Earthquake Analysis of Arch Dams

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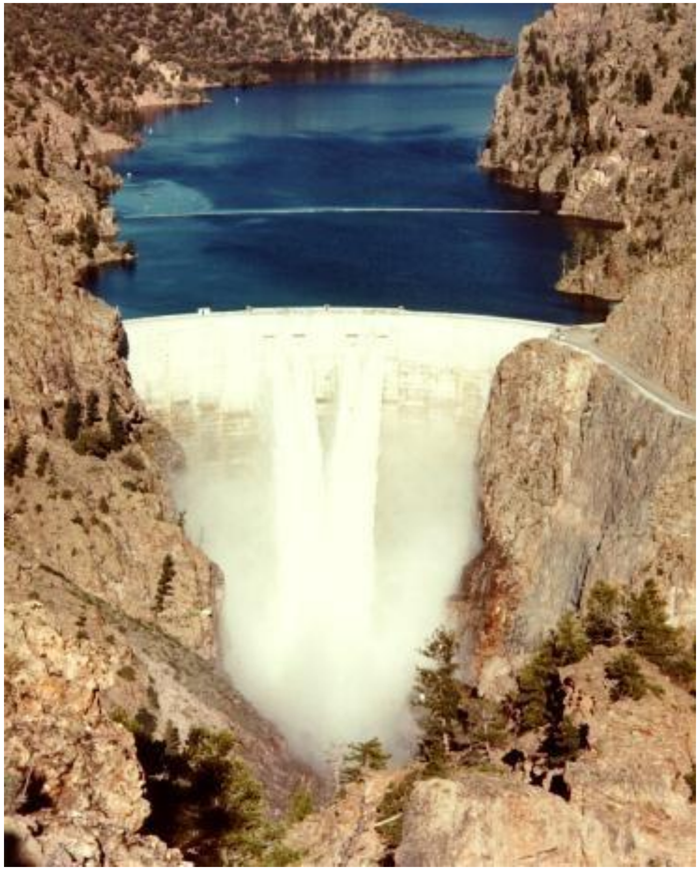
Earthquake Analysis of Arch Dams: Factors To Be Considered

- Focus on linear analysis
- Before embarking on nonlinear analysis for any project, the "best possible" linear analysis should be implemented
- Comment on nonlinear analysis

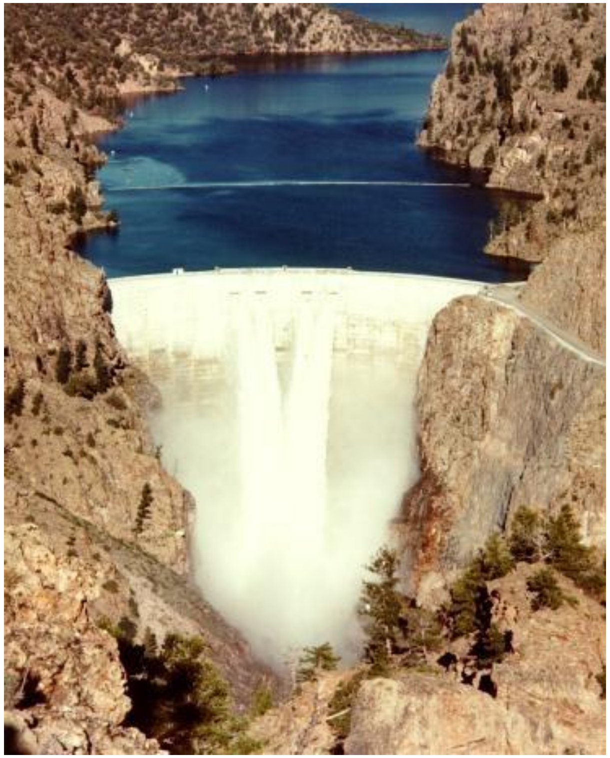
Complex System Geometry

- Three-dimensional system
- Reservoir: unbounded in the upstream direction
- Foundation: semi-unbounded domain



Dynamic Analysis Should Consider:

- Dam-water interaction
- Reservoir boundary absorption
- Water compressibility
- Dam-foundation rock interaction
- Spatial variations in ground motion



Early Research at Berkeley

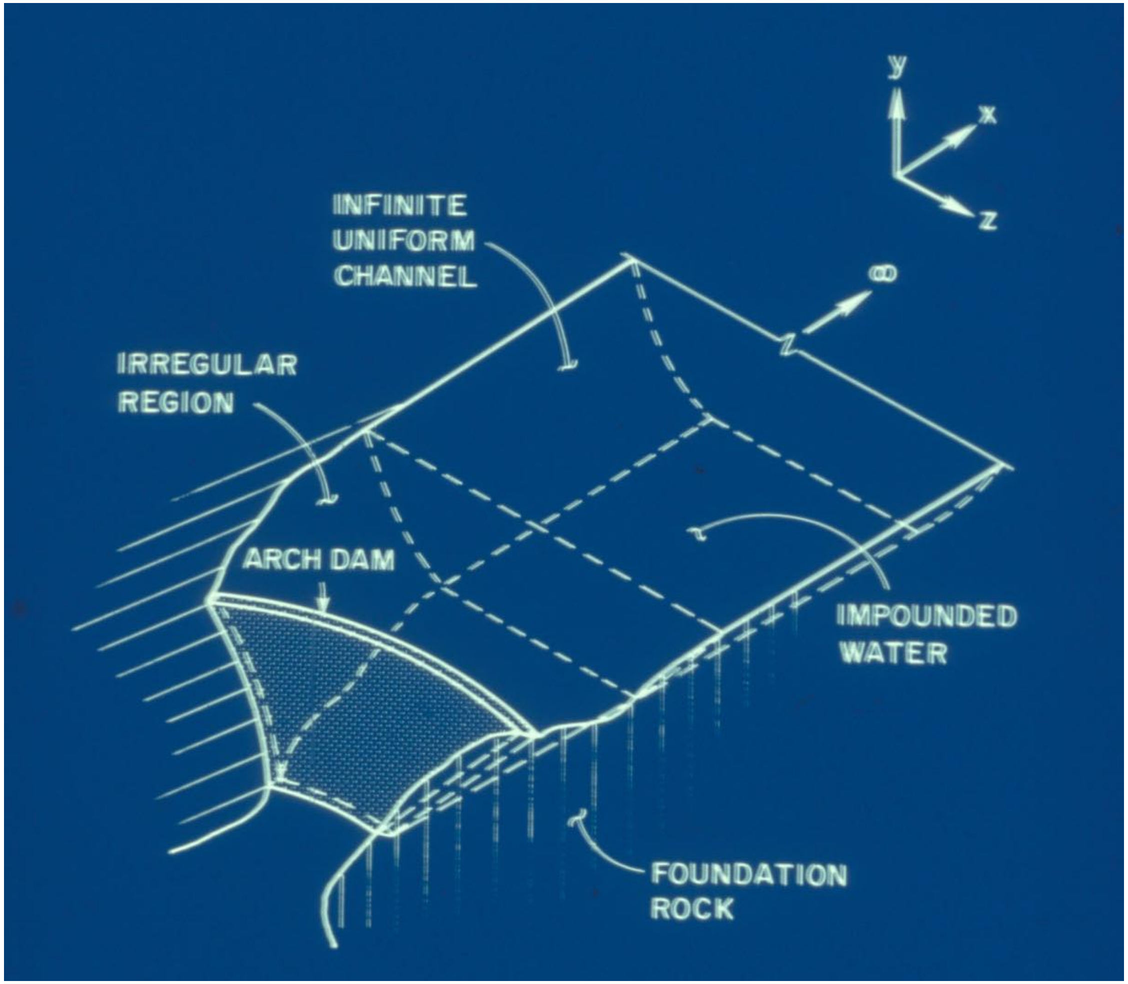
- Six Ph.D. theses at U.C. Berkeley (1972-96)
- Substructure method for linear systems
- Frequency domain method
- Implemented in computer programs distributed by NISEE
  - EAGD-84: Gravity Dams, 1984
  - EACD-3D-96: Arch Dams, 1996

EACD-3D-96 Computer Program Considers

- 3D semi-unbounded geometry
- Dam-water interaction
  - Reservoir-boundary absorption
  - Water compressibility
- Dam-foundation rock interaction
  - Foundation flexibility, inertia, and damping (material and radiation)

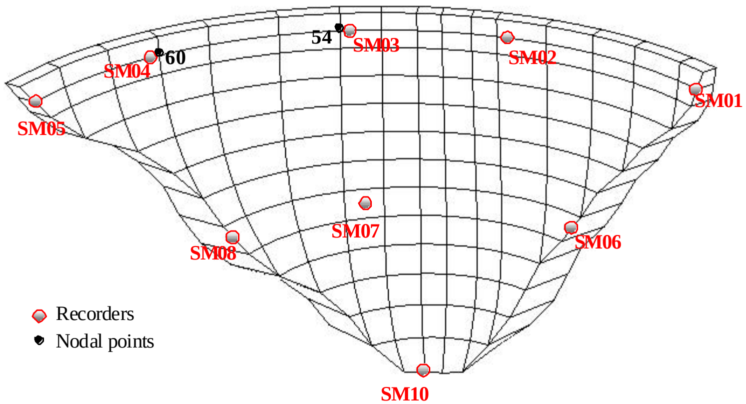
3D ANALYSIS OF DAM-WATER-FOUNDATION ROCK SYSTEM

Arch Dam-Water Foundation Rock System

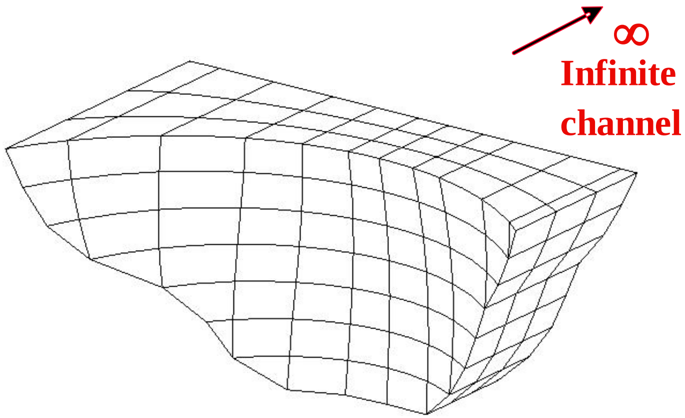


EACD-3D-2008 Model

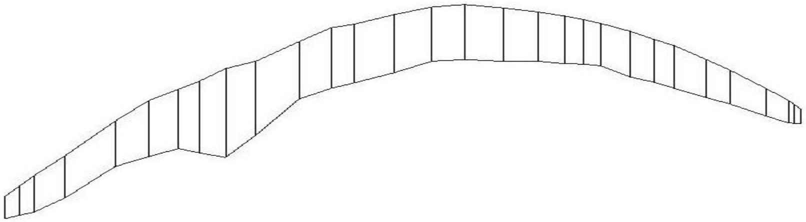
(a) Finite element model: Dam



(b) Finite element model: Fluid Domain



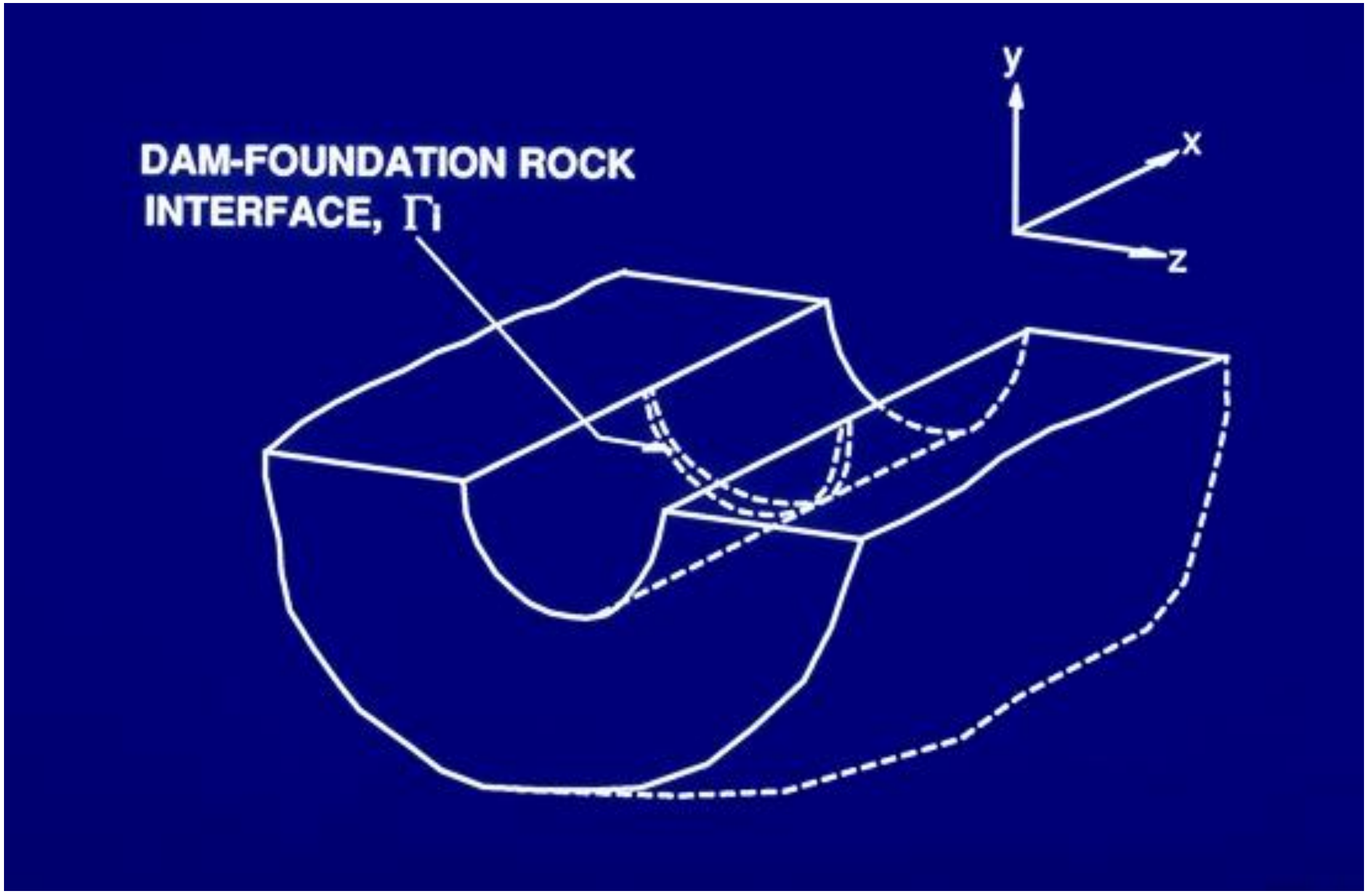
(c) Boundary element mesh: dam-foundation rock interface



Foundation Dynamic Stiffness Matrix, $S_f(\omega)$

- Foundation idealization
- Canyon cut in a viscoelastic half-space
- Infinitely long canyon
- Arbitrary but uniform cross-section of canyon

Infinitely Long Canyon Arbitrary but Uniform Cross Section



Computation of Foundation Dynamic Stiffness Matrix, $S_f(\omega)$

- Direct boundary element procedure
  - Full-space Green's function
  - 3D boundary integral equation
  - Analytical integration along canyon axis
  - Infinite series of 2D problems
  - Each 2D problem for one wave number
  - Superpose solution of 2D problems

Foundation Dynamic Stiffness Matrix, $S_f(\omega)$

- Defined for DOFs in finite element idealization of dam at dam-foundation interface, Γ_I

$$\mathsf{S}_f(\omega)\hat{\mathbf{r}}(\omega)=\hat{\mathbf{R}}(\omega)$$

$\omega =$ excitation frequency

$\mathrm{R}(t) =$ interaction forces

$\mathrm{r}(t) =$ interaction displacements

Earthquake Analysis of Dams: Computer Programs

- EAGD-84 and EACD-3D-96 include all factors
- Developed before desktop computers
- Developed by graduate students
- Primarily research programs
- Applied to several actual projects

Practical Applications of EACD-3D-96

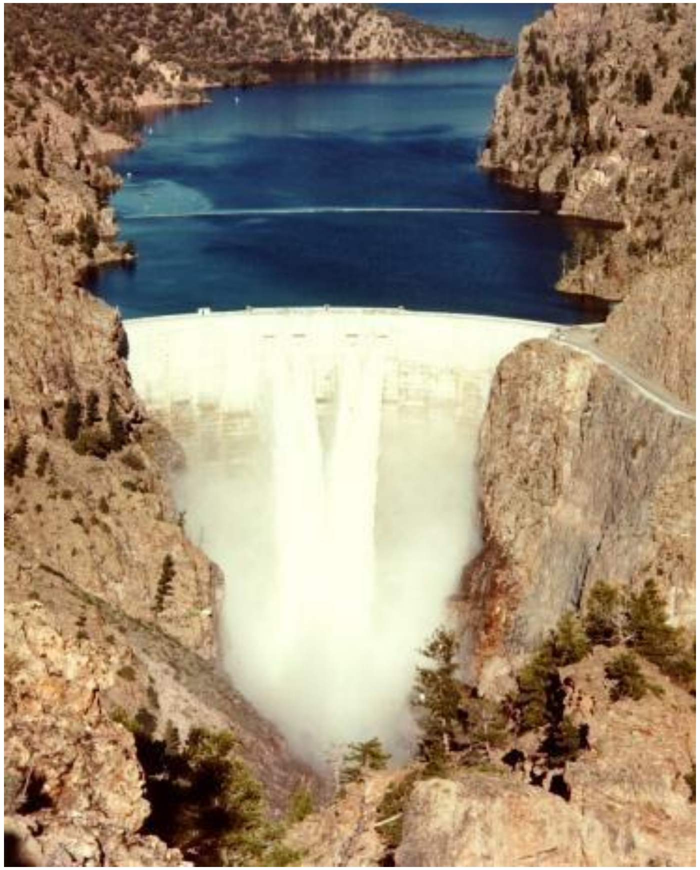
- Seismic safety evaluation of
  - Englebright Dam, California, USA
  - Valdecanas Dam, Spain
  - Pardee Dam, California, USA
  - Deadwood Dam, Idaho, USA
  - Morrow Point Dam, Colorado, USA
  - Monticello Dam, California, USA
  - Hoover Dam, Nevada/Arizona, USA

EACD-3D-96 Computer Program Considers

- 3D semi-unbounded geometry
- Dam-water interaction
  - Reservoir-boundary absorption
  - Water compressibility
- Dam-foundation rock interaction
  - Foundation flexibility, inertia, and damping (material and radiation)

Popular Finite Element Techniques for Dams

- Ignore dam-water interaction and water compressibility
- Ignore wave absorption by sediments at reservoir boundary
- Assume foundation rock to be massless, i.e., consider only foundation rock flexibility



BUREAU OF RECLAMATION PROGRAM TO EVALUATE EXISTING DAMS

Bureau of Reclamation Program to Evaluate Existing Dams

- Major program, started in 1996
- Twelve dams were investigated, including:
  - Hoover dam (221 meter-high curved gravity dam)

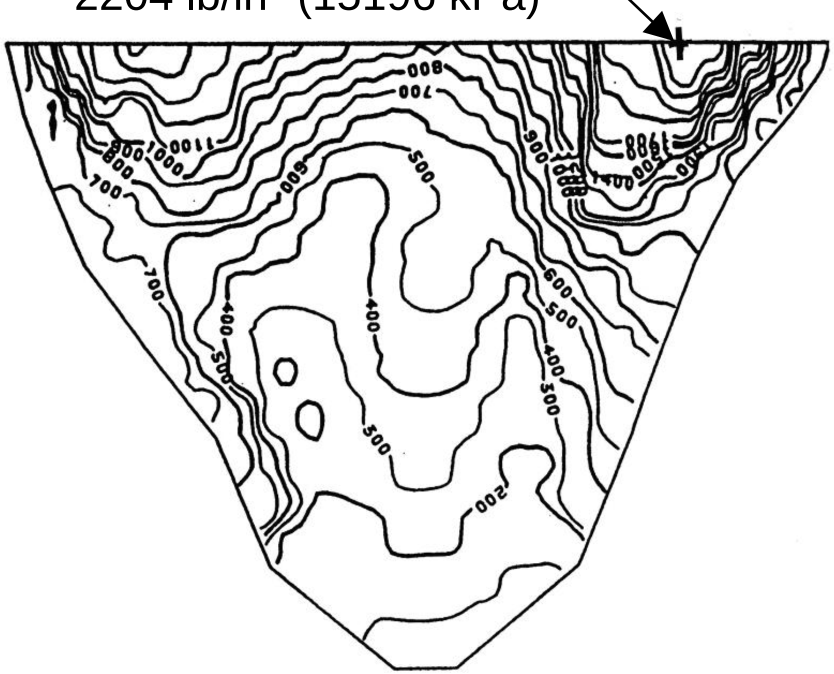
Hoover Dam

221-meter high, curved gravity dam

Evaluation of Hoover Dam

- Stresses computed by state-of-the-art finite element analysis
- Dam will crack through the thickness
- Did not seem credible to Reclamation engineers

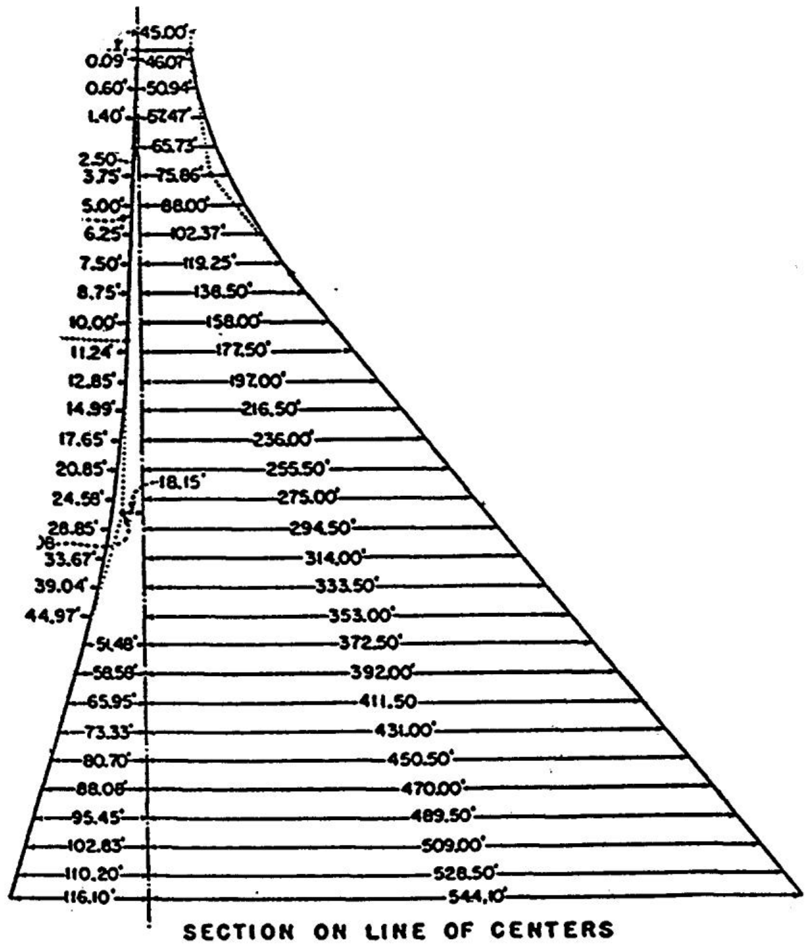
2204 lb/in^2 (15196 kPa)



Hoover Dam

221-meter high, curved gravity dam

Hoover Dam: Cross Section



Bureau of Reclamation Program (1996-   )

- Found it necessary to consider:
  - Dam-foundation rock interaction
  - Dam-water interaction
  - Water compressibility
  - Reservoir boundary absorption
- Started using EACD-3D-96 computer program for linear analysis
- LS-DYNA for nonlinear analysis
- Realistic models based on field tests

Reclamation Program To Evaluate Existing Dams

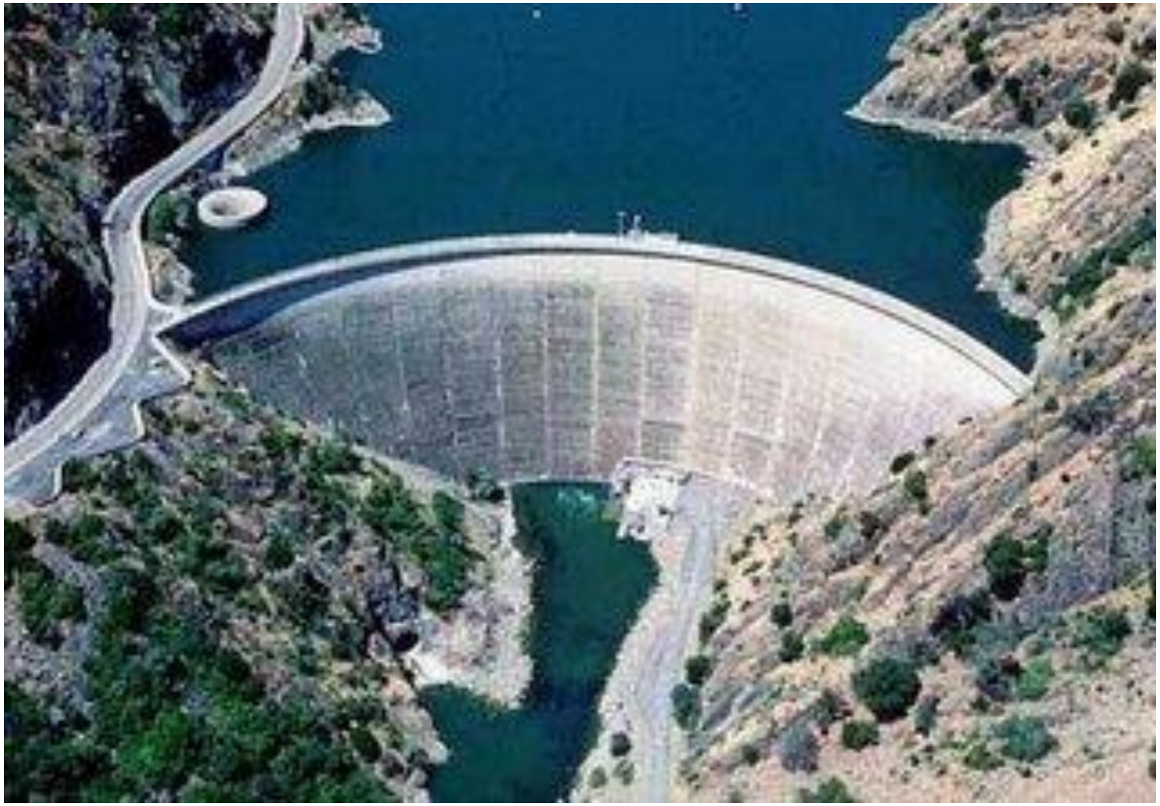
- Deadwood Dam, 50-meters high, single curvature
- Monticello Dam, 93-meters high, single cuvature
- Morrow Point Dam, 142-meters high, double curvature
- Hoover Dam, 221-meters high, thick arch
- Other dams

Deadwood Dam

50-meter high, single curvature dam

Monticello Dam

93-meter high, single curvature dam



Morrow Point Dam

142-meter high, double curvature dam

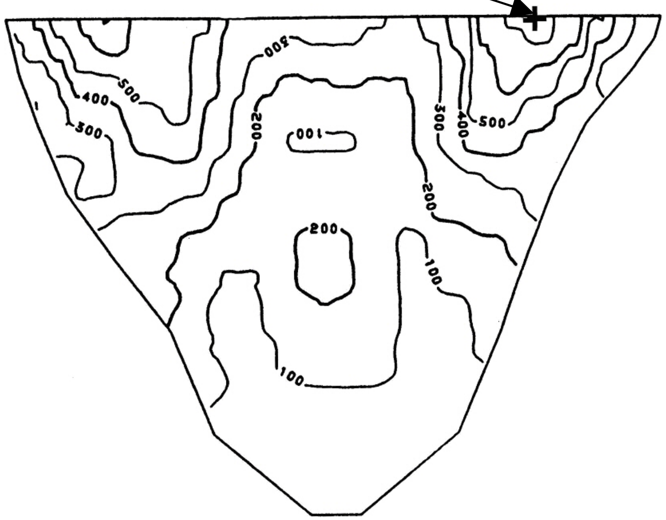
Hoover Dam

221-meter high, curved gravity dam

Hoover Dam

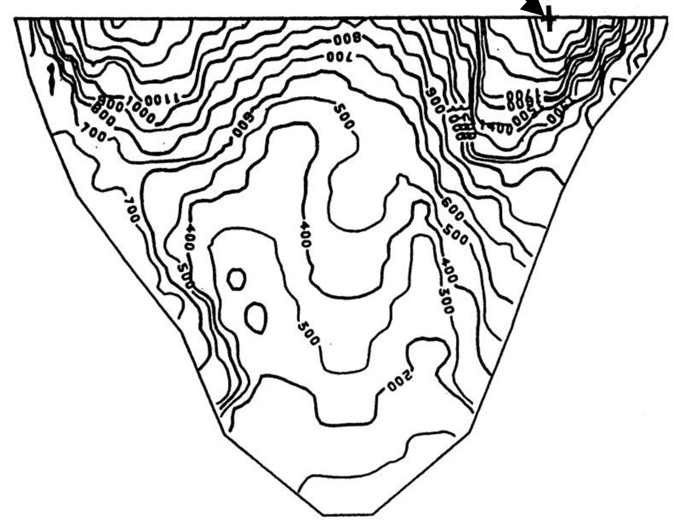
Dam-foundation interaction

758 lb/in^2 (5226 kPa)



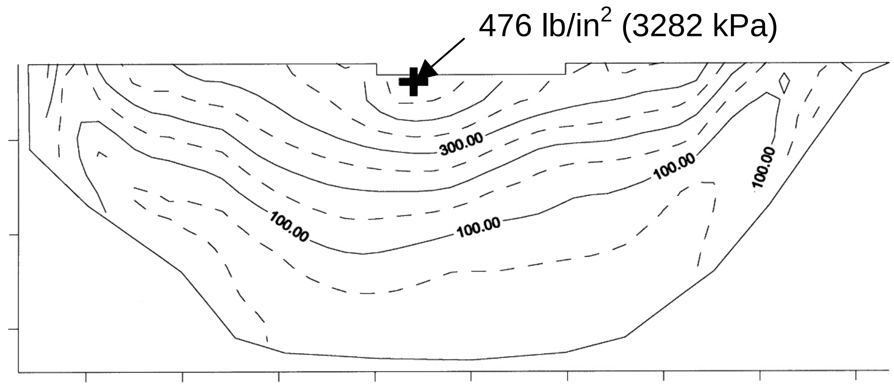
Massless foundation rock (flexibility only)

2204 lb/in^2 (15196 kPa)



Deadwood Dam

Dam-foundation interaction



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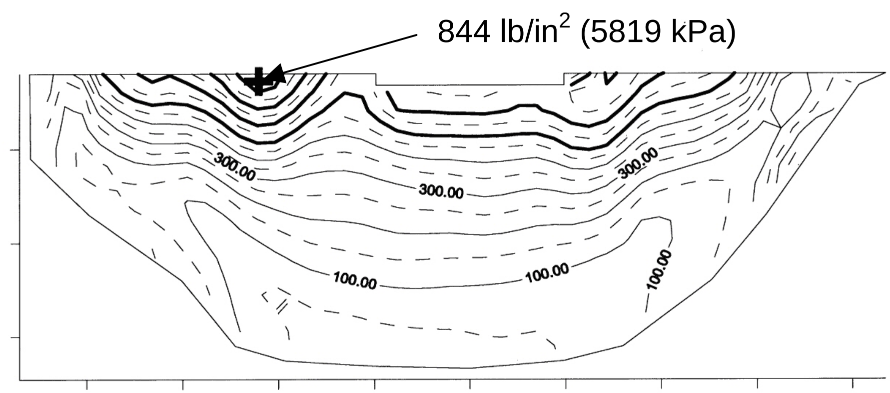
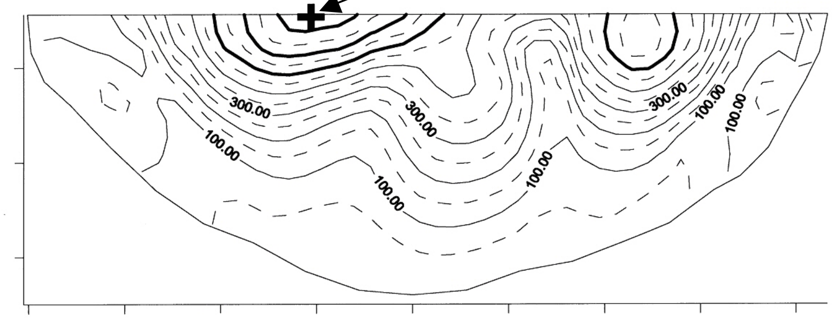


Monticello Dam

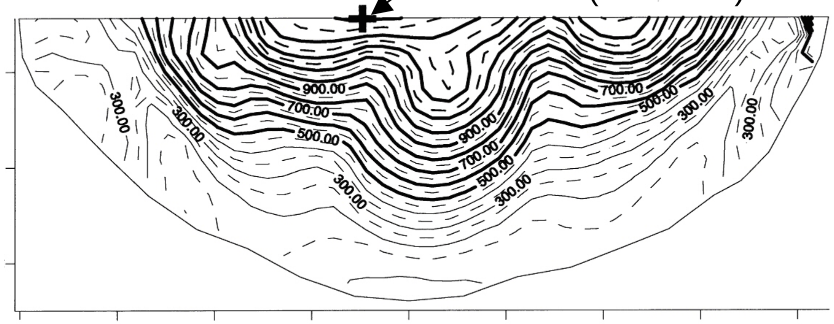
Dam-foundation interaction

730 lb/in^2 (5033 kPa)



Massless foundation rock (flexibility only)

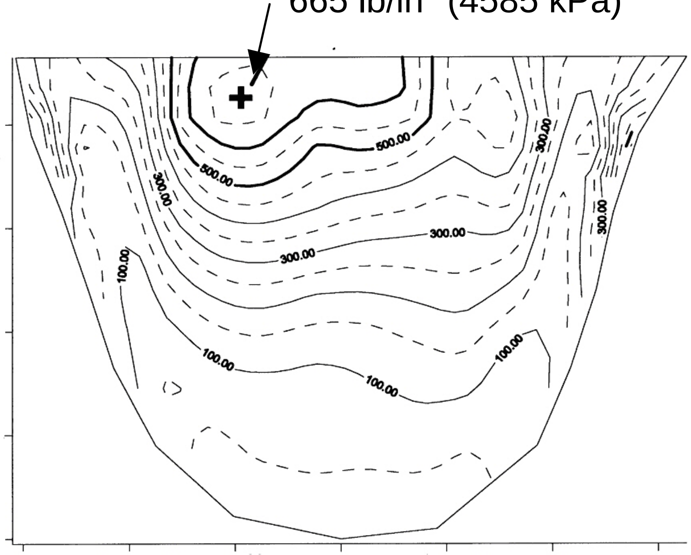
1410 lb/in^2 (9722 kPa)



Morrow Point Dam

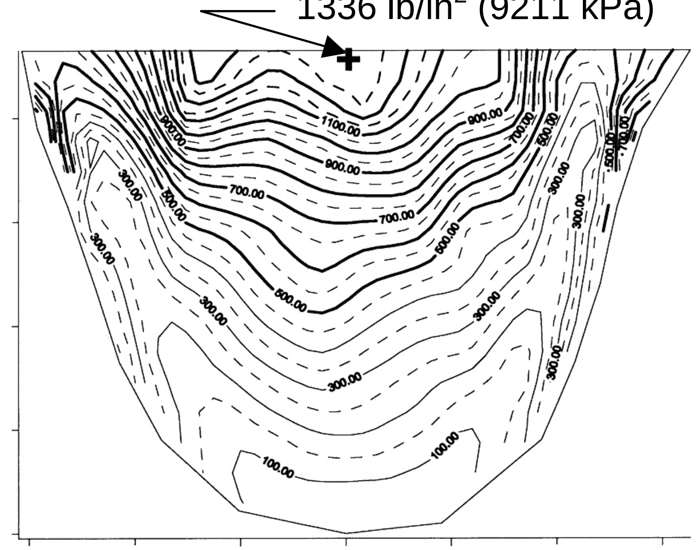
Dam-foundation interaction

665 lb/in^2 (4585 kPa)



Massless foundation rock (flexibility only)

1336 lb/in^2 (9211 kPa)



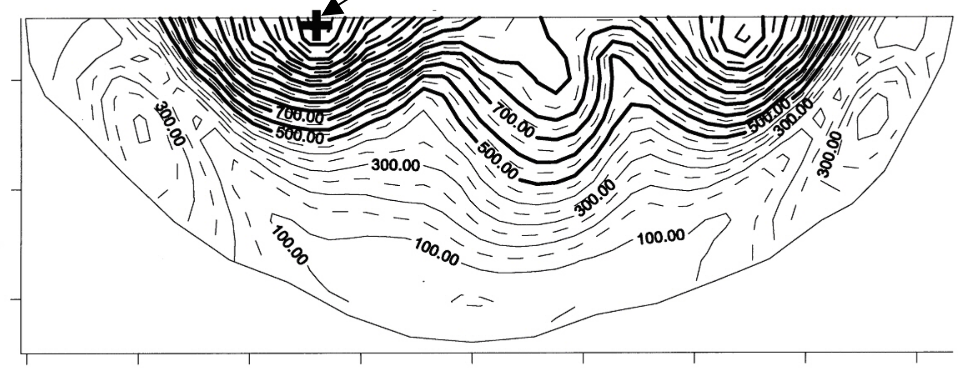
Neglecting Foundation Rock Inertia and Damping

- Stresses are overestimated by a factor of 2 to 3
- Such overestimation may lead to
  - Overconservative designs of new dams
  - Erroneous conclusion that an existing dam requires remediation.
- Analysis must include dam-foundation rock interaction
- Ignored in most practical analyses—only rock flexibility is considered

Monticello Dam

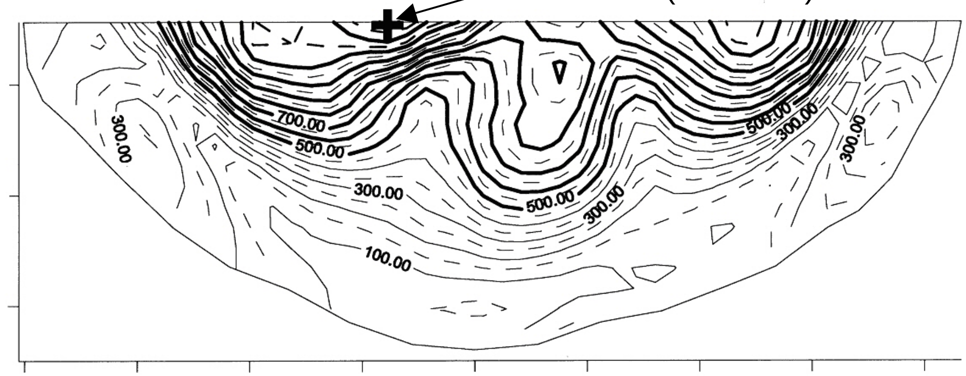
Water compressibility considered

1565 lb/in^2 (10790 kPa)



Water compressibility neglected

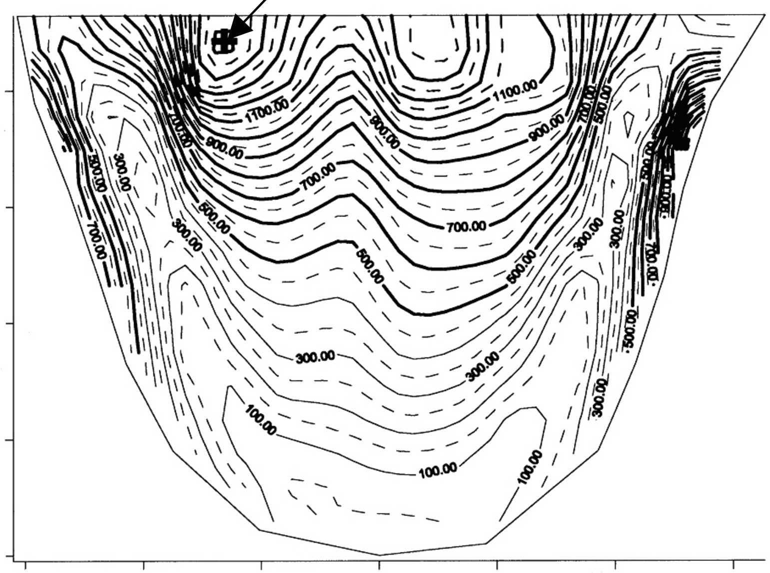
1309 lb/in^2 (9025 kPa)



Morrow Point Dam

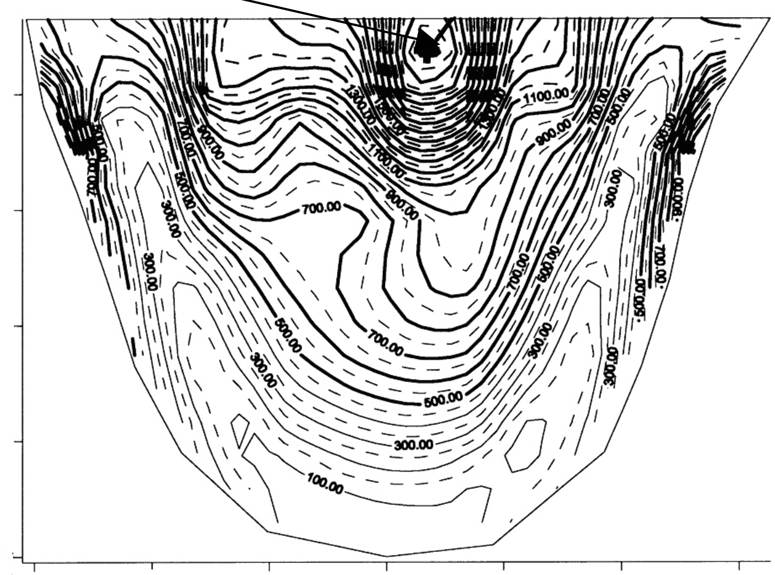
Water compressibility considered

1513 lb/in^2 (10431 kPa)



Water compressibility neglected

2215 lb/in^2 (15272 kPa)



Neglecting Water Compressibility

- Stresses may be significantly
  - Underestimated (e.g., Monticello Dam)
  - Overestimated (e.g., Morrow Point Dam)
- Must include water compressibility
- Ignored in most practical analyses—hydrodynamic effects approximated by added mass of water

COMPUTED VERSUS RECORDED RESPONSES

Comparison of Computed and Recorded Responses

- Large disparity in results depending on numerical model used
- Important to calibrate numerical models against motions of dams recorded during:
  - Forced vibration tests
  - Earthquakes

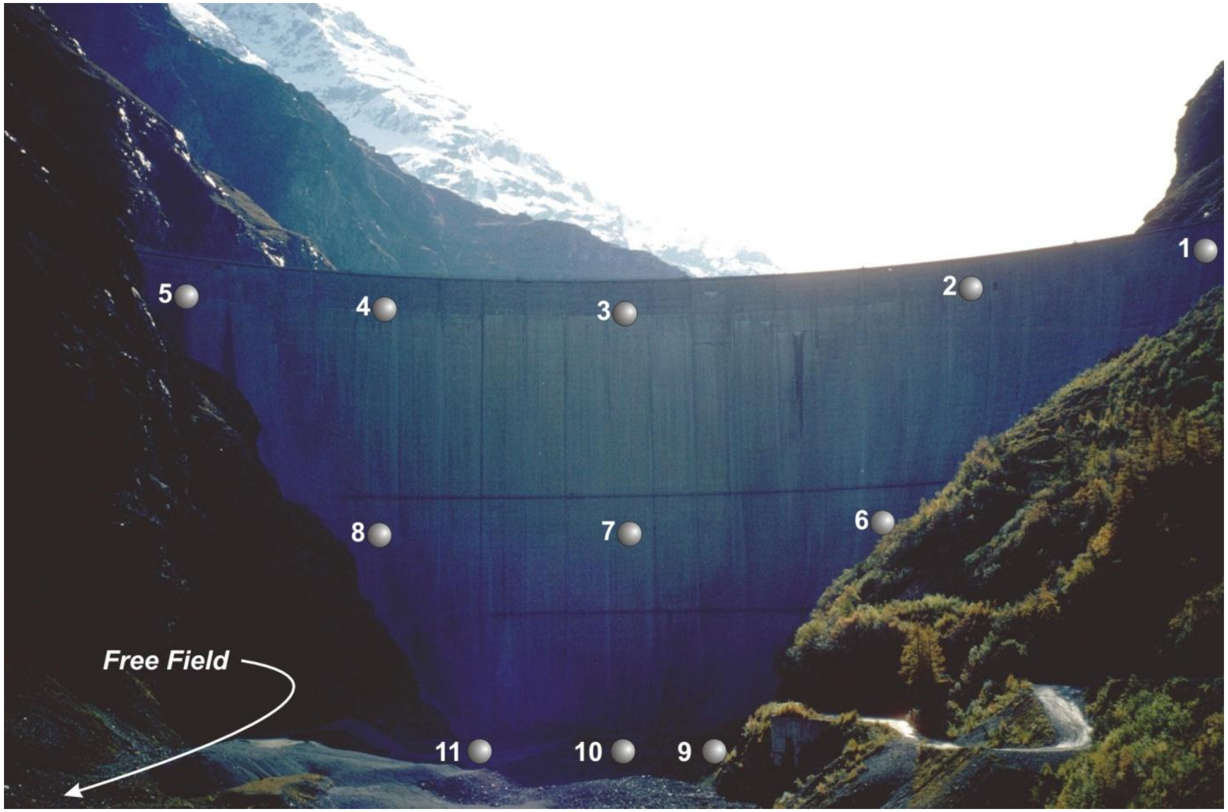
Forced Vibration Tests: Morrow Point Dam

Bureau of Reclamation concluded:

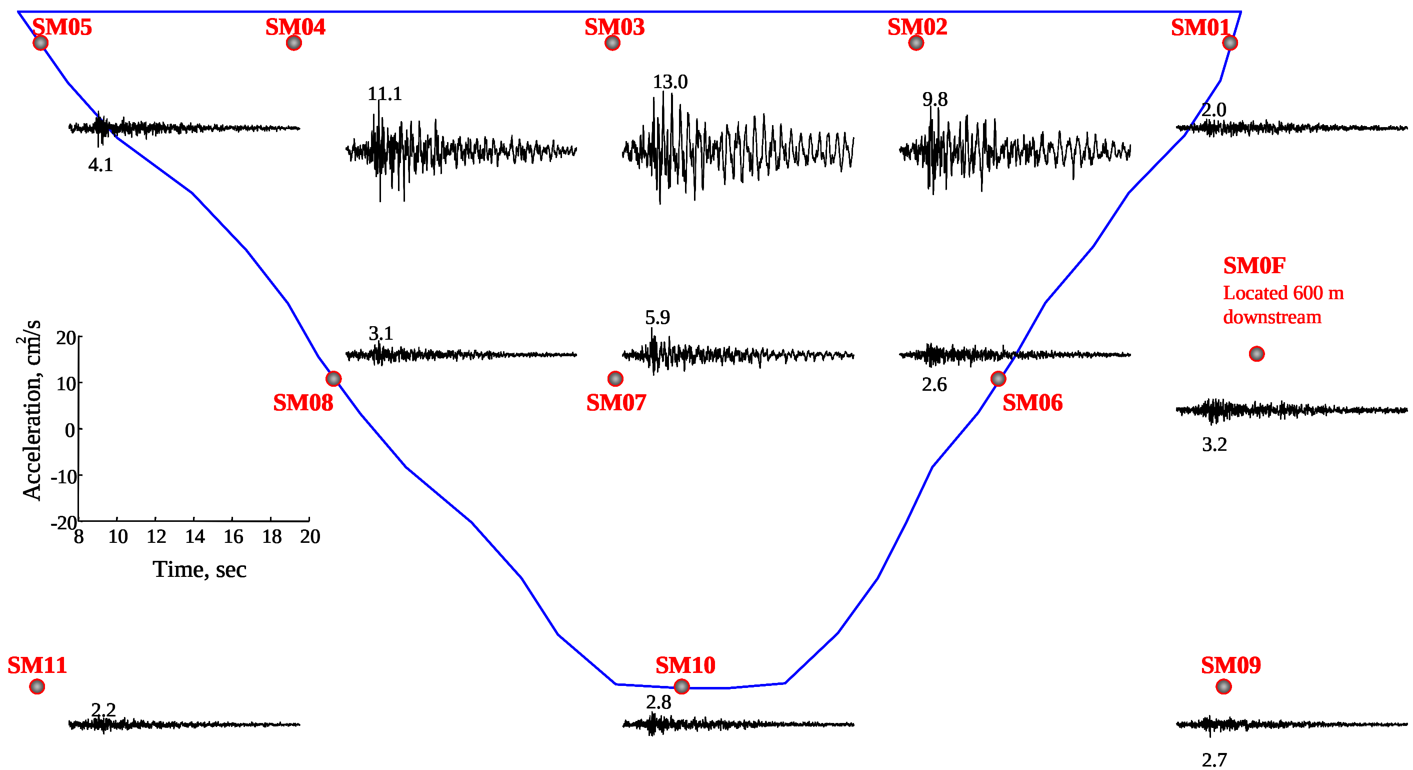
- Massless foundation rock model far from matching measured response
- Including dam-foundation rock interaction (EACD-3D-96 model) reasonably matched measured response

Mauvoisin Dam, Switzerland
250 meters high

Mauvoisin Dam, Switzerland
Location of Recorders



Recorded Motions at Mauvoisin Dam
Stream Direction

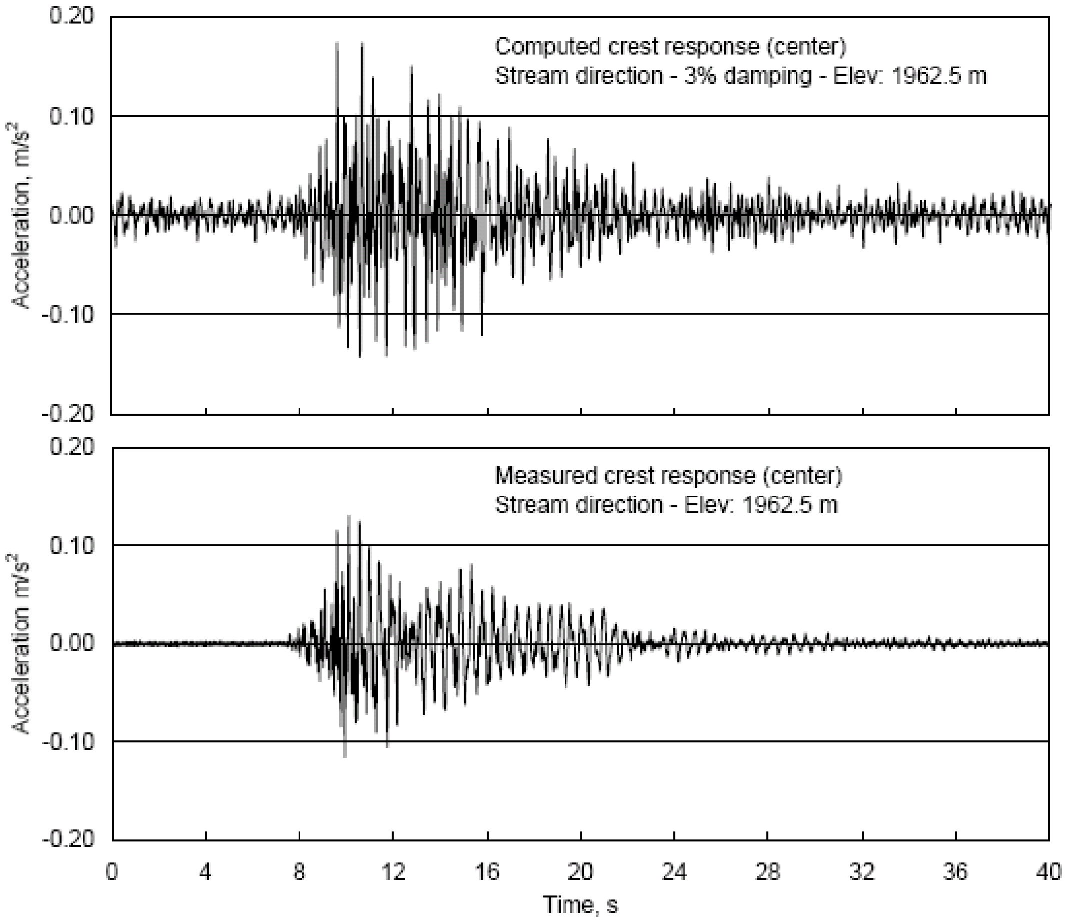


1996 Valpelline earthquake: Magnitude 4.6, 12 km away

Analysis of Mauvoisin Dam: Massless Foundation (Proulx, Darbre, and Kamileris, 2004)

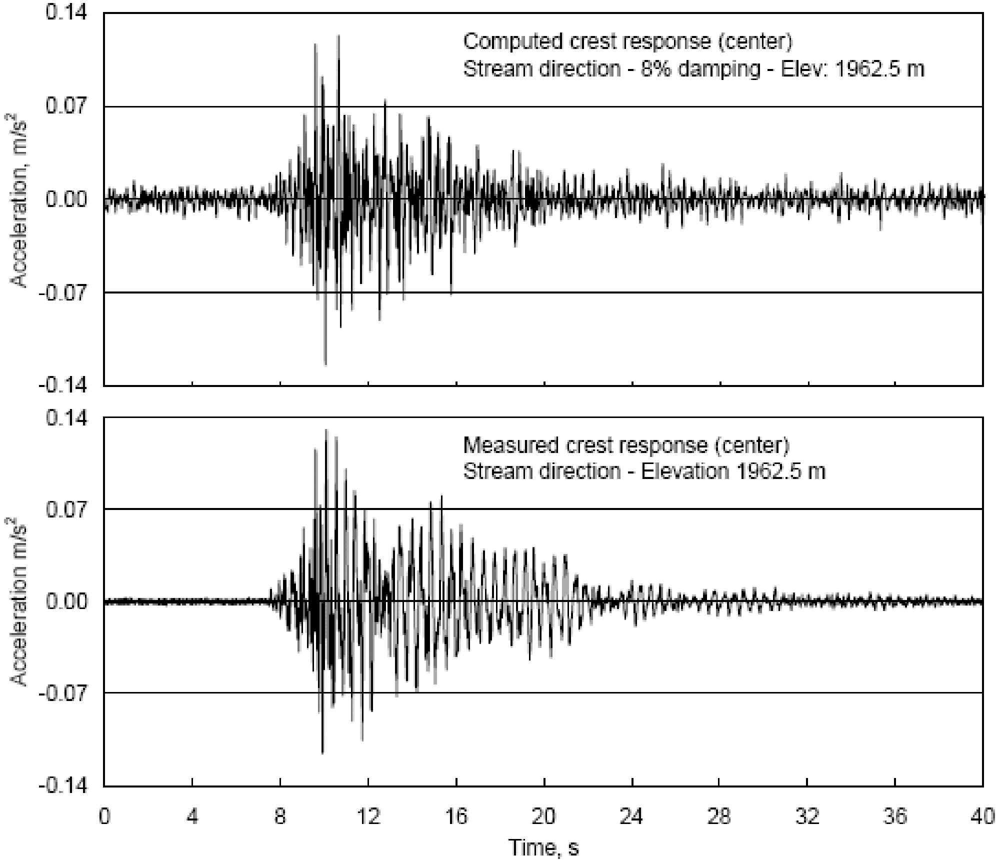
- Finite element model properties calibrated against ambient vibration test data
- Using measured 2-3% damping, response was overestimated
- 8% damping provided better match
- 15% damping required in model for Emosson Dam

Analysis of Mauvoisin Dam: Massless Foundation (Proulx, Darbre, and Kamileris, 2004)



Using measured 3% damping, response was overestimated

Analysis of Mauvoisin Dam:
Massless Foundation
(Proulx, Darbre, and Kamileris, 2004)



8% damping provided better match

How to justify 8% damping in model when measured value is 2-3%?

Analysis of Mauvoisin Dam: Massless Foundation (Proulx, Darbre, and Kamileris, 2004)

- Finite element model properties calibrated against ambient vibration test data
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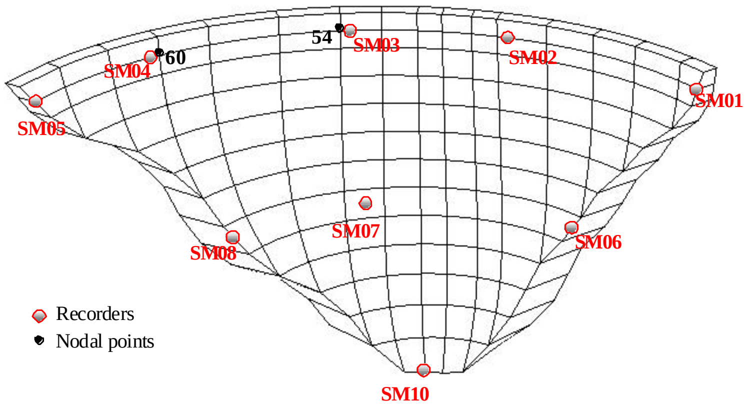
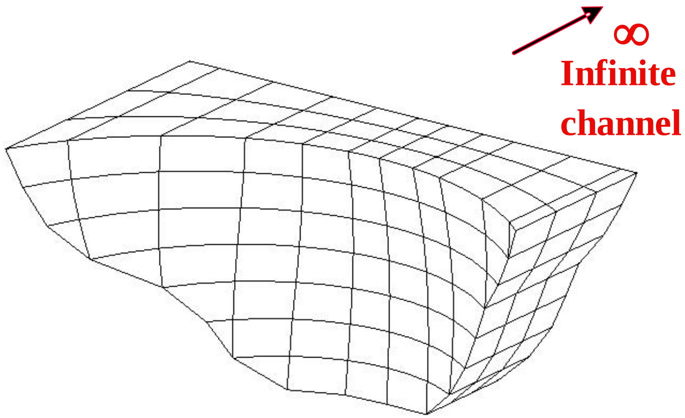
EACD-3D 2008 Model

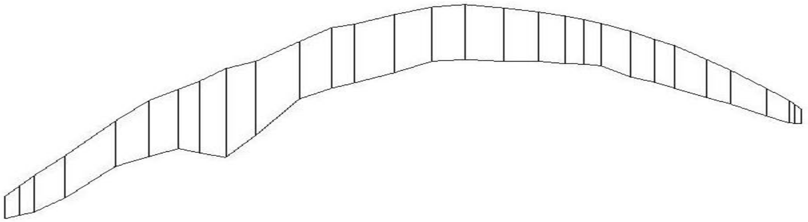
(a) Finite element model: Dam



(b) Finite element model: Fluid Domain

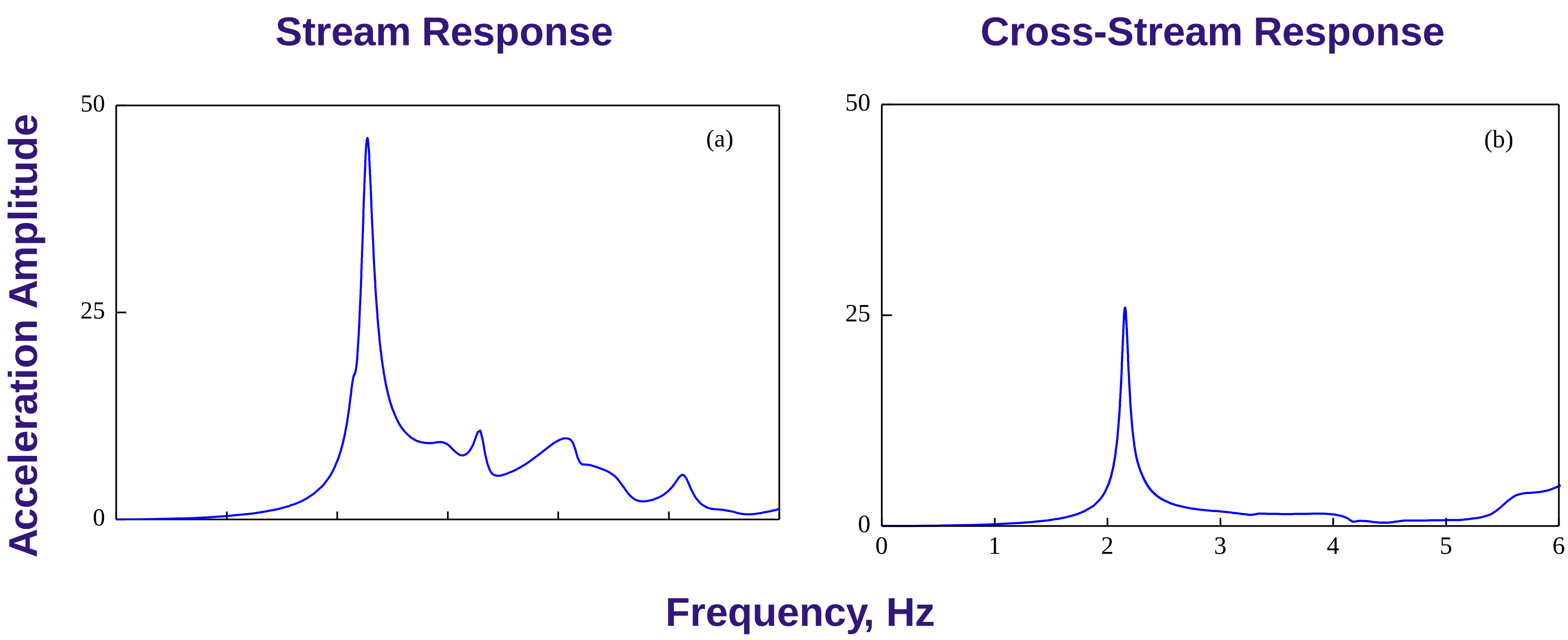


(c) Boundary element mesh: dam-foundation rock interface



Selection of Damping
Based on Frequency Response Functions

Damping: Dam 1%; Rock 3% ⇨ 2% in overall system



Improved Agreement between Computed and Recorded Response When Foundation Inertia and Damping Included

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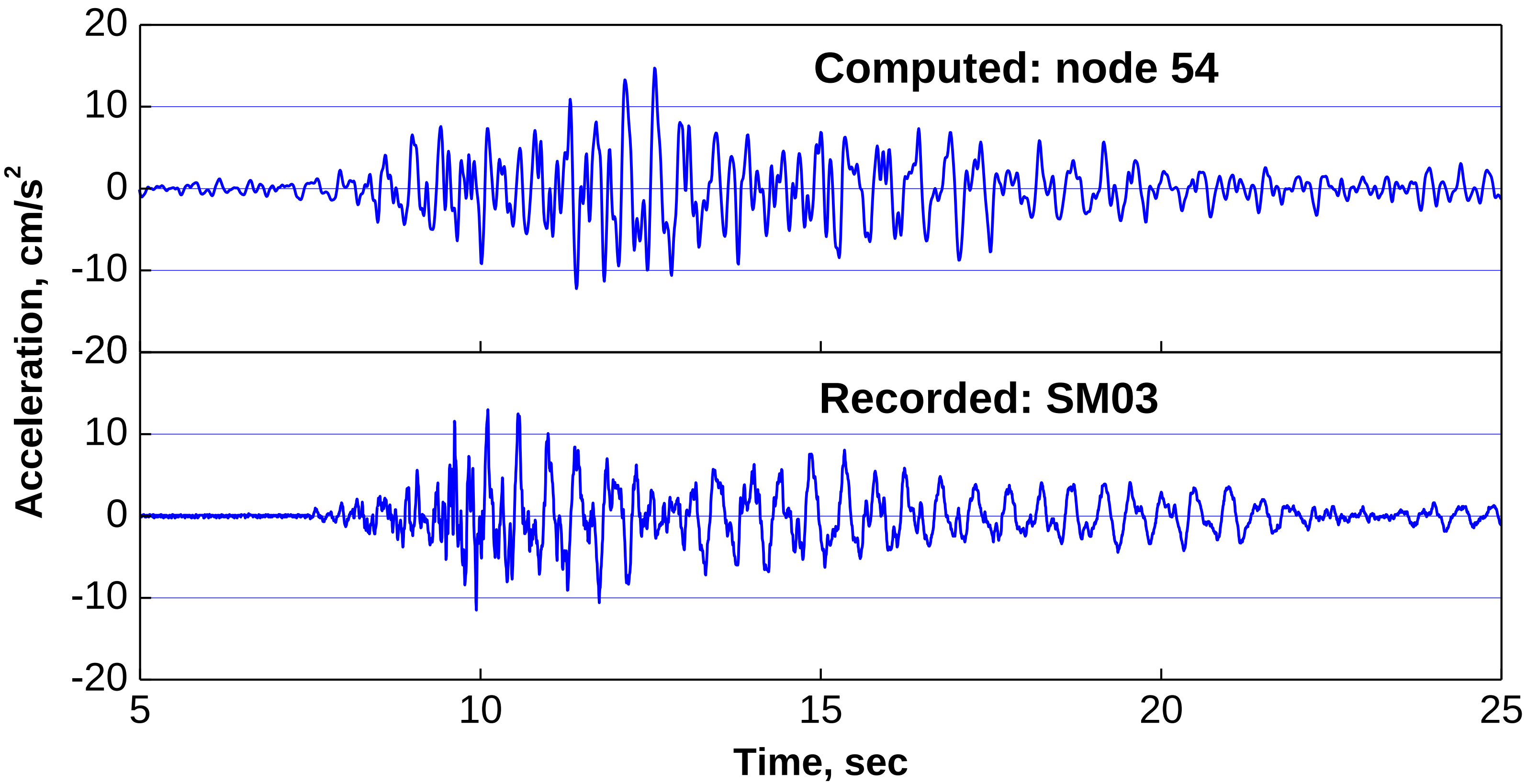

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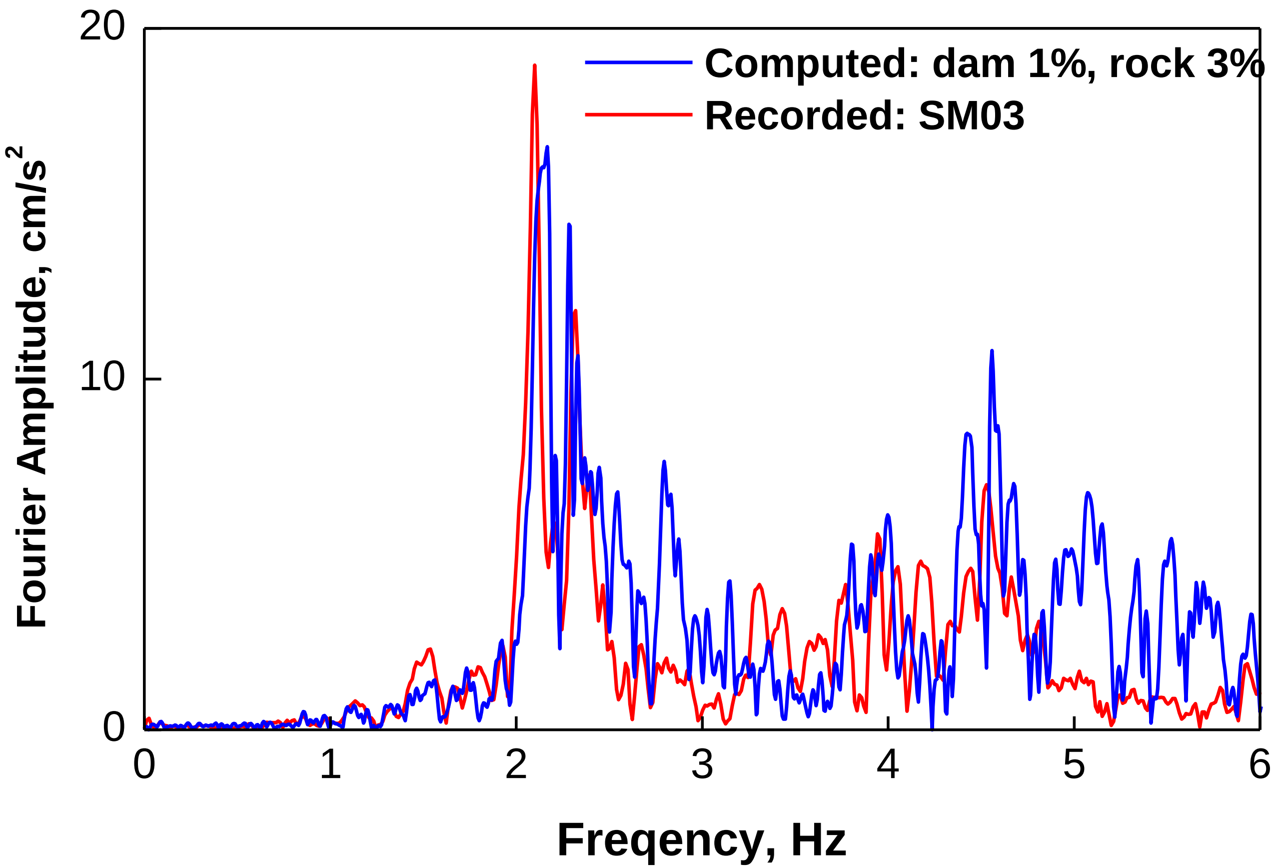

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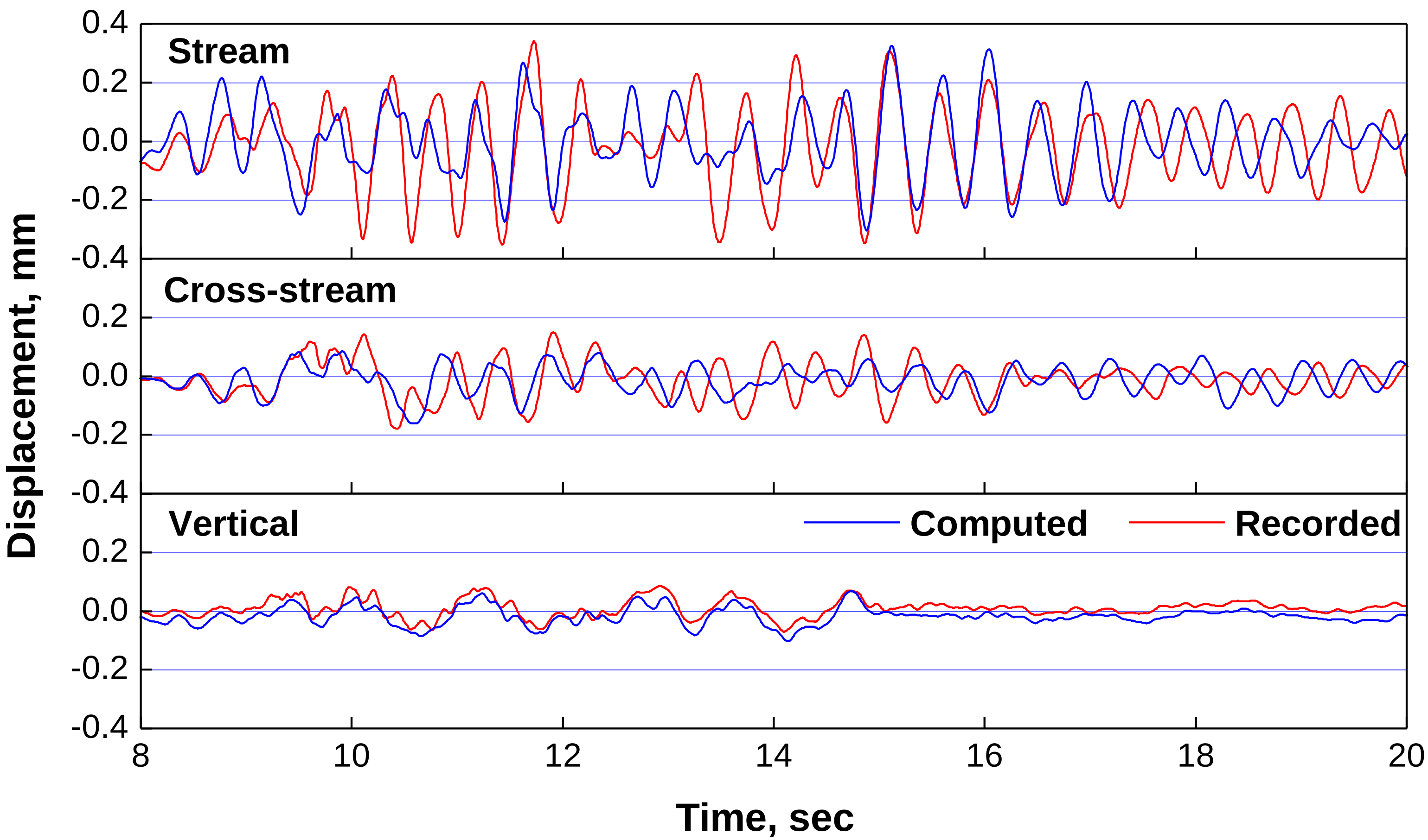
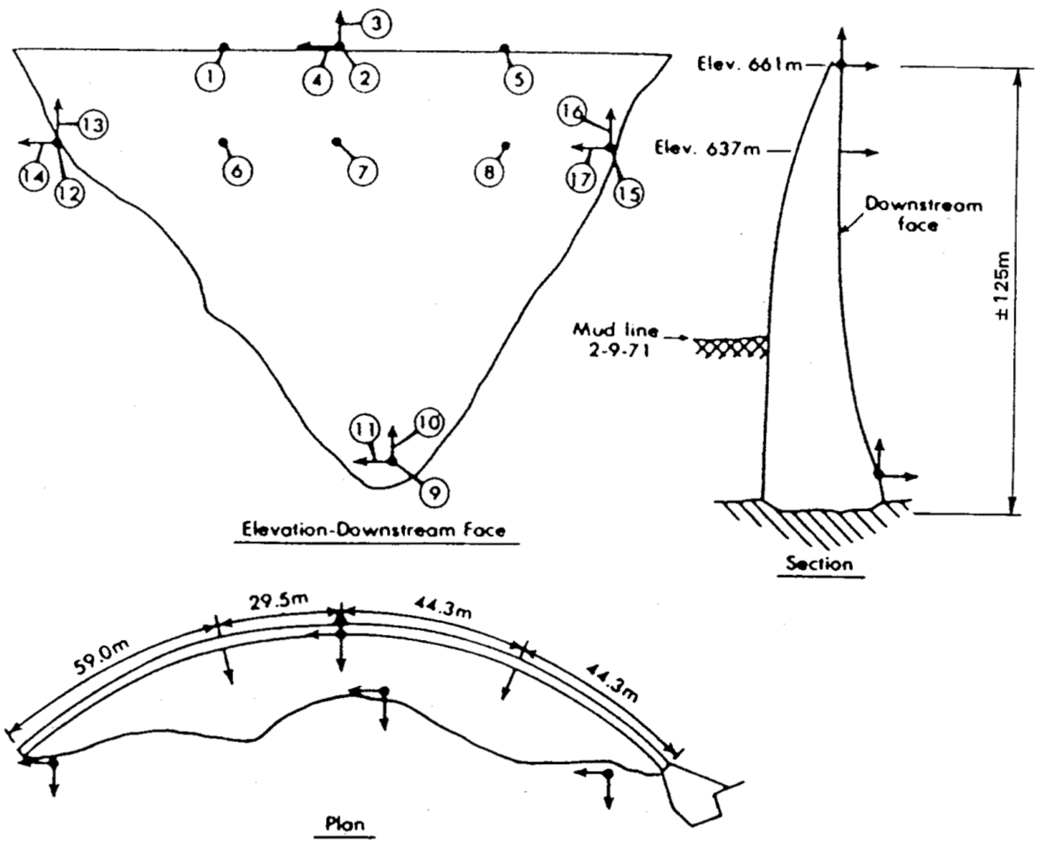


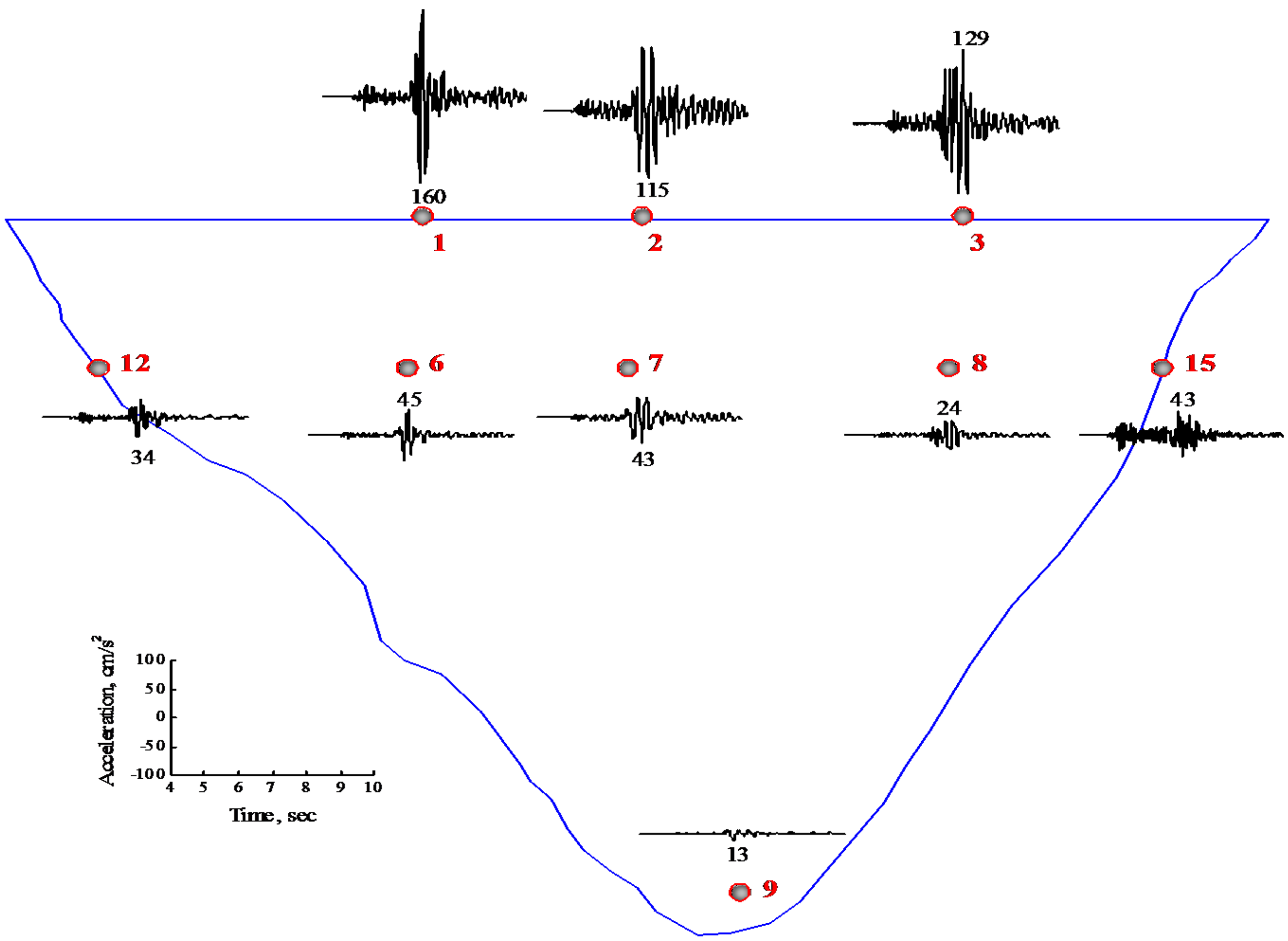
Pacoima Dam, California, USA
113 meters high

Instrumentation at Pacoima Dam



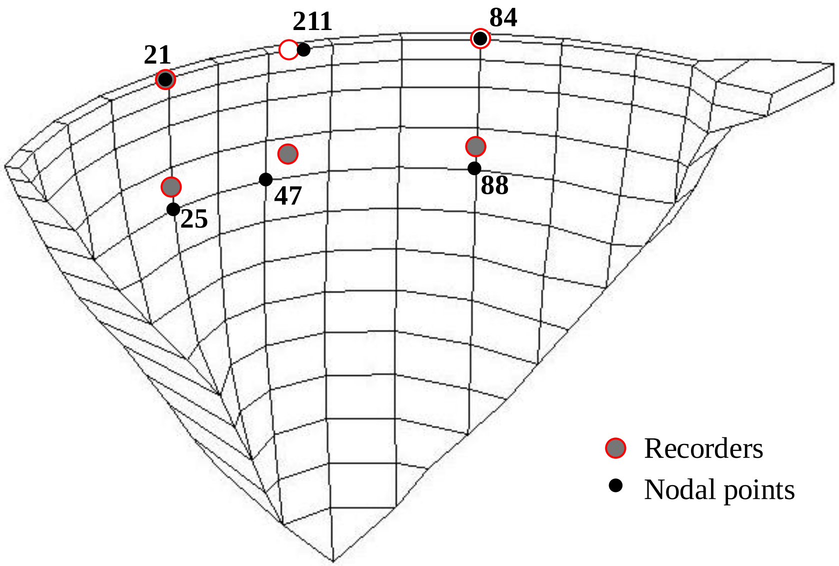
CDMG Sensor Locations

Recorded Motions at Pacoima Dam
2001 Earthquake, Stream Direction

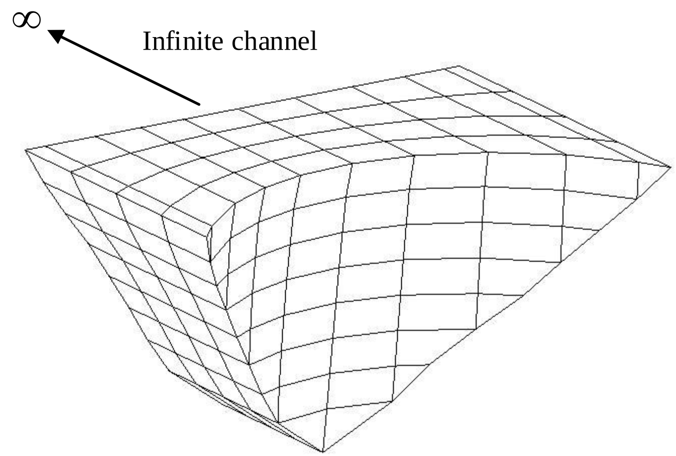


EACD-3D-2008 Model

(a) Finite element model: dam



(b) Finite element model: reservoir



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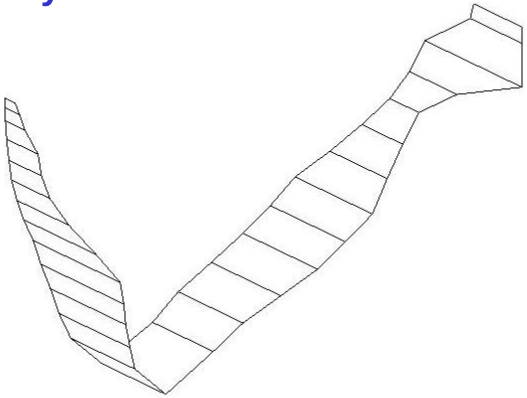
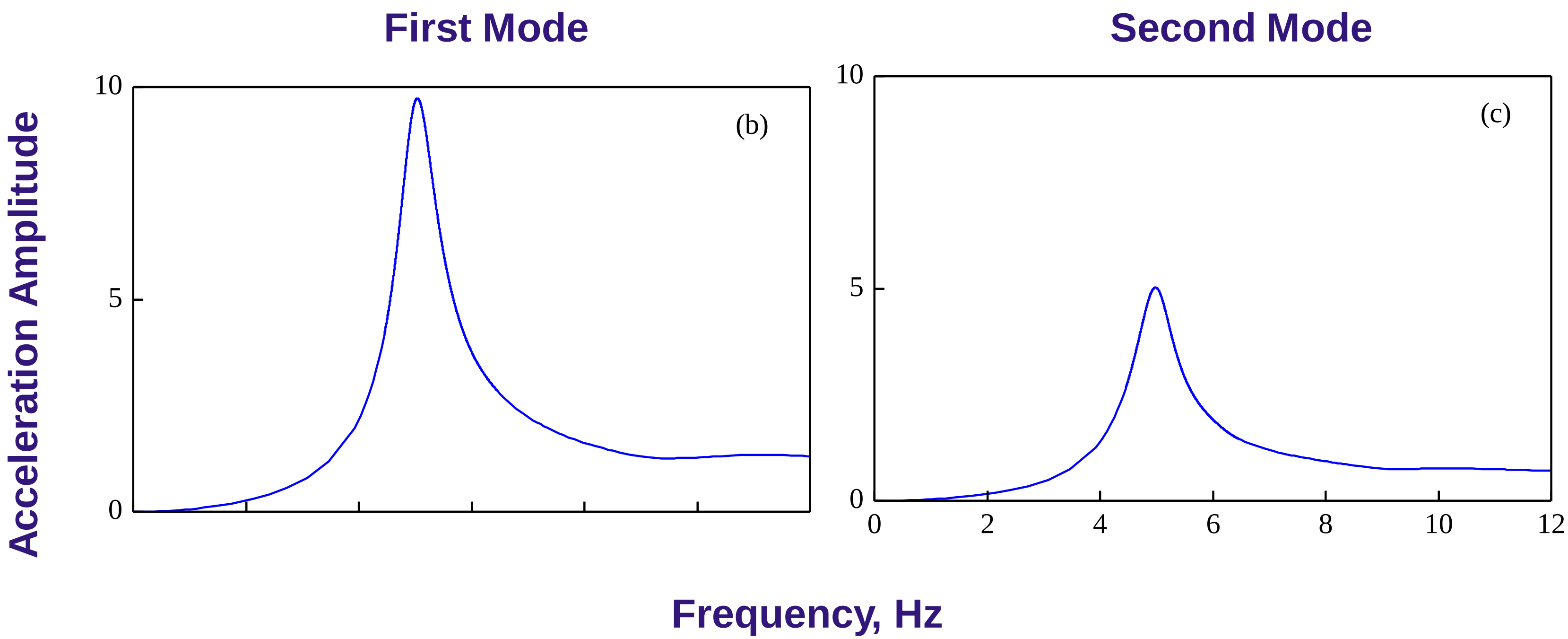
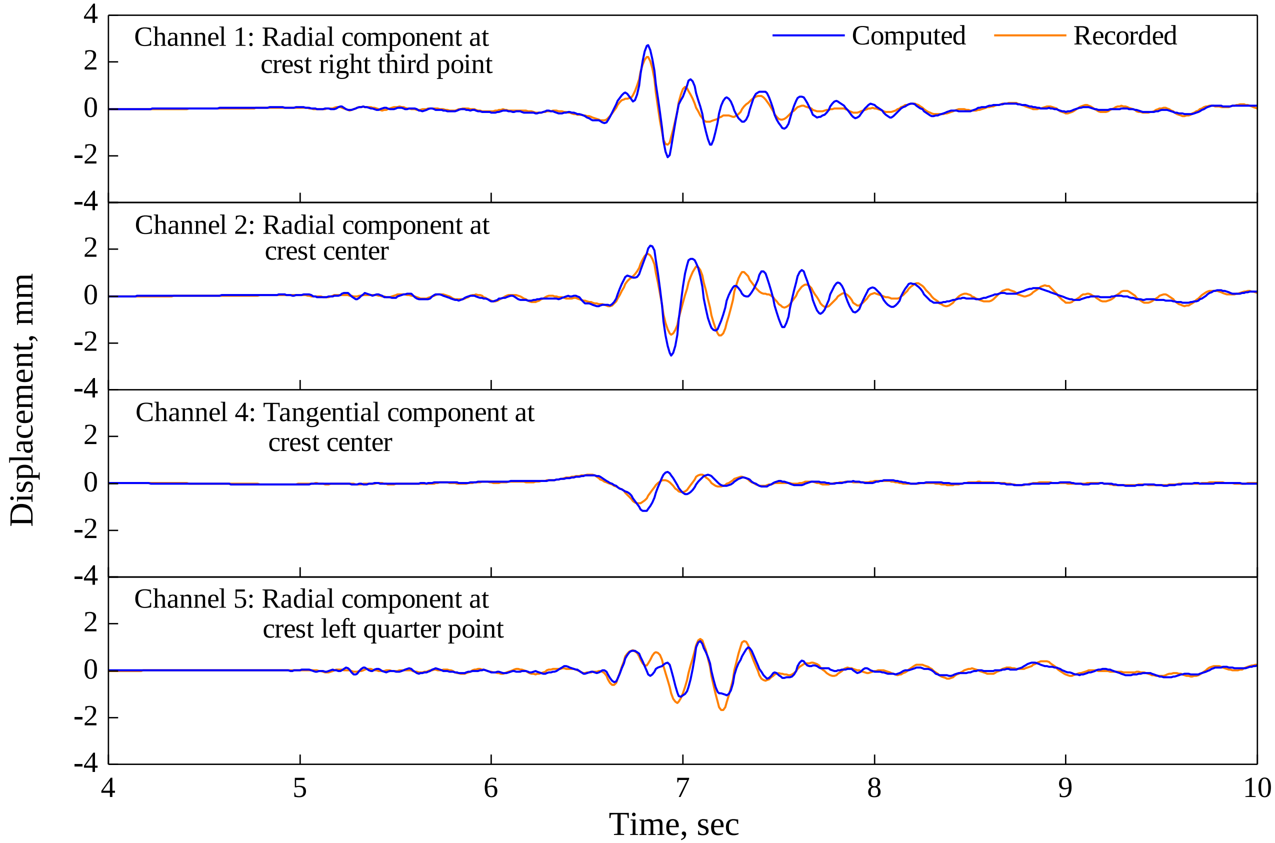


Selection of Damping
Based on Frequency Response Functions

Damping: Dam 2%; Rock 4% ⇨ 6.2-6.6% in overall system



Comparison of Computed and Recorded Displacements Pacoima Dam, 2001 Earthquake



SPATIAL VARIATIONS IN GROUND MOTION

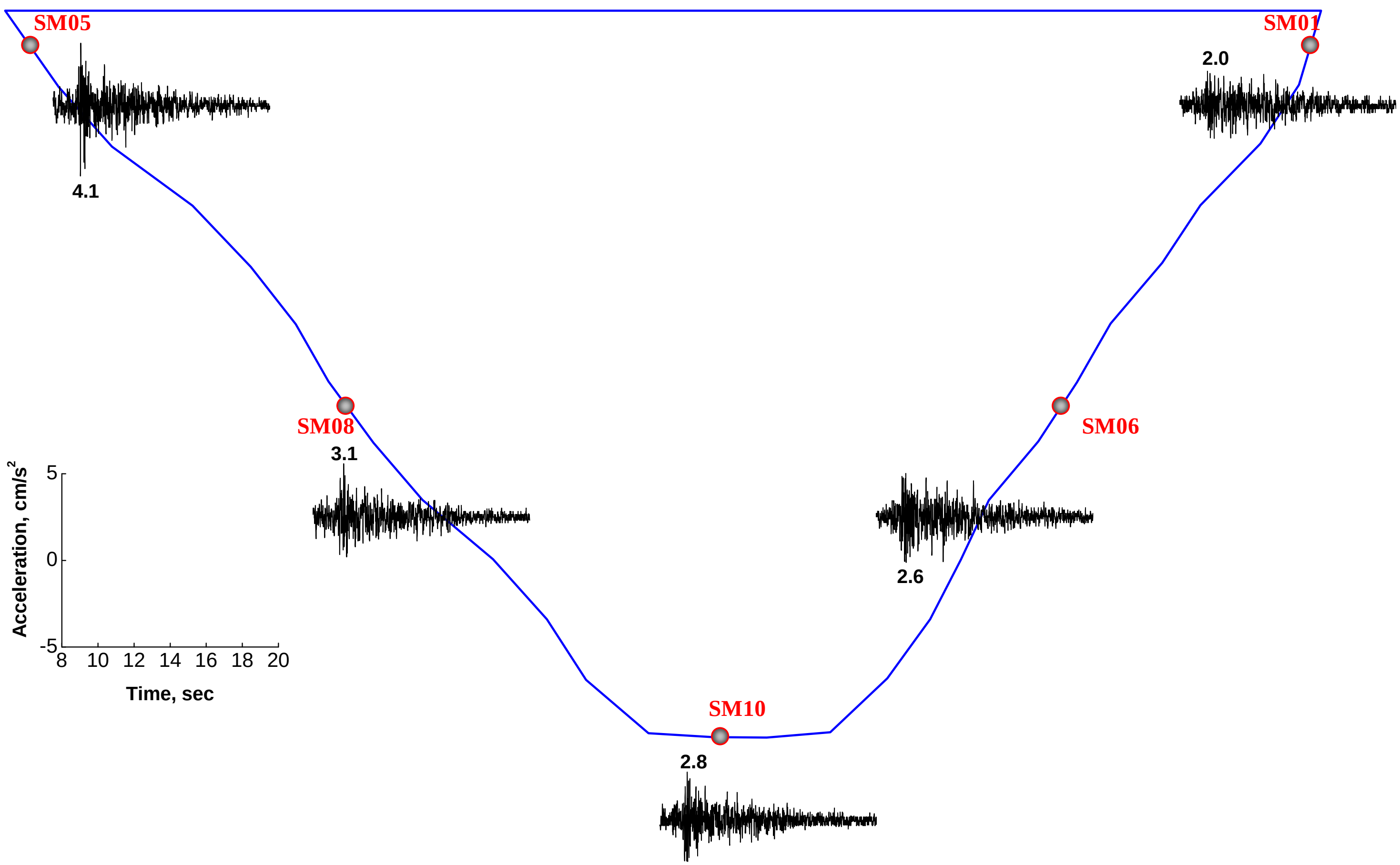
Extended Analysis Procedure 2007-2008

- Spatial variations in ground motion
- Dam-water interaction
- Reservoir boundary absorption
- Water compressibility
- Dam-foundation rock interaction
- EACD-3D-2008 computer program

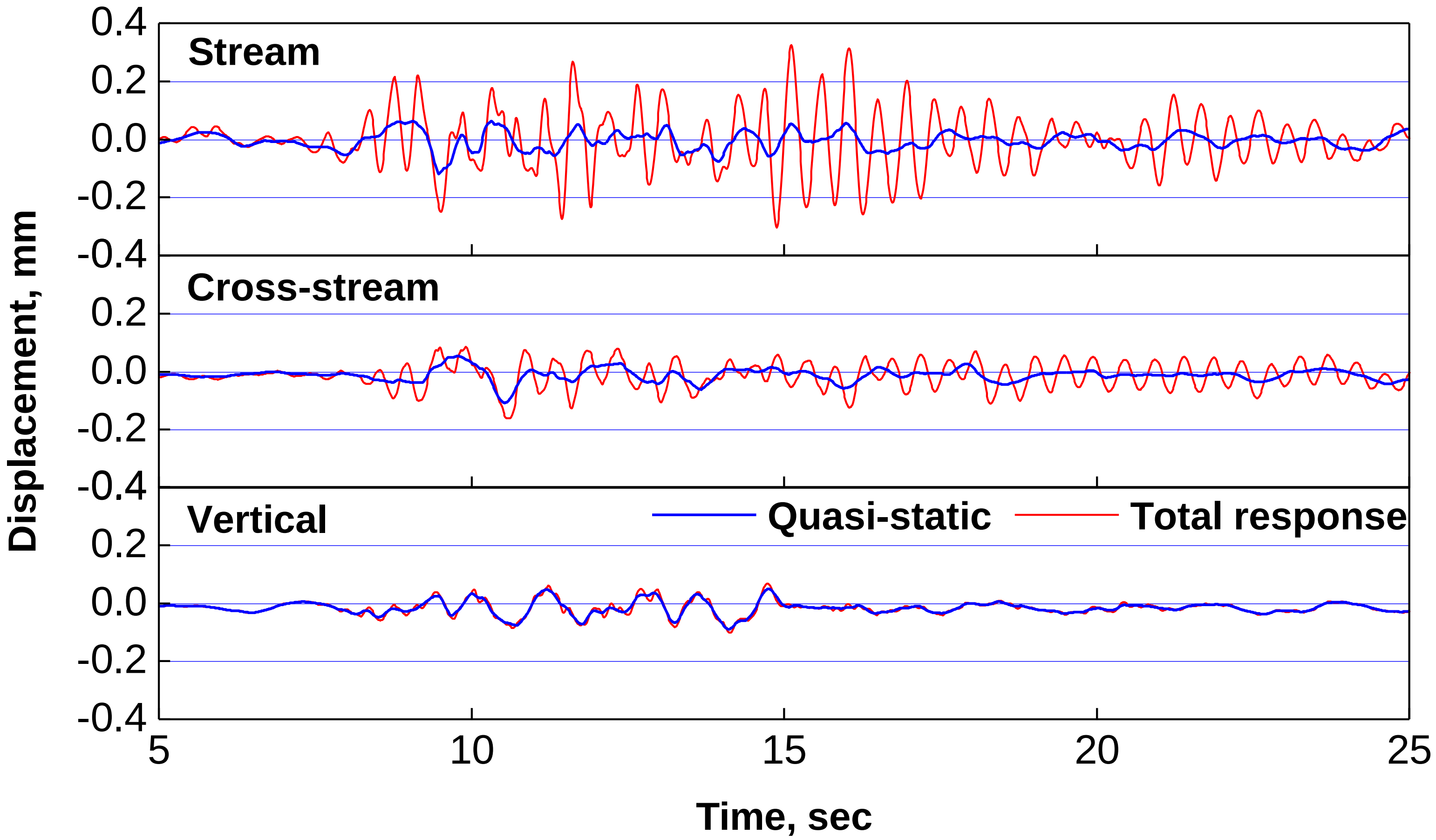
Significance of Spatial Variations in Ground Motion

- Structural response split in two parts:
  - Quasi-static component: due to static application of interface displacements at each time instant
  - Dynamic component
- Key factor is significance of quasi-static component
- Depends on degree to which ground motion varies spatially

Mauvoisin Dam: Spatial Variations in Interface Motions Are Small

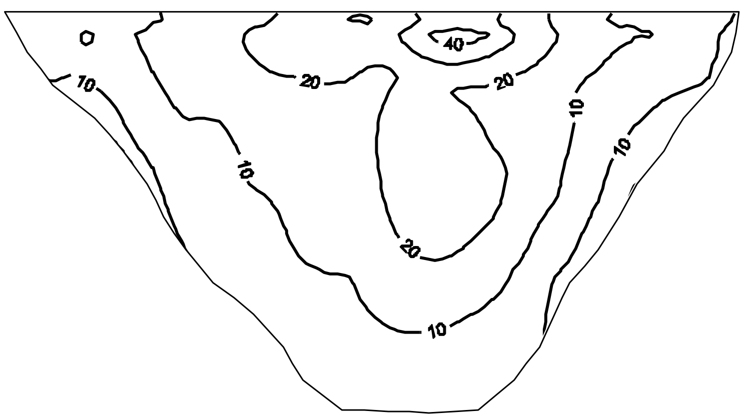


Quasi-Static Component Is Only a Small Part of Mauvoisin Dam Response

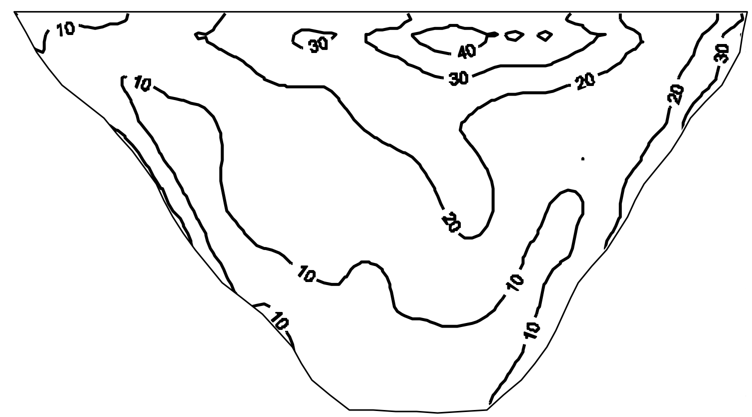


Spatial Variations in Ground Motion
Small Influence on Stresses in Mauvoisin Dam

Arch stresssses on upstream face in kPa

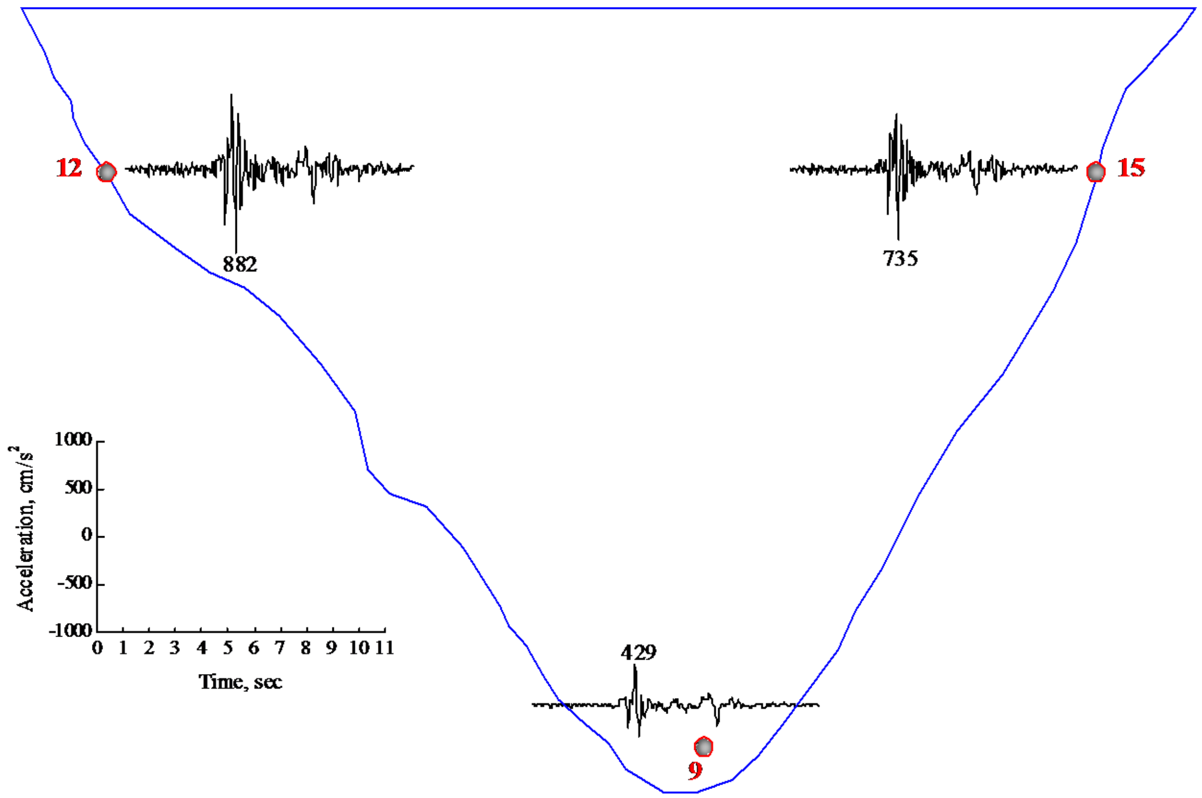


Spatially-Uniform Excitation



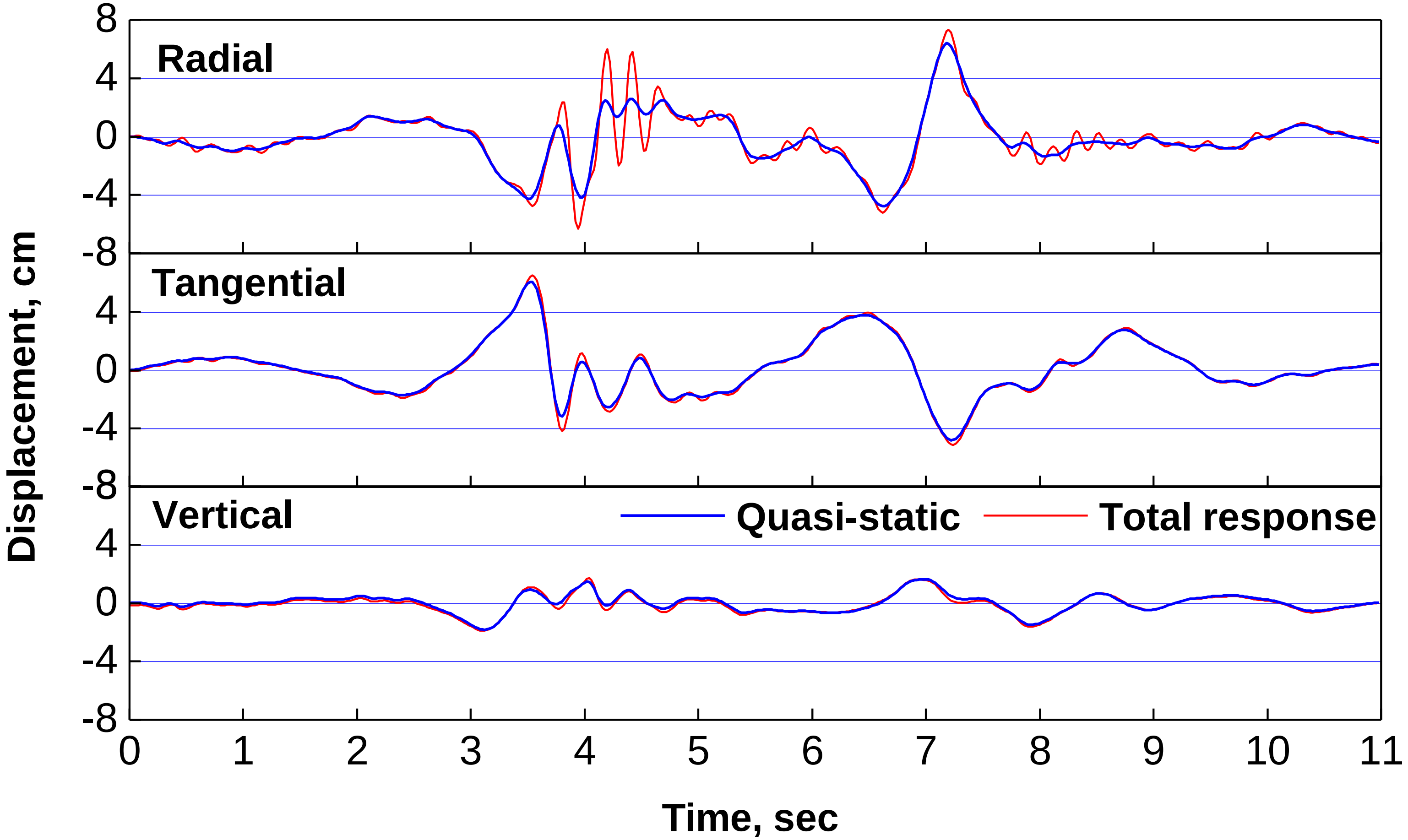
Spatially-Varying Excitation

Pacoima Dam: Spatial Variations in Interface Motions Are Large
Northridge Earthquake, 1994



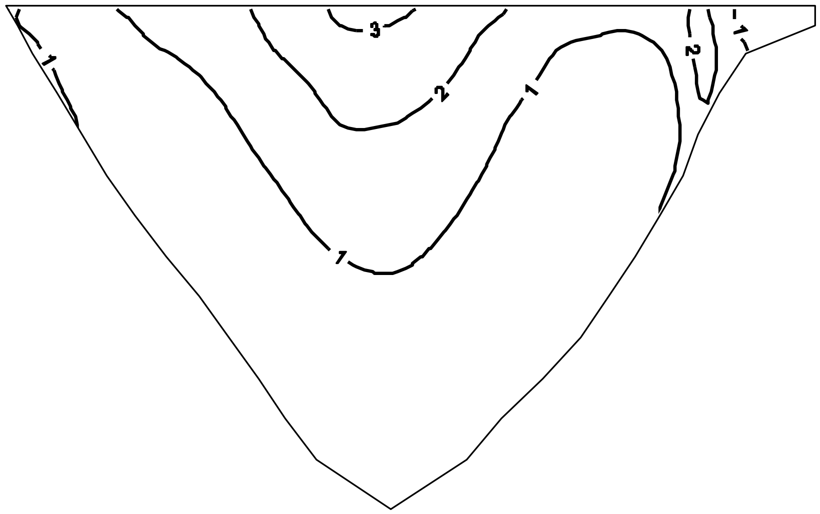
Missing segments estimated by Alves & Hall (2004)

Quasi-Static Component Dominates Pacoima Dam Response

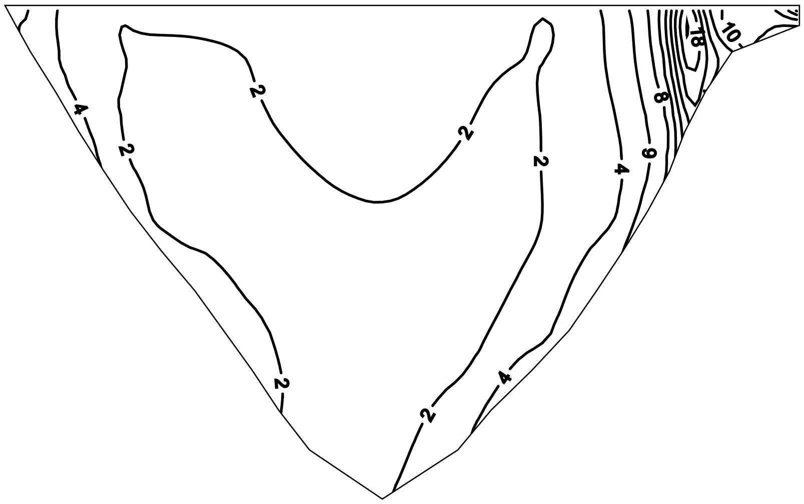


Spatial Variations in Ground Motion Major Influence on Stresses in Pacoima Dam during 1994 Earthquake

Arch stresssses on upstream face in MPa



Spatially-Uniform: Base



Spatially-Varying Excitation

Pacoima Dam, California, USA

113 meters high

Pacoima Dam, Cracking Visible

Applications to Evaluation and Remediation of Existing Dams

Seismic Evaluation of Existing Dams

- Geological and seismological investigations
  - Probabilistic seismic hazard analysis
  - Uniform Hazard Spectrum
- Ground motion selection and scaling
- Dynamic analysis
- Concrete testing: tensile strength
- Performance evaluation
- Remediation strategies

Deadwood Dam

50-meter high, single curvature dam

Seismic Upgrading of Deadwood Dam

- EACD-3D-96 analysis including dam-water-foundation interaction (2001)
- Compute forces transmitted to foundation
- Stabilize 3 unstable foundation blocks
- 60 rock bolts
- Cost: US $1.0 M
- Higher cost if analyses assumed massless foundation rock

Stewart Mountain Dam

Built 1928 to 1930

Height :	**207 ft**
	63 m
Crest width:	**8 feet**
	2.4 m
Base width:	**33 feet**
	10 m

Arizona

Problems:

Concrete placed very wet

- **Segregated concrete**

No lift line cleanup

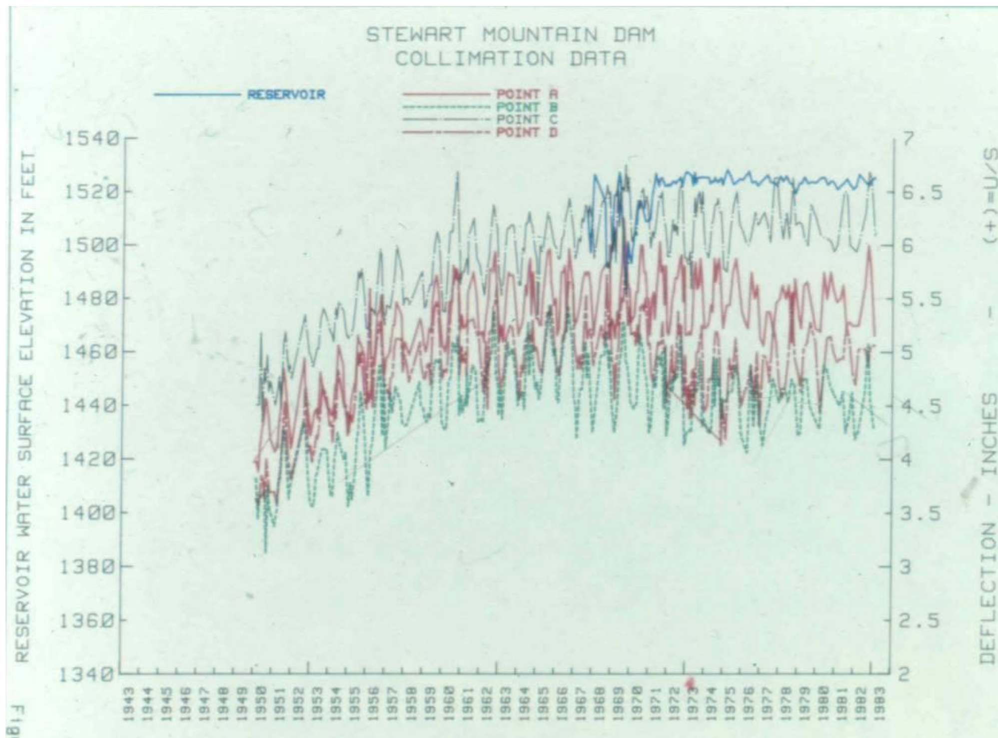
- **Unbonded lift lines (16 of 23 unbonded)**

Alkali-aggregate reaction

- **Crest expanded 6-inches (15 cm) upstream**

Earthquake shaking

- **Generates 2.6 g at dam crest**
- **Concrete blocks move upstream**

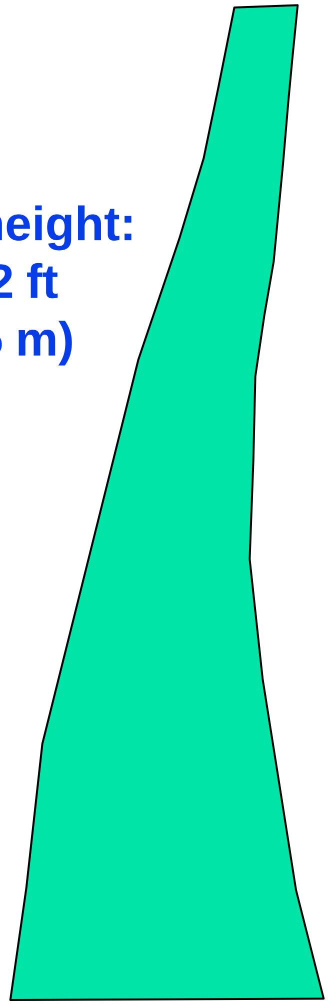


Seismic Upgrading of Stewart Mountain Dam

62 post-tensioned anchors
10-ft spacing

Dam passes flood

Special Drilling and Surveying Required Because of Thin Arch Dam



Seismic Upgrading of Stewart Mountain Dam

- Earthquake analyses assumed massless foundation rock (1994)
- 62 post-tensioned anchors @10 ft
- Cost: US $6.8 M
- Lower cost if analyses included dam-water-foundation rock interaction

Pardee Dam, California

345 ft high

Englebright Dam, California

280 ft high

East Canyon Dam, Utah

260 ft high

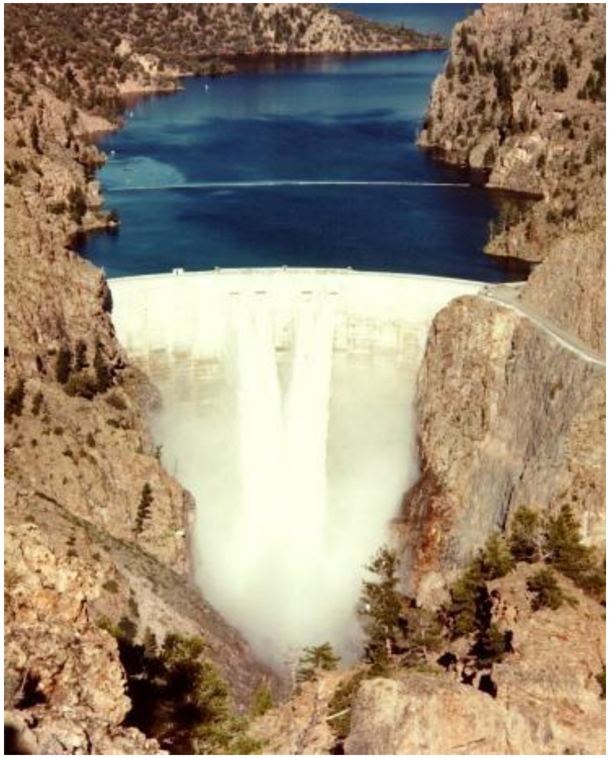
Valdecanas Dam, Spain

332 ft high

CLOSURE

Dynamic Analysis Should Consider:

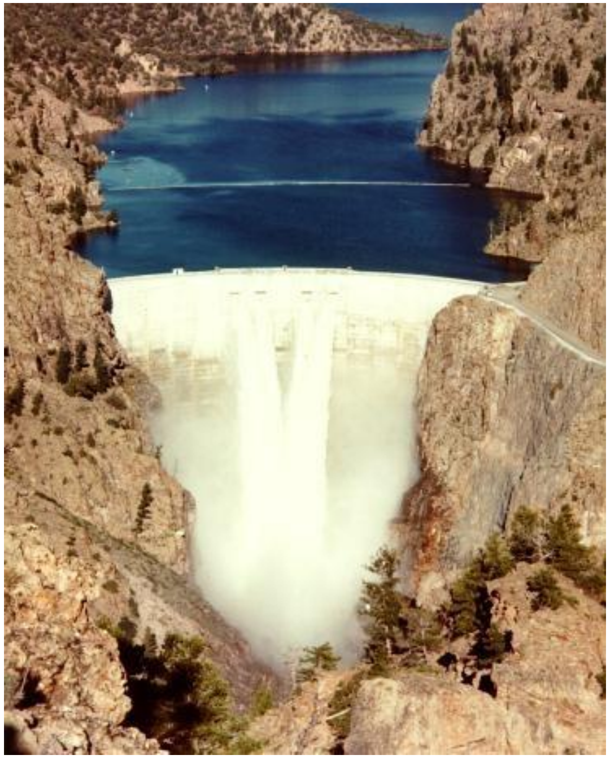
- Dam-water interaction
- Reservoir boundary absorption
- Water compressibility
- Dam-foundation rock interaction
- Spatial variations in ground motion



Slow Adoption in Engineering Practice

- Most analytical advances to include dam-water-foundation rock interaction were reported
  - Over 20 years ago for gravity dams
  - Over 10 years ago for arch dams
- 2007-2008: Extended to include spatial variations in ground motion
- EACD-3D-2008 computer program for linear analysis
- User-friendly software is needed

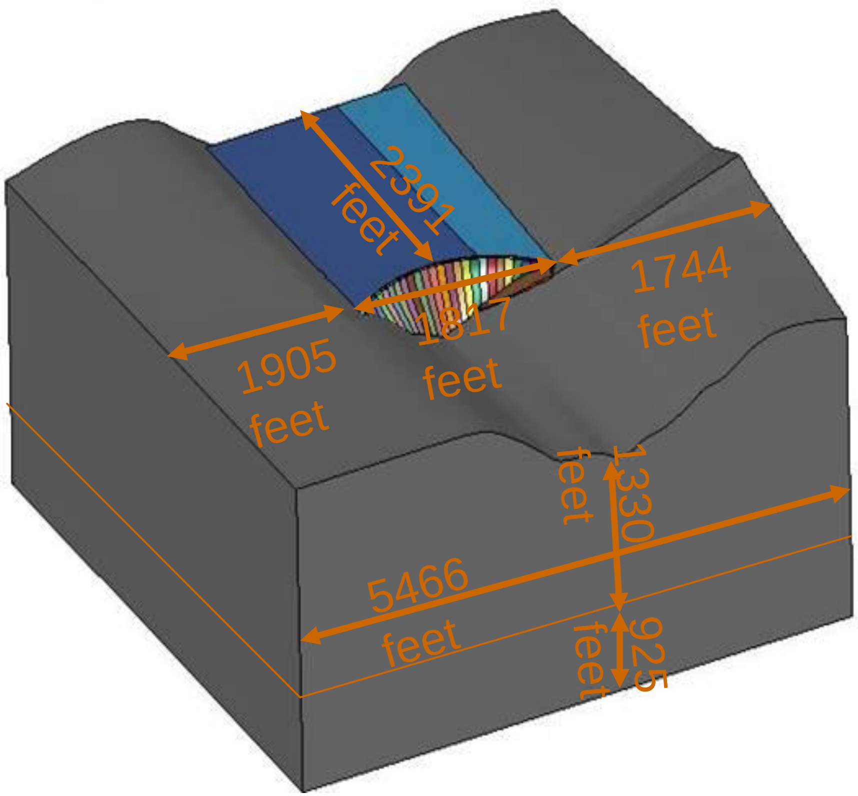
Dynamic Analysis Should Consider:



- Dam-water interaction
- Reservoir boundary absorption
- Water compressibility
- Dam-foundation rock interaction
- Spatial variations in ground motion

Nonlinear Analysis of Dams

If radiation boundary is simple, large FE model is necessary to simulate semi-unbounded domains and dam-water-foundation rock interaction.



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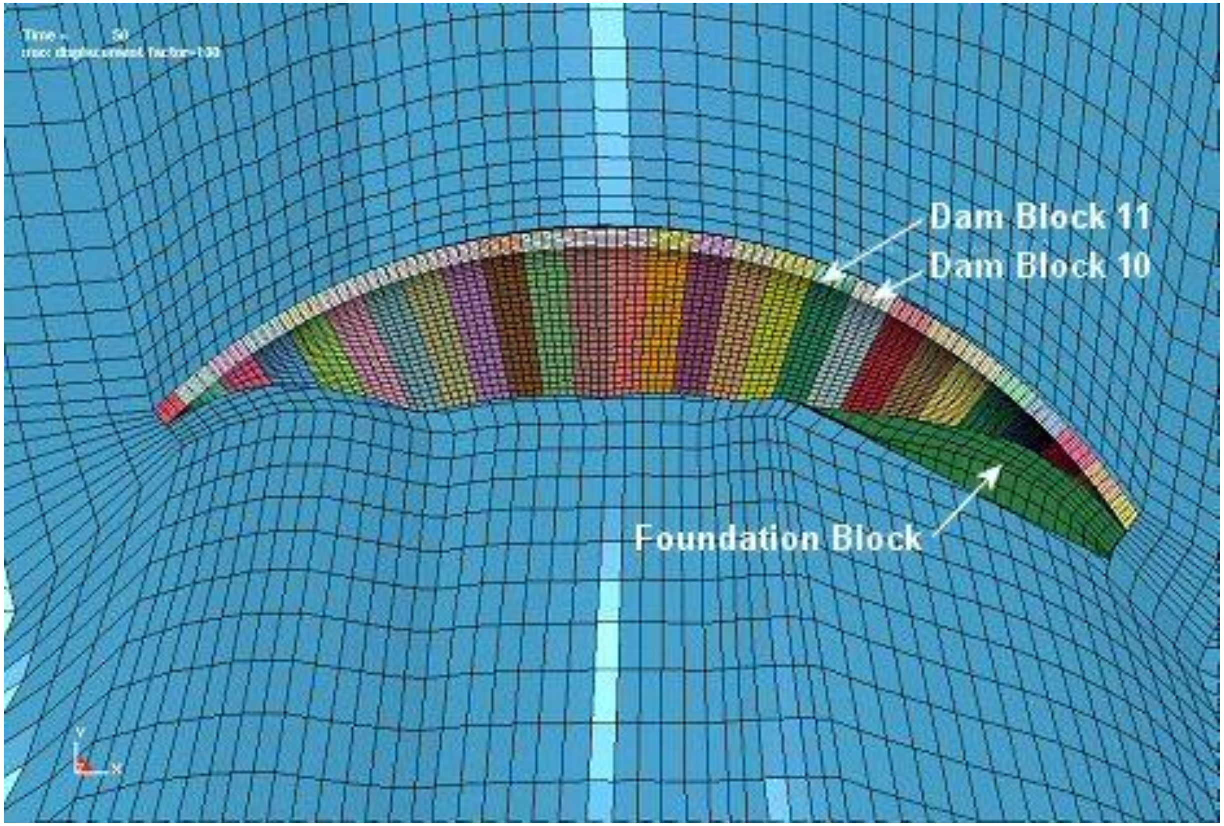
LS-DYNA Finite Element Model

Finite Elements: Dam = 12,000;
Foundation = 92,000; and Water = 38,000



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Nonlinear Analysis of Dams

Recently developed PML boundary drastically reduces size of model, now implemented in LS-DYNA