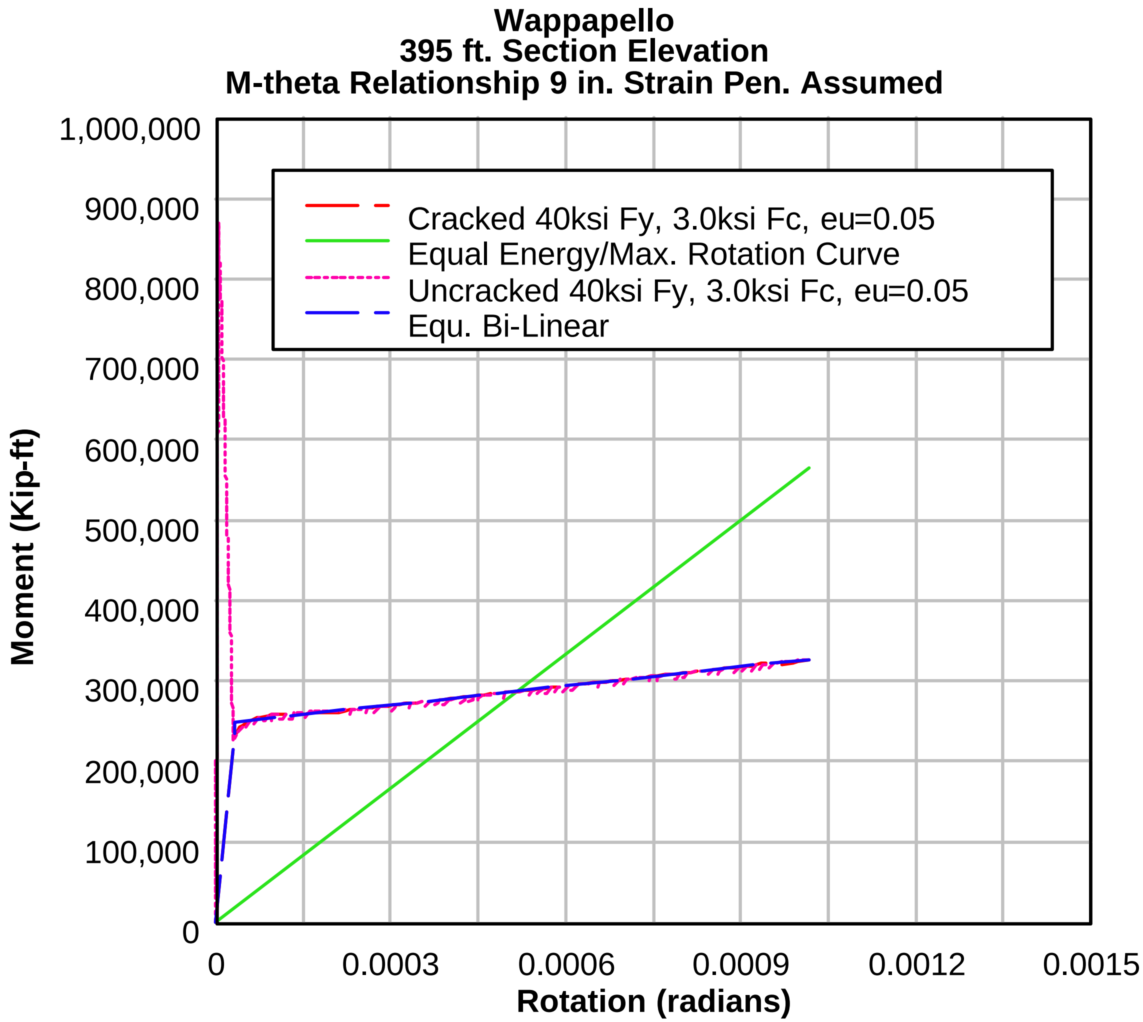
C_u is the crack width measured at failure of the critical section

e_r is the rupture strain capacity of the rebar in the structure

Structural Model



Torsional Spring Model



Summary

- Crack width is controlled by steel rupture strain.
- Steel rupture strain is well understood.
- Direct relationship between crack width and ultimate structure deflection.
- Model provides simple method of estimating deflection capacity, consistent with mechanics of the response of lightly reinforced structures.

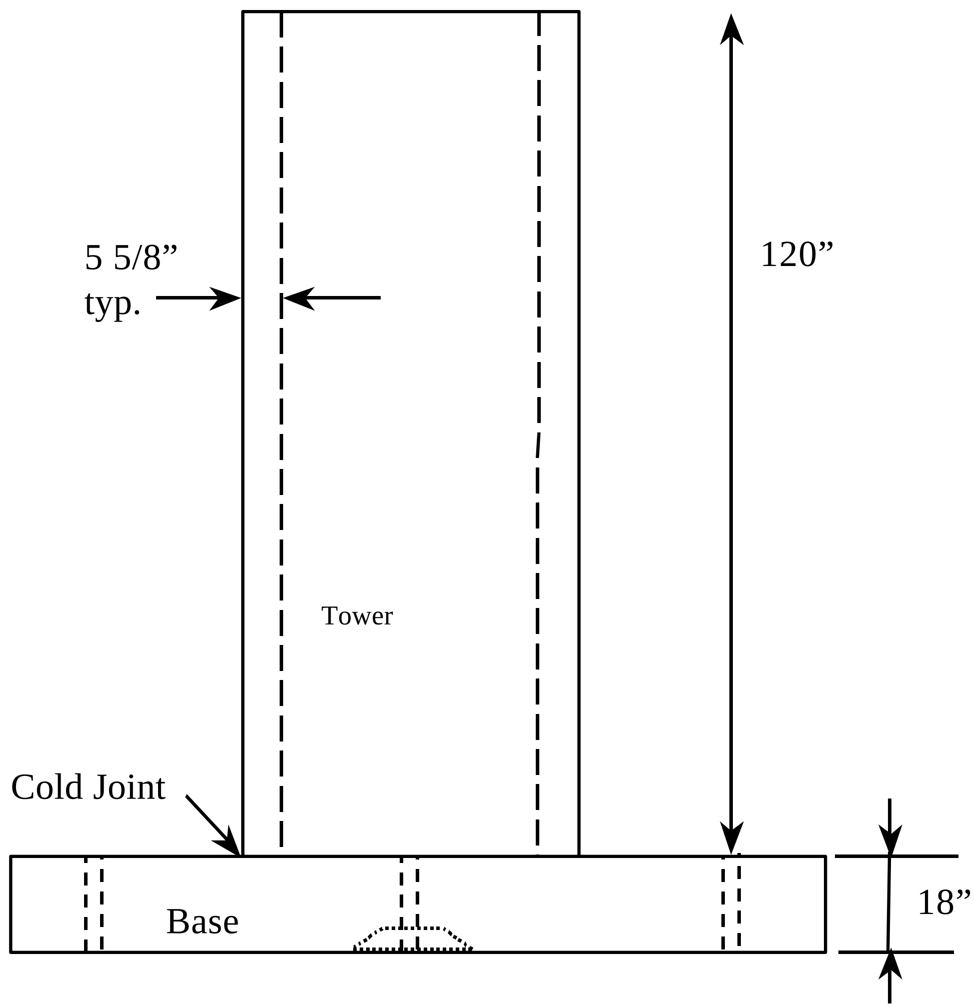
Dynamic Experimentation

- **Experiment will be conducted at CERL Shake Table Facility**
- **Objective is dynamic validation of displacement based technique.**

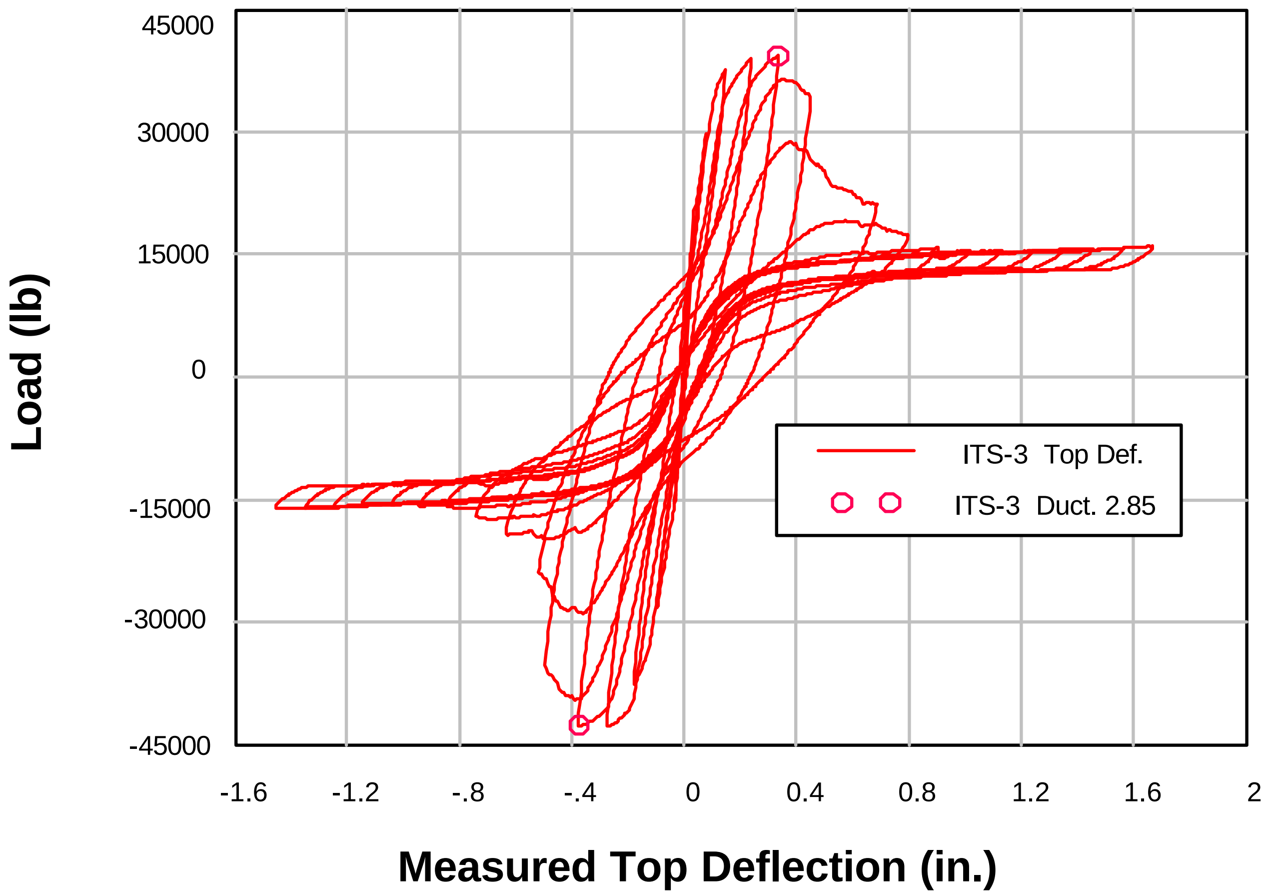
Dynamic Experimentation

- **1/8th scale model of a typical intake tower configuration, the same design as the ITS3 static model.**
- **Model consists of a 40 in. by 52 in., 10 ft tall tower section with 5 5/8 in thick walls, mounted on a heavily reinforced concrete base.**
- **The vertical steel percentage 0.36%, horizontal steel percentage from 0.48%.**

Model Configuration



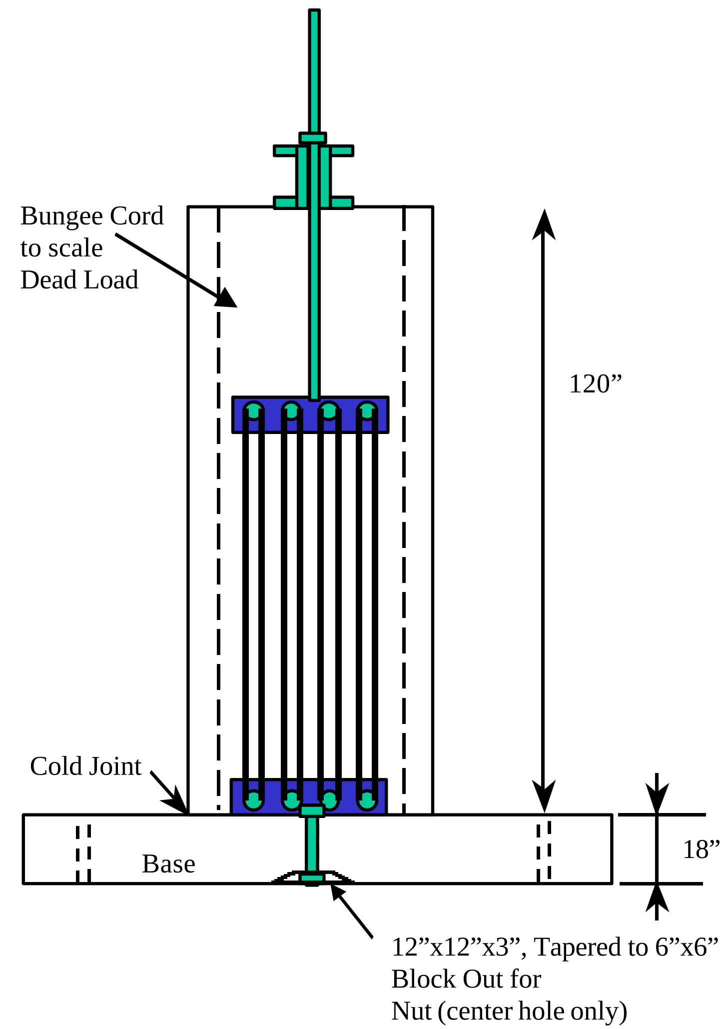
Ductility of ITS-3 Model



Dynamic Experimentation

- **Load to failure about weak axis by horizontal sinusoidal vibration at a frequency slightly higher than the natural frequency.**
- **Vertical load to model gravity will be applied using elastic "shock cords".**
- **Shock cords allow proper combination of inertial and gravity loads and have been used successfully in prior experiments.**

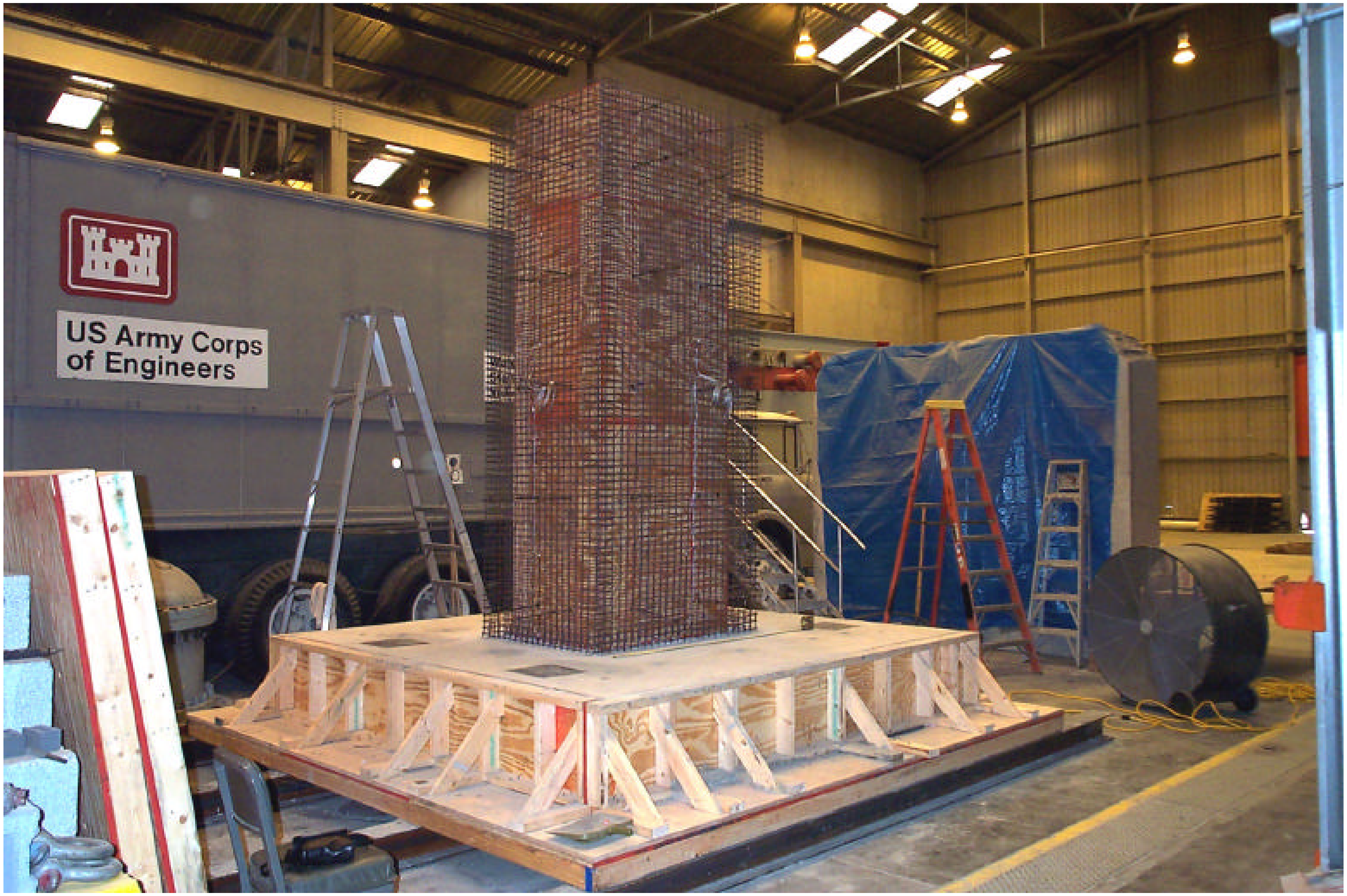
Vertical Load Application



Shock Cord Testing

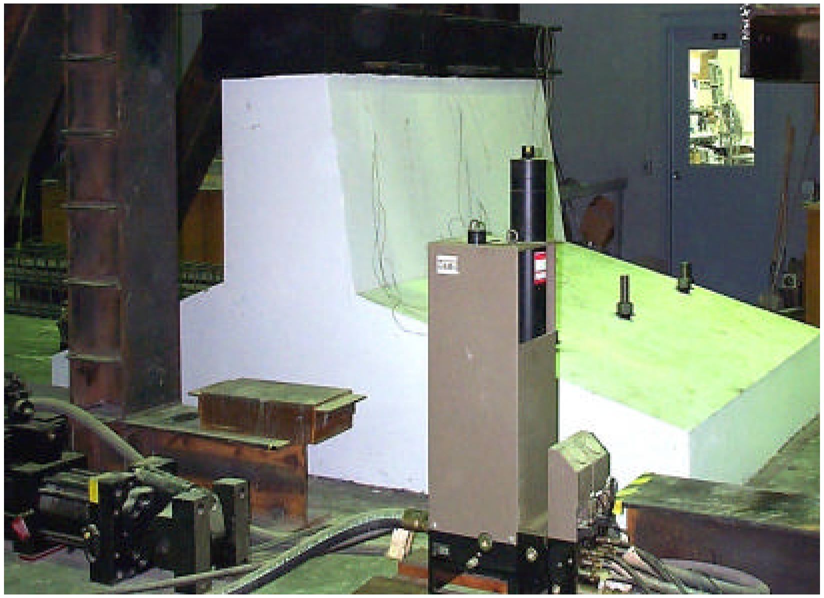
Model Construction

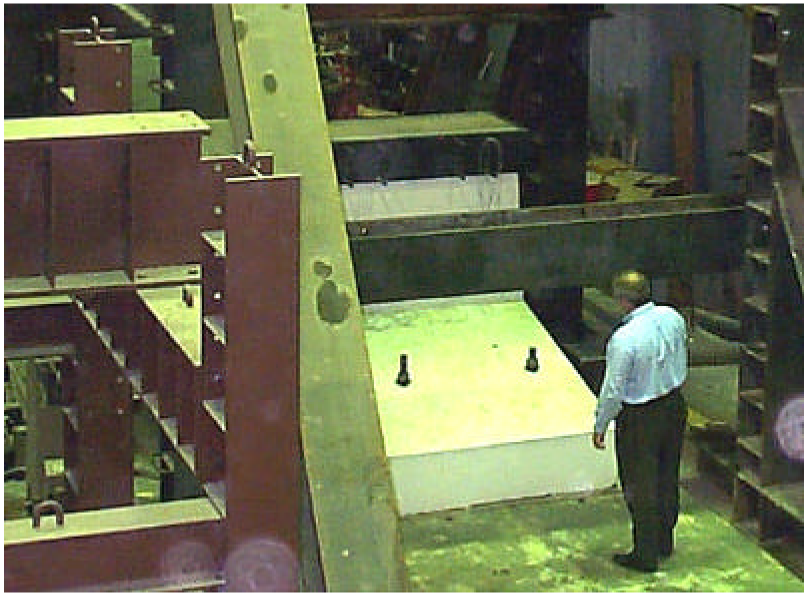
Model Construction



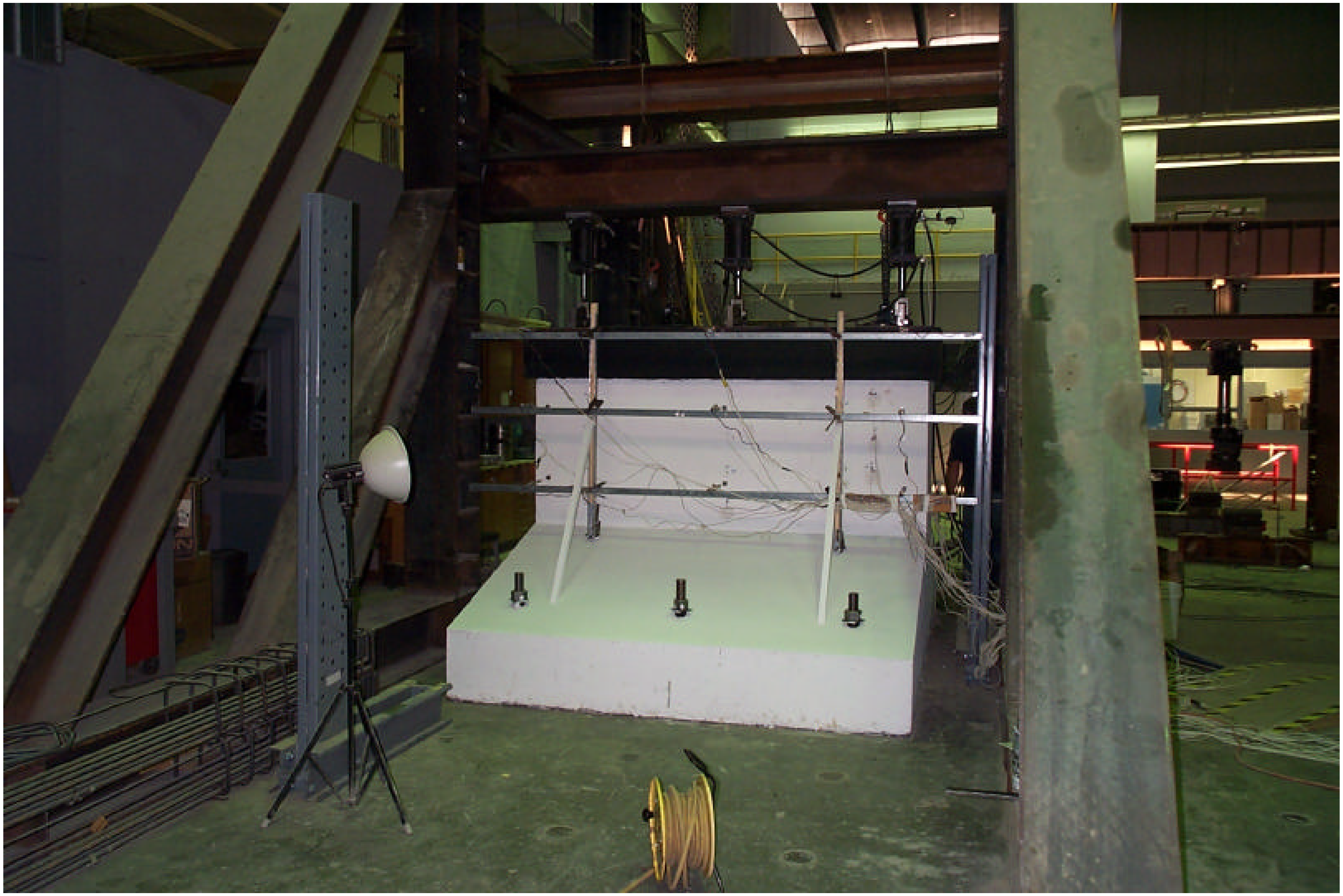
Ductility for Outlet Works

Constructed retaining wall model for experiment to be conducted this FY.

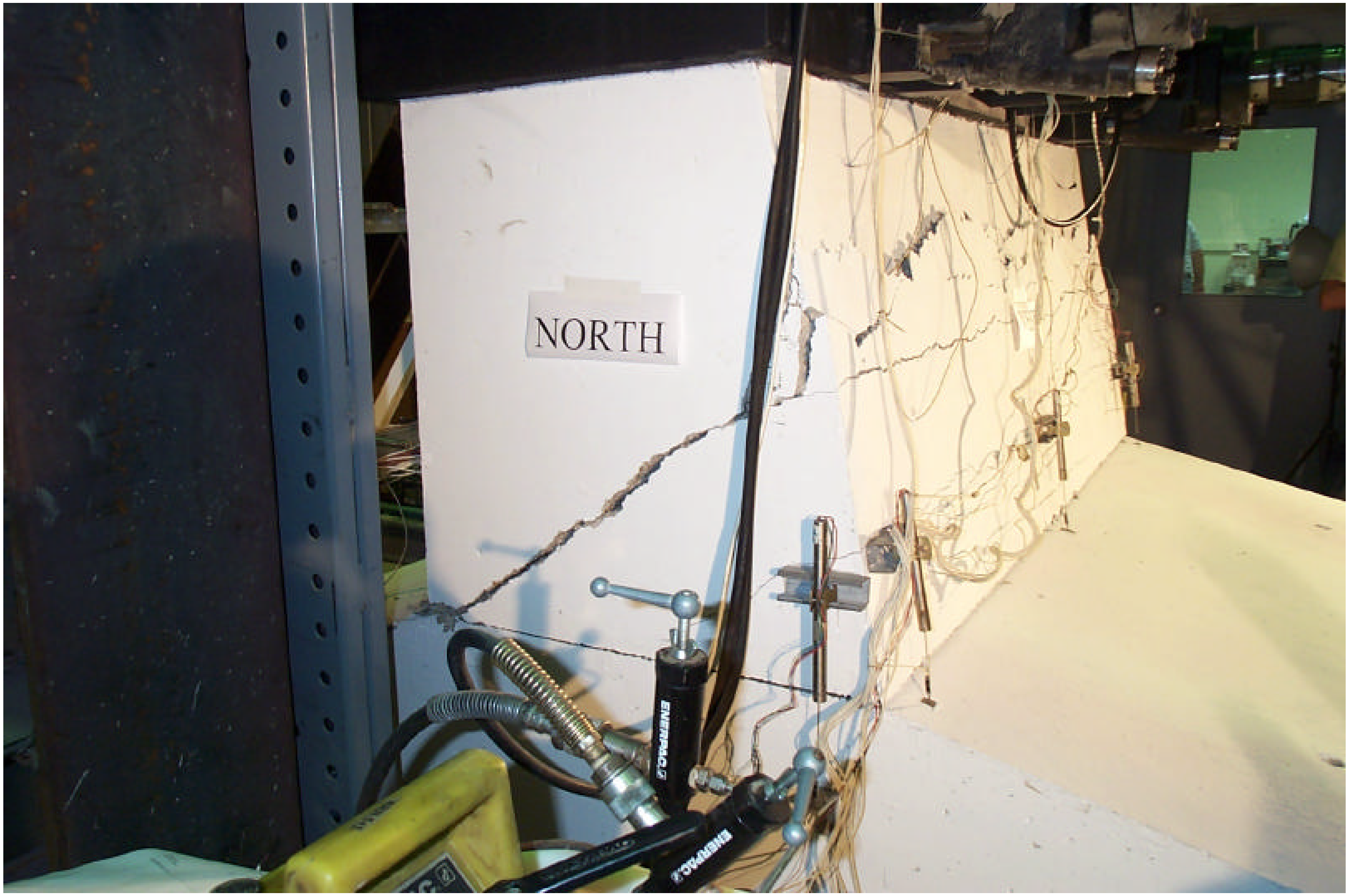




Ductility for Outlet Works



Ductility for Outlet Works

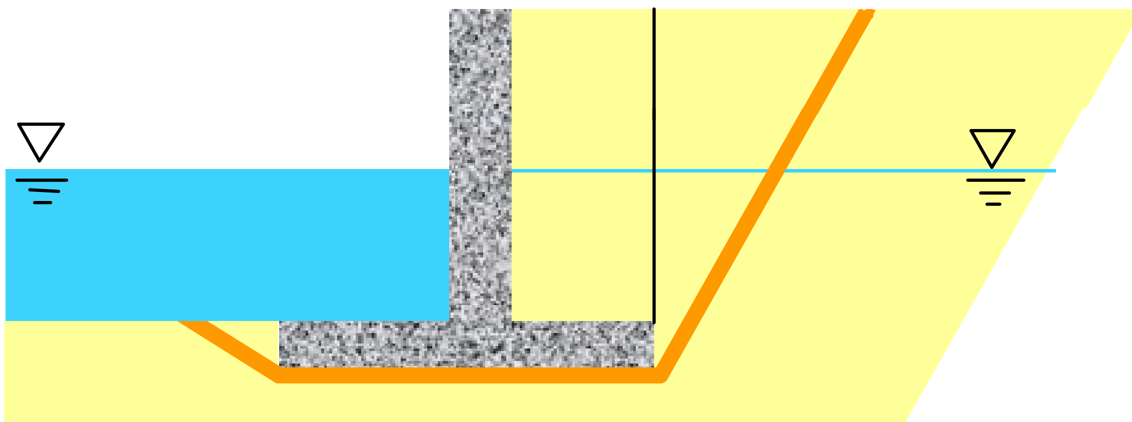


Seismic Design of Cantilever Retaining Walls

- **Development of CLIP Computer Program**

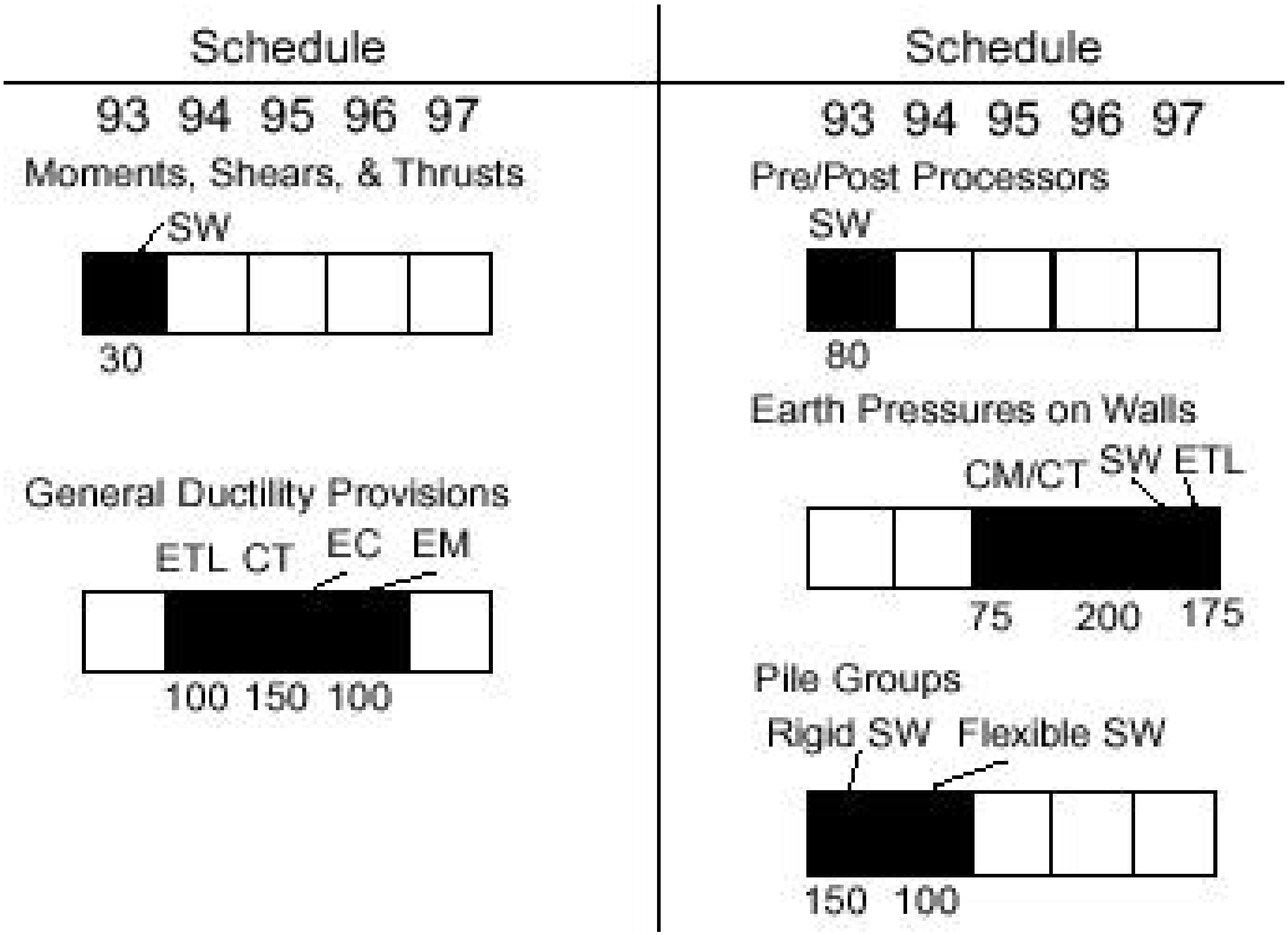
N*g

Maximum Transmissible Acceleration
or
Yield Acceleration

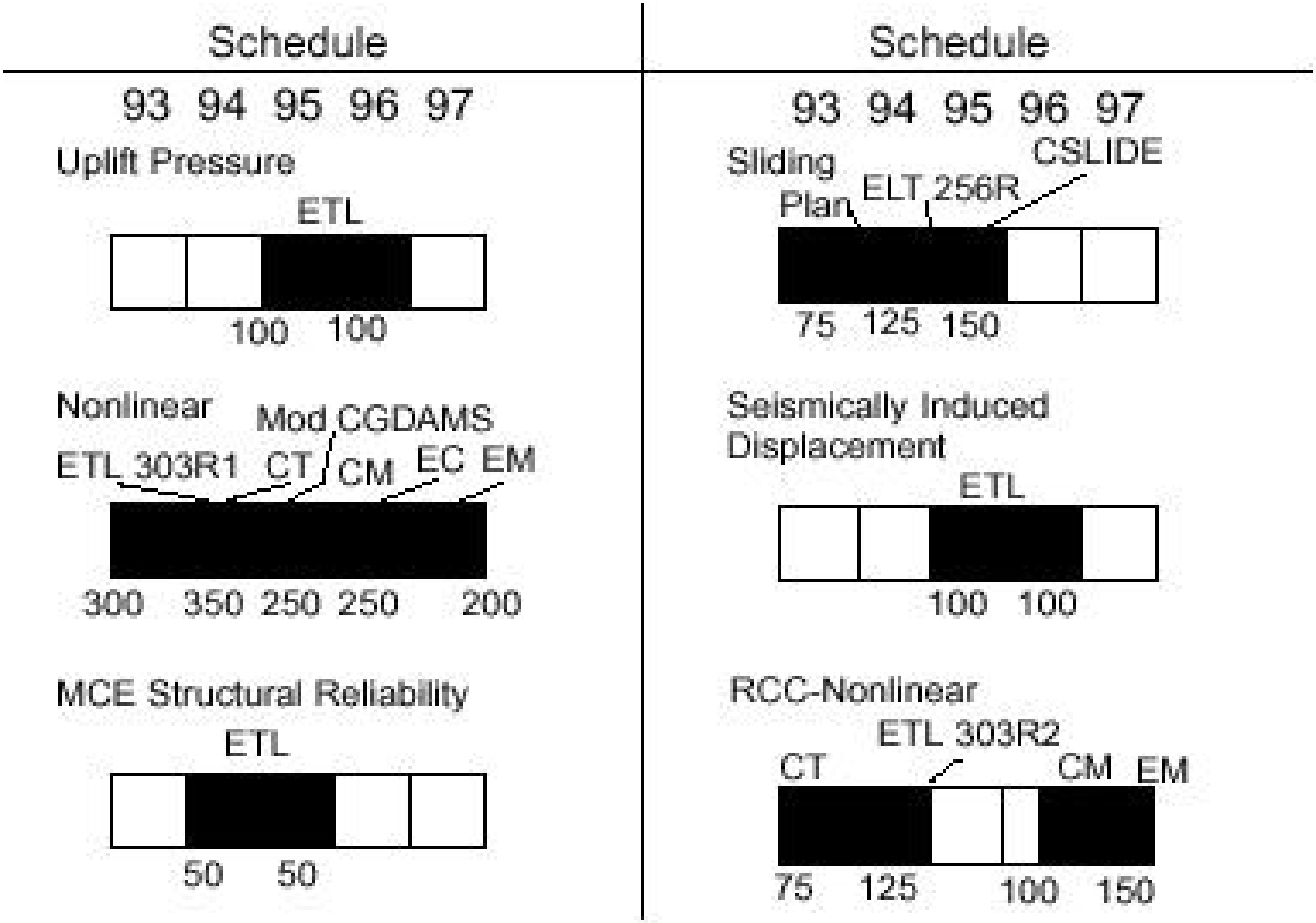


Limiting Acceleration
Resulting in $FS_{SLIDE} = 1.0$

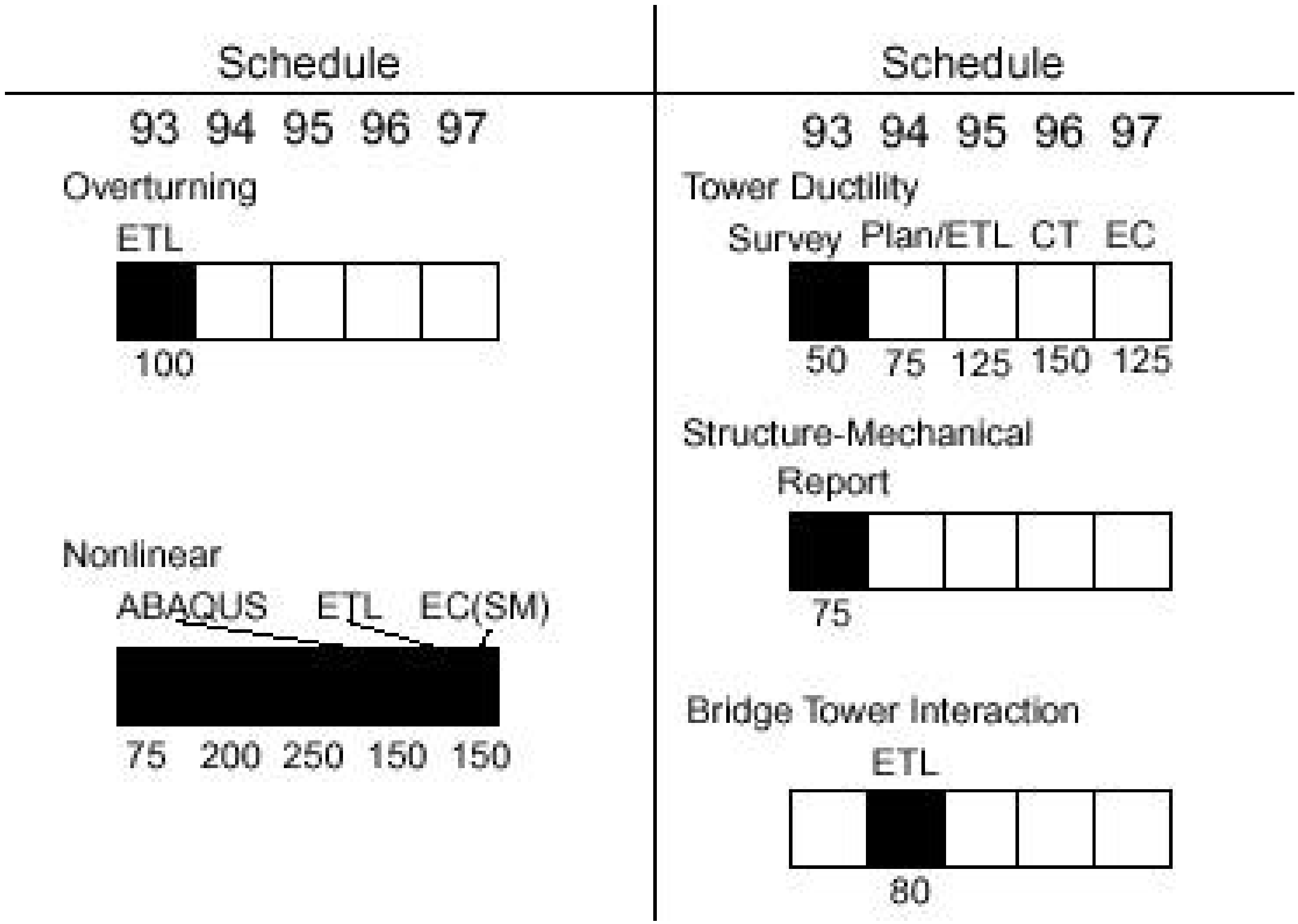
Earthquake Analysis Tools for Structures



Seismic Response to Concrete Dams



Seismic Response of Outlet Works



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

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