Seismic Response Analysis of Arch Dams to Spatially-Varying Ground Motions

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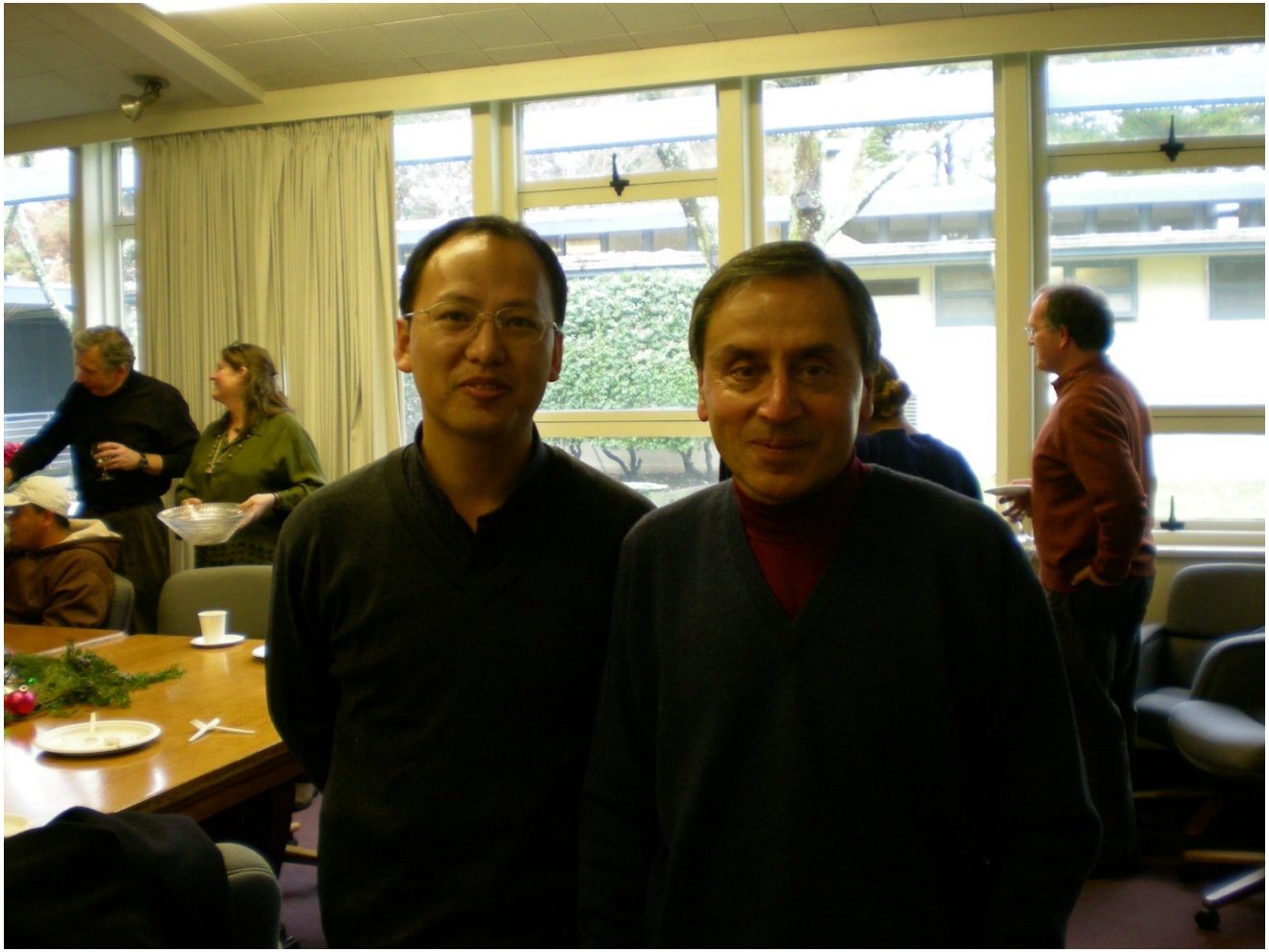


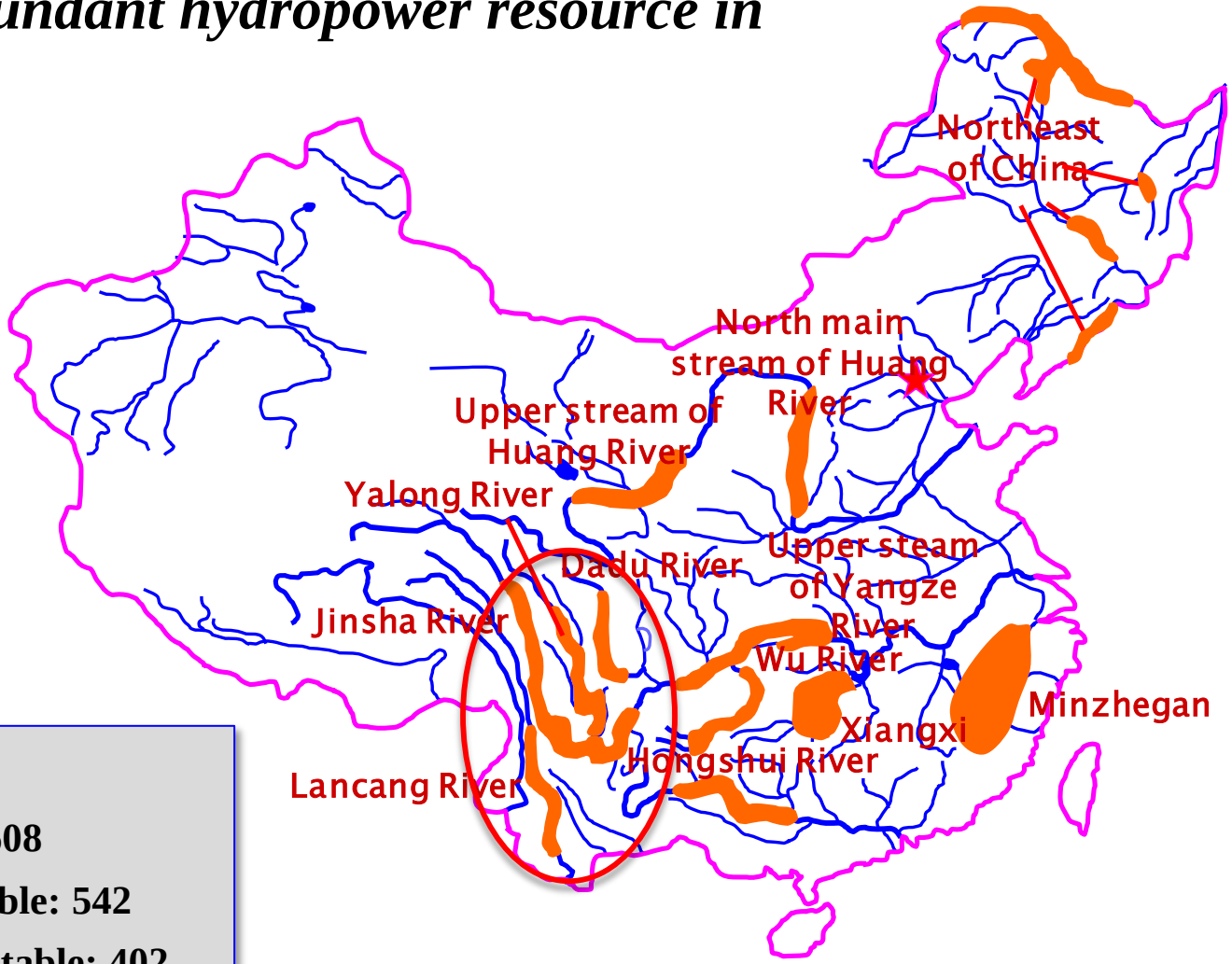
December 17, 2007

OUTLINES

1. High Dam Construction in China
2. Linear Analysis of Arch Dams to Spatial Motions
3. Nonlinear Analysis of Arch Dams to Spatial Motions
4. Simulation of Ground Motions from Source to Site

High Dam Construction in China

- ***The most abundant hydropower resource in the word***



CAPACITY, GW

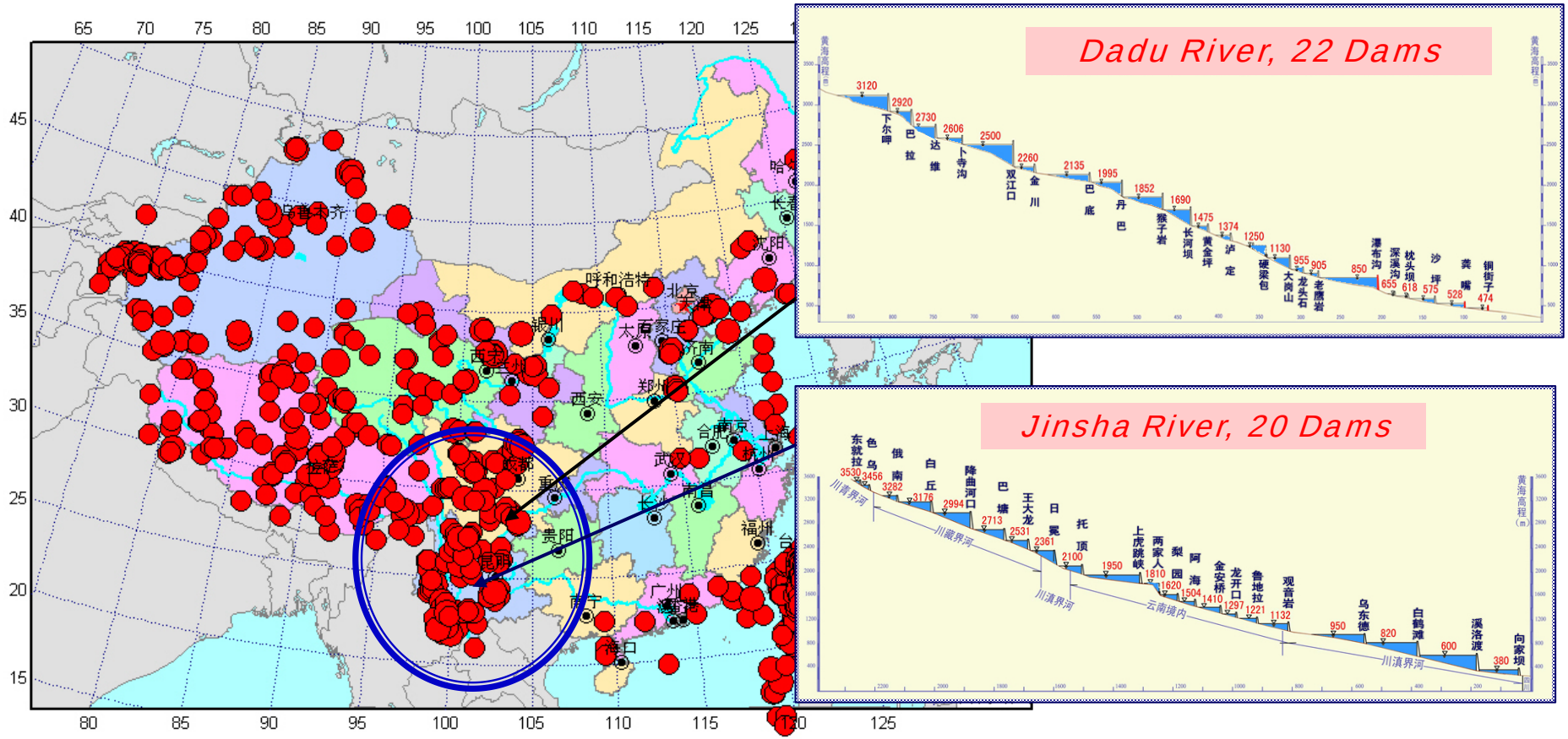
Gross theoretical: 608

Technically exploitable: 542

Economically exploitable: 402

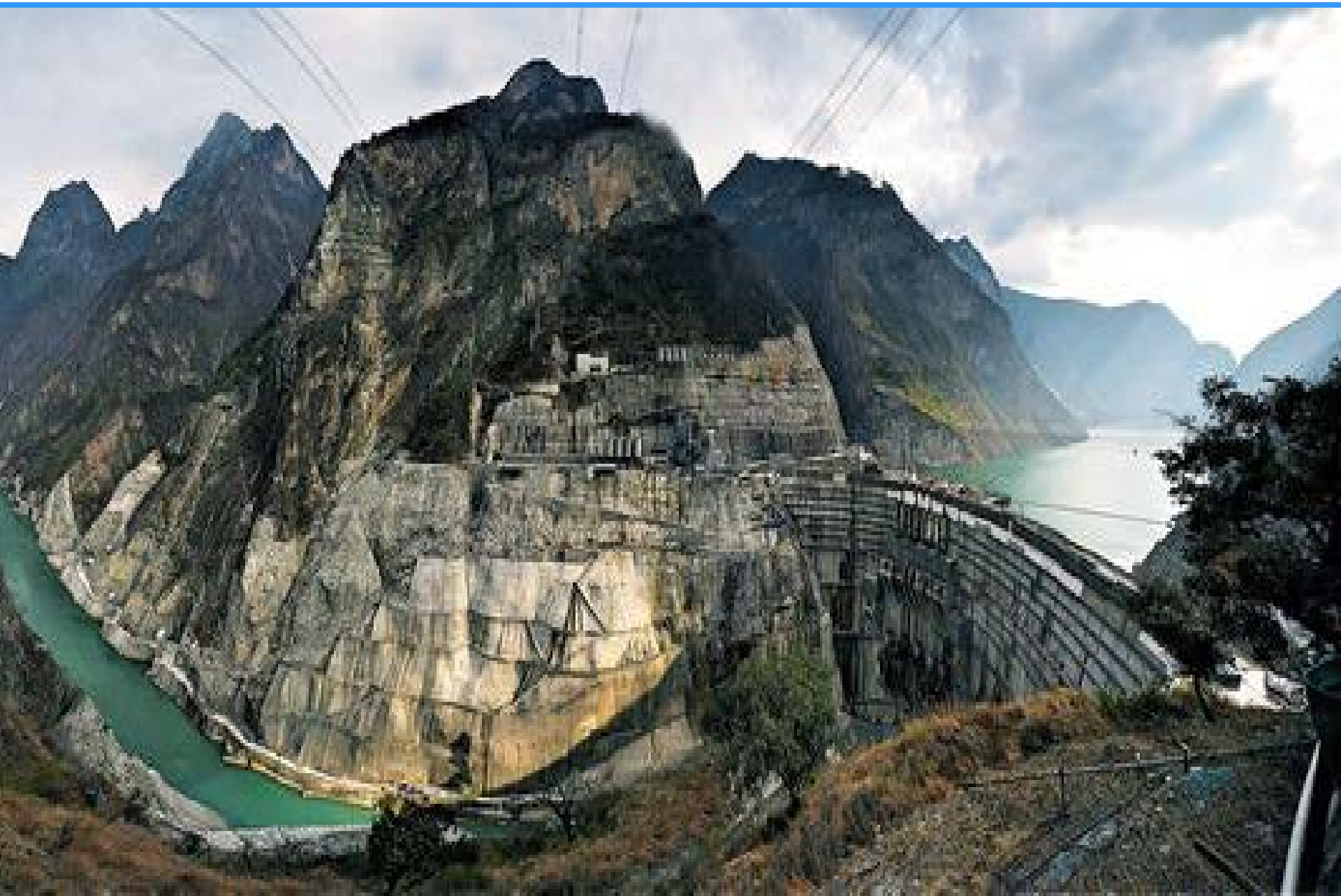
High Dam Construction in China

- ***Many high dams have been built in Southwest China in seismic active region.***



China Earthquake Records（ 1900-， M≥6.0）

Jinping-I dam (305m high, PGA=0.2g)



Xiaowan dam (294.5m high, PGA=0.308g)

Xiluodu dam (285.5m high, PGA=0.357g)

Dagangshan dam (210m high, PGA=0.5575g)

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Linear Analysis of Arch Dams to Spatial Motions

One-Year Overseas Research Project

UNIVERSITY OF CALIFORNIA, BERKELEY

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

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July 24, 2007

Professor Jinting Wang
Department of Hydraulic Engineering
Tsinghua University
Beijing 100084, China

Dear Professor Wang:

I am pleased to invite you to work with me as a post-doctoral researcher. This invitation is extended in recognition of your outstanding academic record and demonstrated research accomplishments of high quality. I understand that your visit will be supported by the Chinese Scholarship Council.

For the past many years, my students, collaborators, and I have done research on earthquake response of concrete dams. Opportunities for fruitful research on this topic exist, and I would welcome your collaboration.

During your stay, you will be provided desk space in Davis Hall, access to the UC Berkeley campus libraries, along with other privileges accorded our visitors. I may be able to provide a desktop computer but I recommend bringing your laptop computer.

Our university will send you an official invitation after you provide verification of financial support for the entire duration of your stay.

Sincerely,

Anil K. Chopra

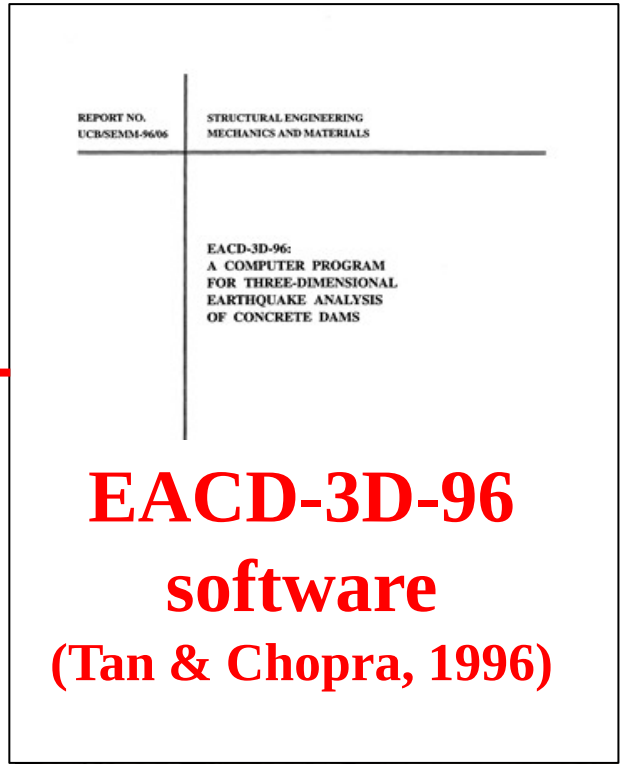
Anil K. Chopra

Linear Analysis of Arch Dams to Spatial Motions

Professor Chopra suggested to work on "Correlation of analytical results with motions of dams recorded during earthquakes"

Computer Program:

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



EACD-3D-96 software

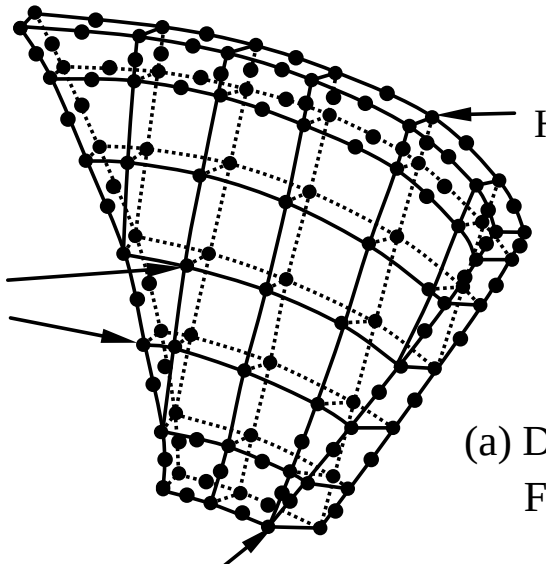
(Tan & Chopra, 1996)

Extension of ECAD-3D-96 computer program

- **Structural response split in two parts**
  - **Quasi-static component due to static application of interface displacements at each time instant**
  - **Dynamic component**

Total displacement

$$\mathbf{r}_c^t = \begin{Bmatrix} \mathbf{r}^s \\ \mathbf{r}_b^s \end{Bmatrix} + \begin{Bmatrix} \mathbf{r} \\ \mathbf{r}_b \end{Bmatrix}$$



Hydrodynamic forces $\mathbf{R}_h$

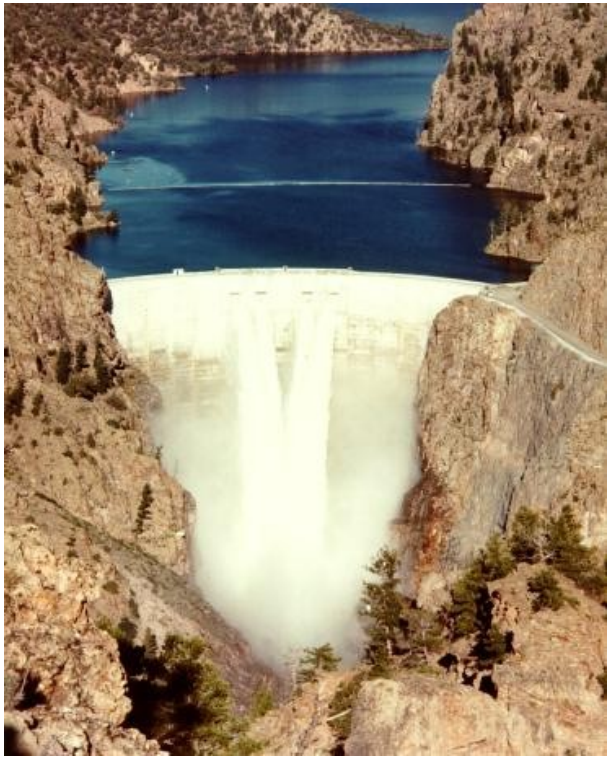
Dam-foundation rock interaction forces $\mathbf{R}_b$

(a) Dam Substructure:
Finite element model

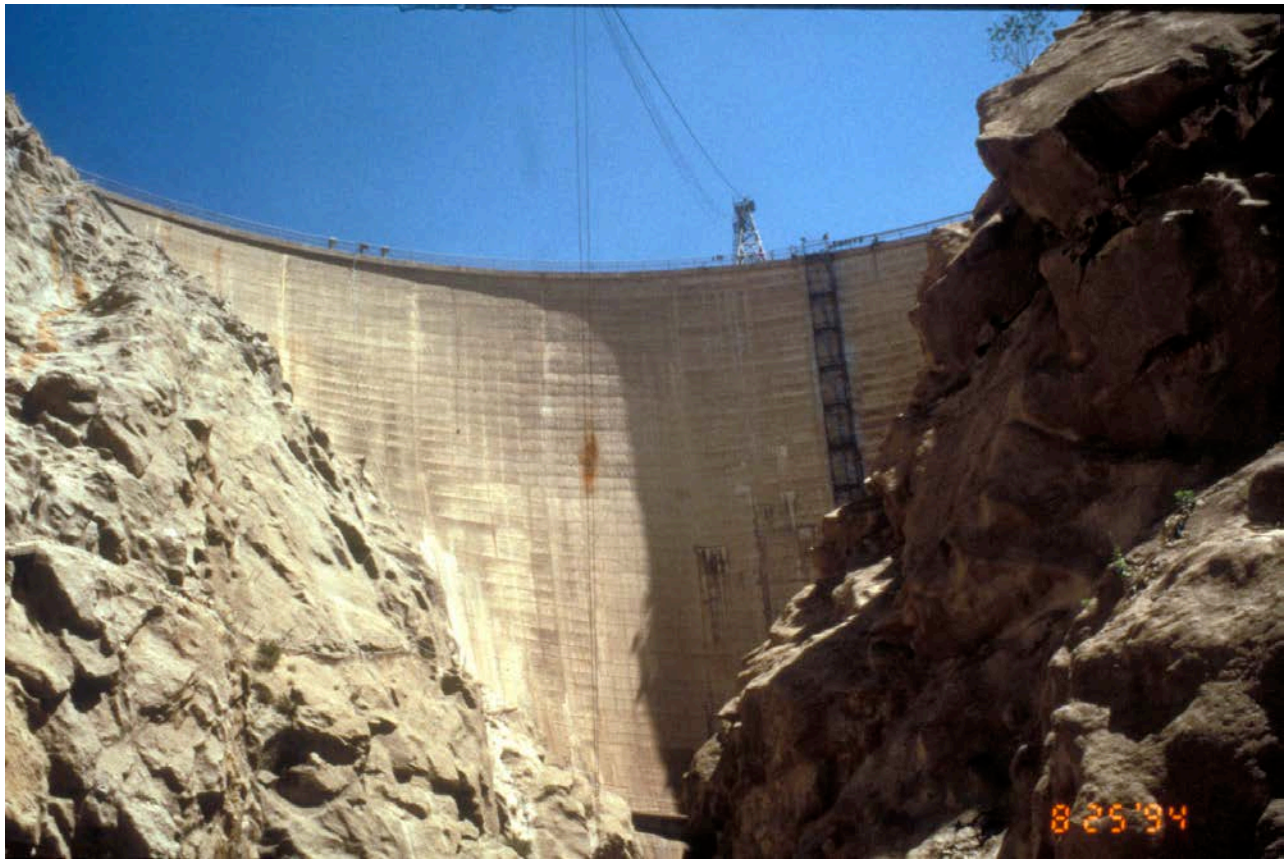
Extension of ECAD-3D-96 computer program

ECAD-3D-2008 Computer Program

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

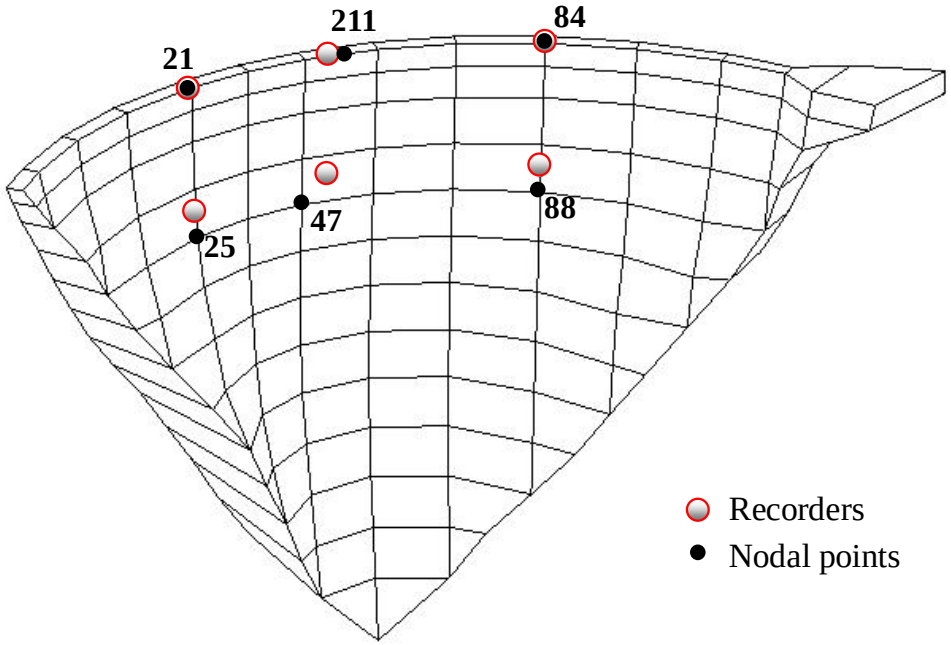


Linear analysis of Pacoima dam in Northridge EQ

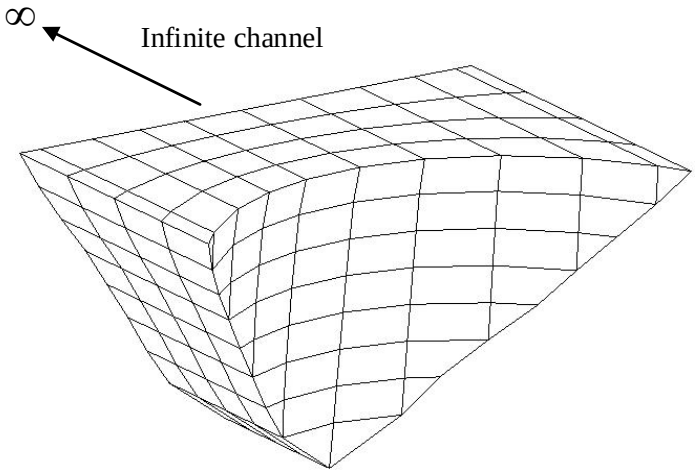


113 meters high

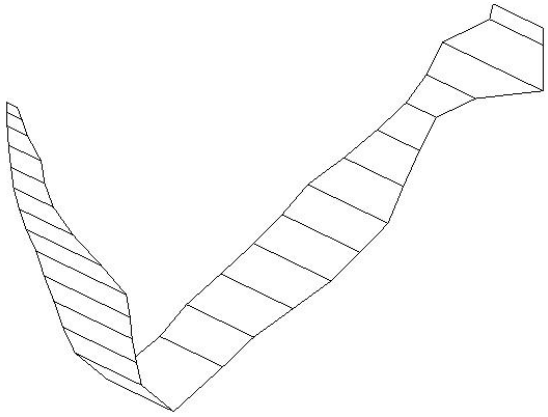
EACD-3D-2008 model for Pacoima dam



Finite element model of dam



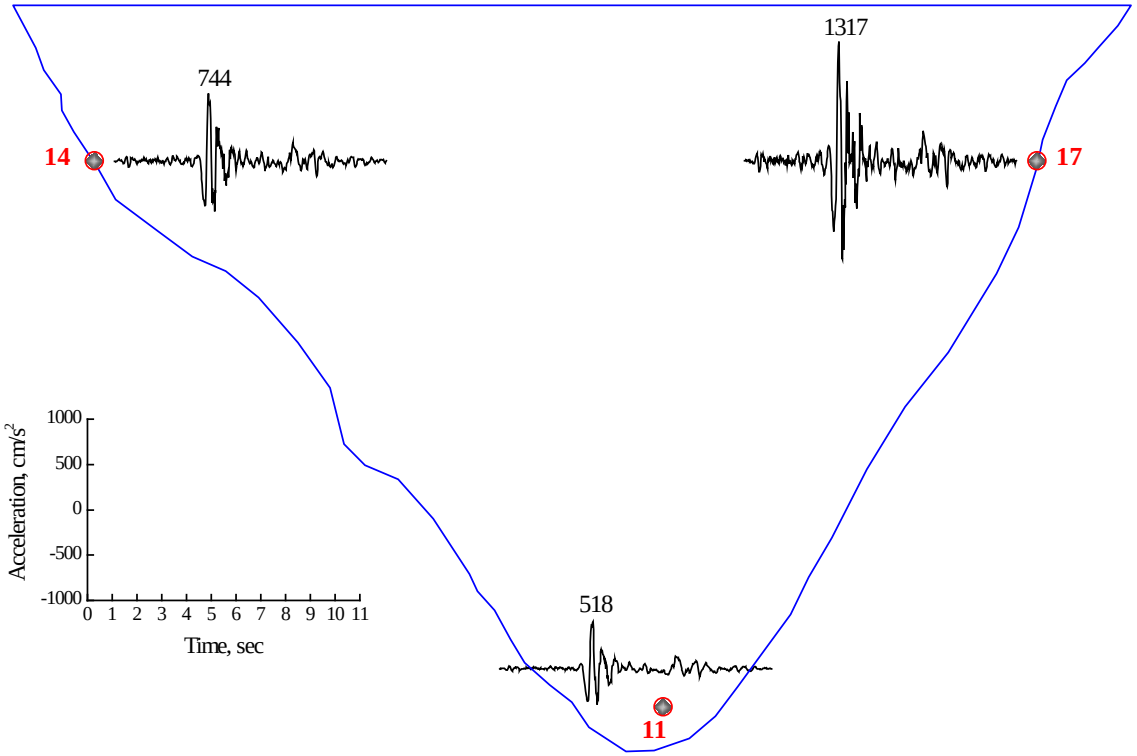
Finite element model of reservoir



Boundary element mesh of interface

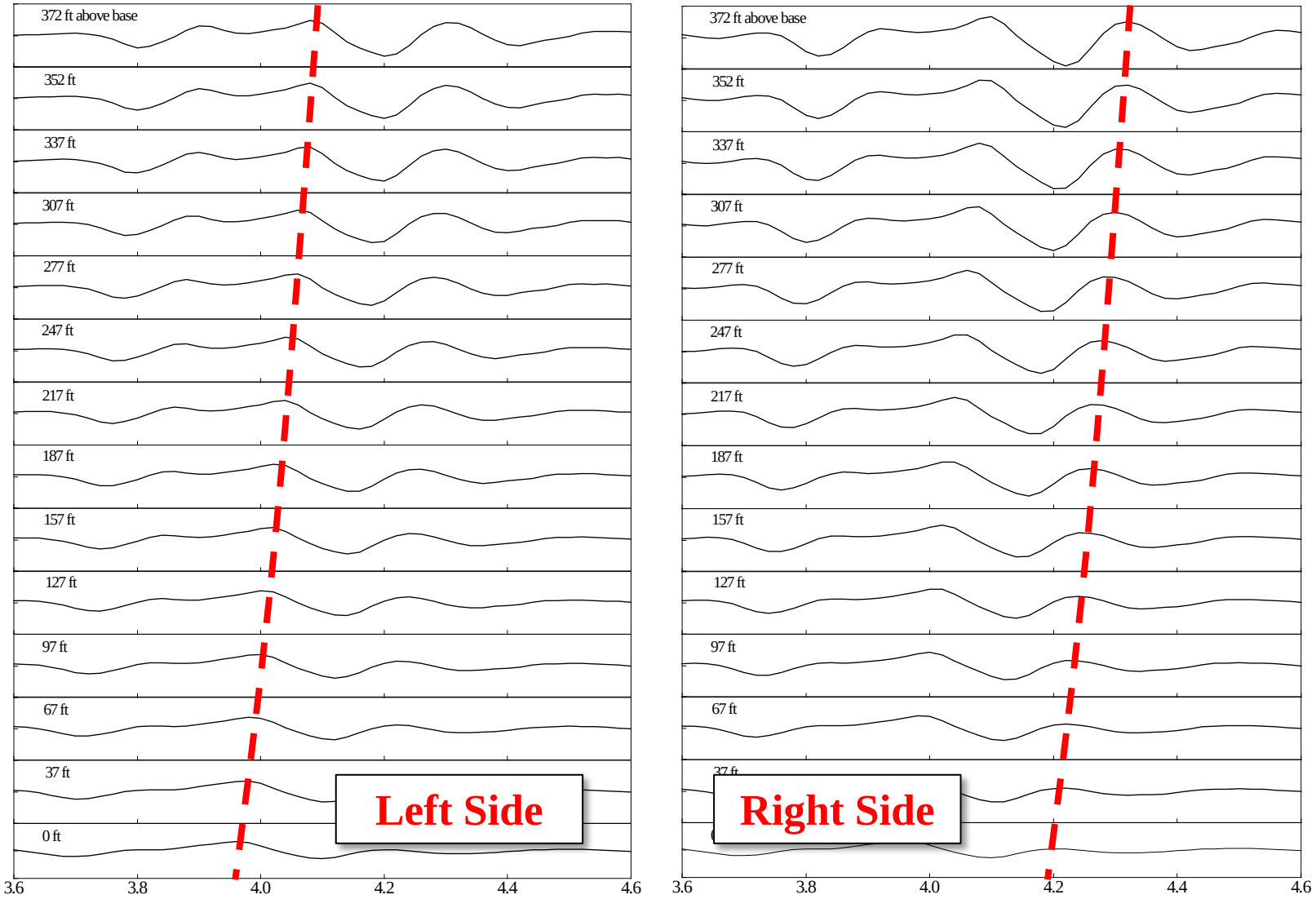
Recorded motions in 1994 Northridge earthquake

Spatial variations of ground motions along the dam-foundation interface is evident.



Accelerations in cross-stream direction (Missing segments estimated by Alves & Hall, 2004)

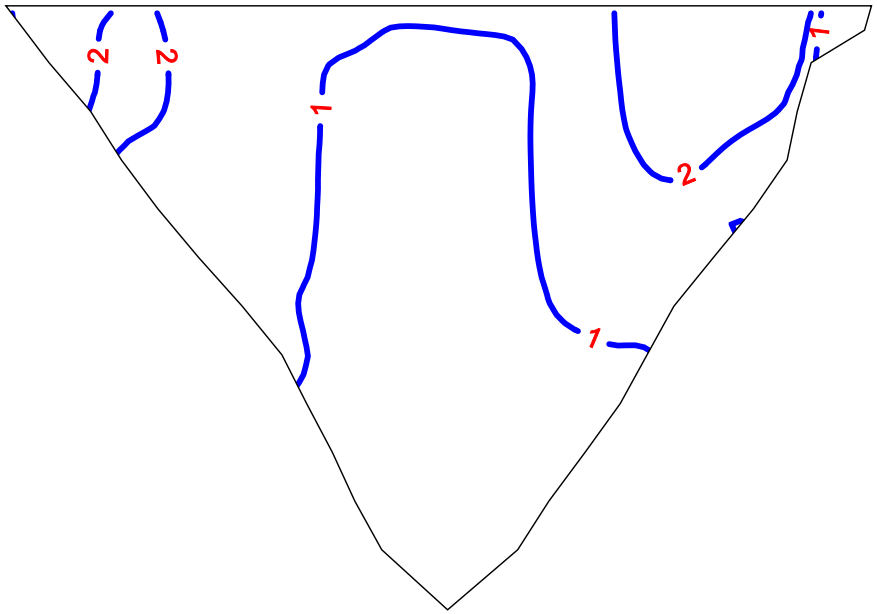
Interpolated spatially-varying Ground Motions



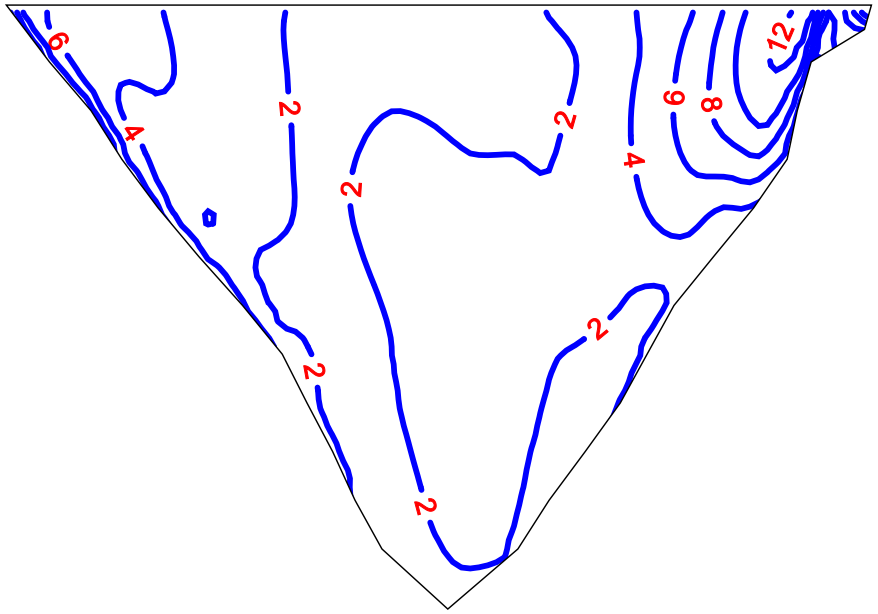
Stream component of ground acceleration at all nodes

Linear seismic analysis in 1994 Northridge EQ

The spatial variations in ground motion had profound influence on dam stresses



(a) Spatially-Uniform: Base



(b) Spatially-Varying Excitation

Arch stresses on downstream face in MPa

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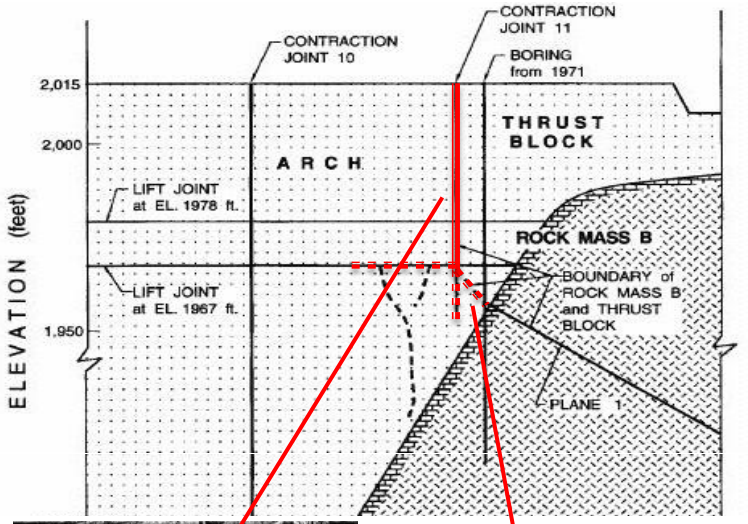
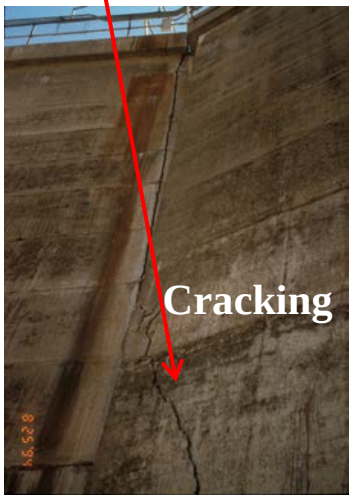
Nonlinear Response of Dams in Strong Earthquakes

Response of the Pacoima dam in 1994 Northridge Earthquake

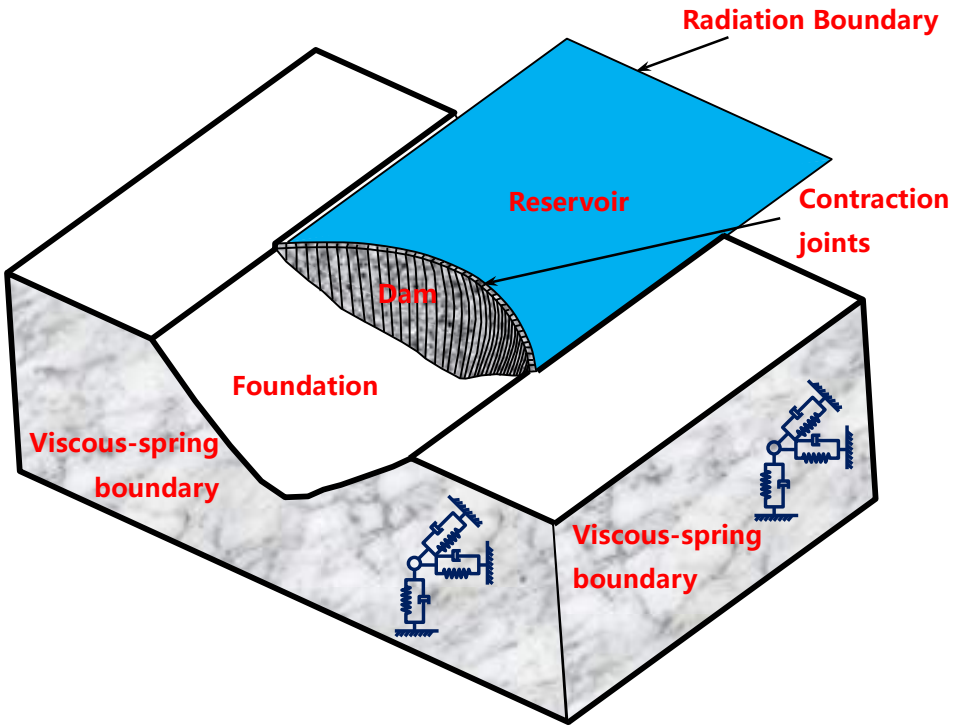




- Some of the joints opened during the earthquake and the thrust block joint remained open after earthquake
- A diagonal crack on the downstream face
- A permanent horizontal offset along the horizontal joint

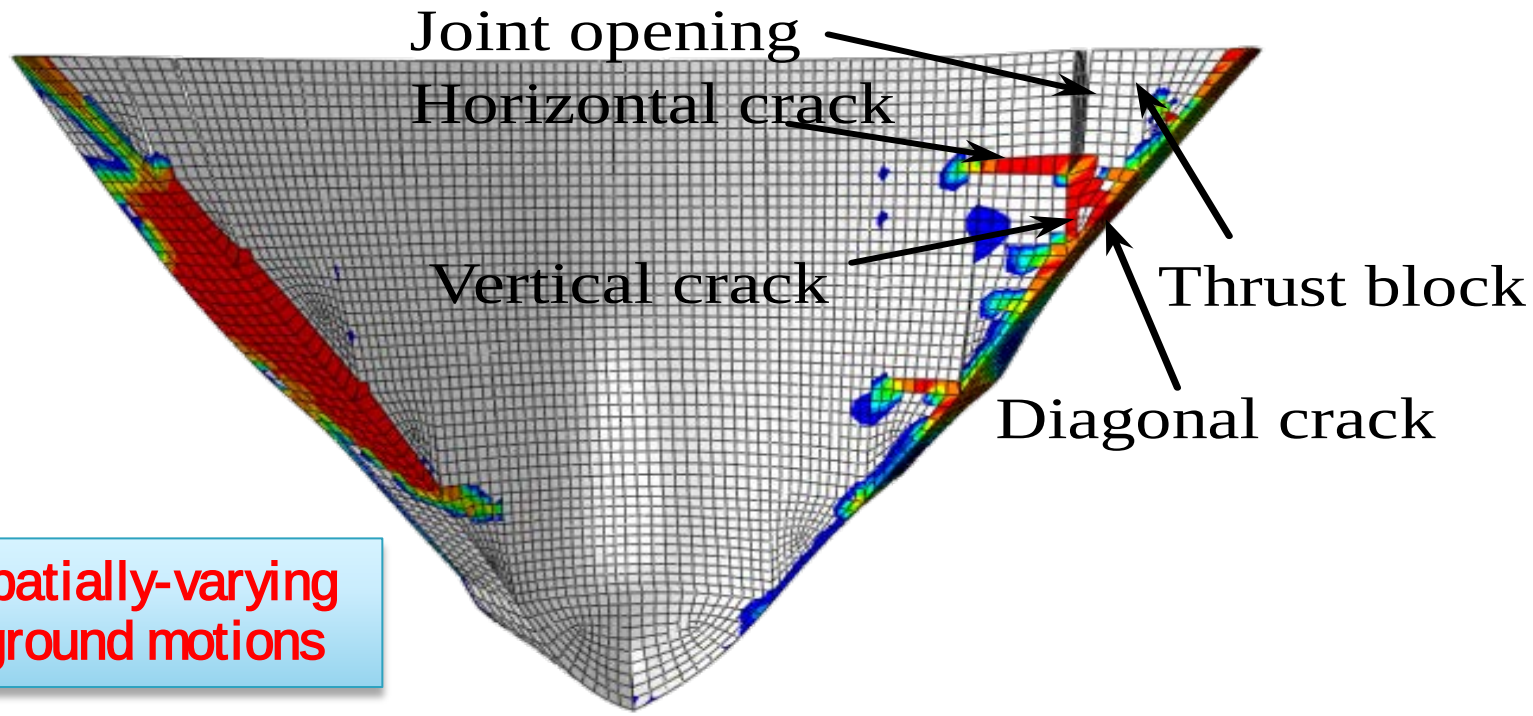
Computational Model

Comprehensive analysis model of dam-water-foundation system



- 3-D semi-unbounded geometry
- Dam-foundation interaction
- Dam-water interaction
- Compressible water
- Opening of contraction joints
- Damage cracking of concrete

Response of Pacoima dam in Northridge EQ



spatially-varying ground motions

- most of the joints are open during the earthquake, and the thrust block joint remains open about 15 mm at the crest level
- The damage extends from the bottom of the thrust block joint in three directions, which agree with the actual cracks observed after the 1994 Northridge earthquake

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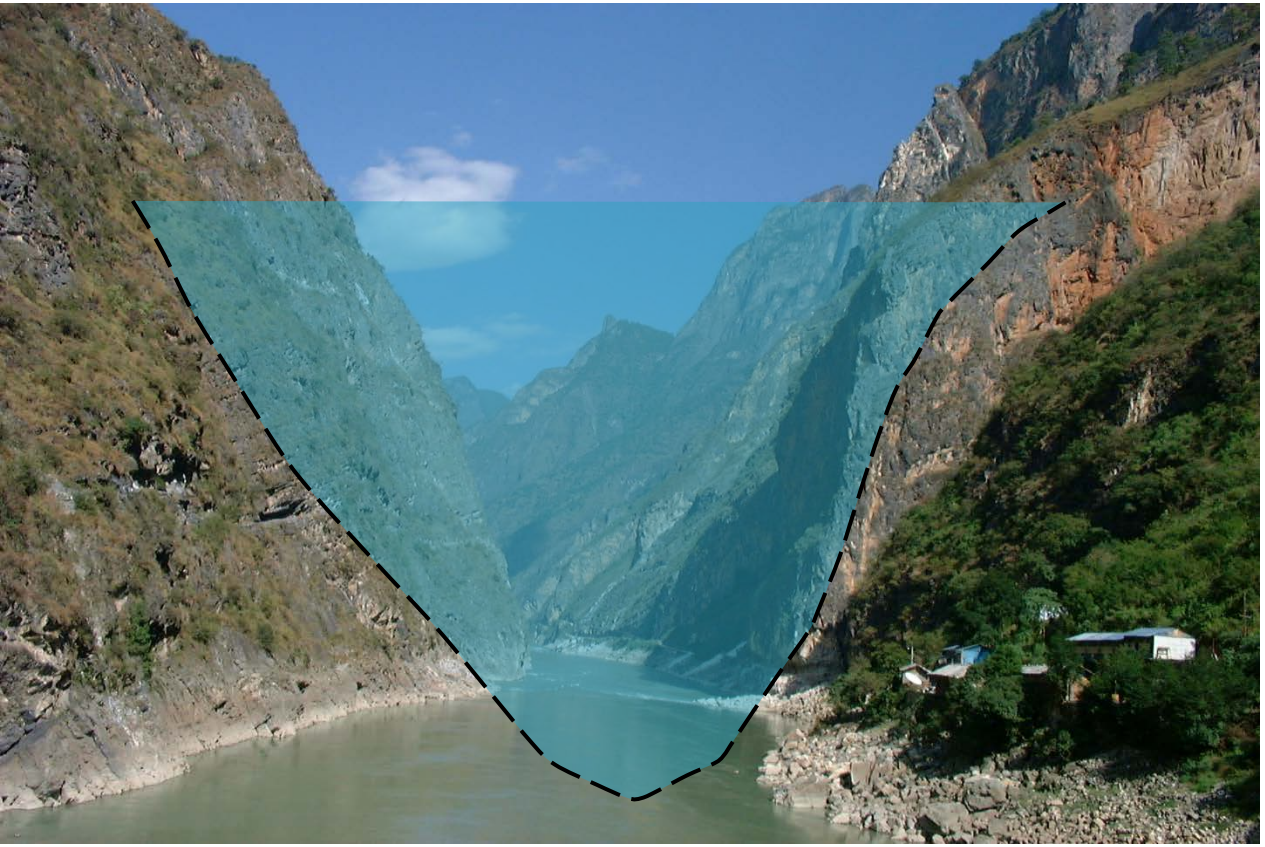
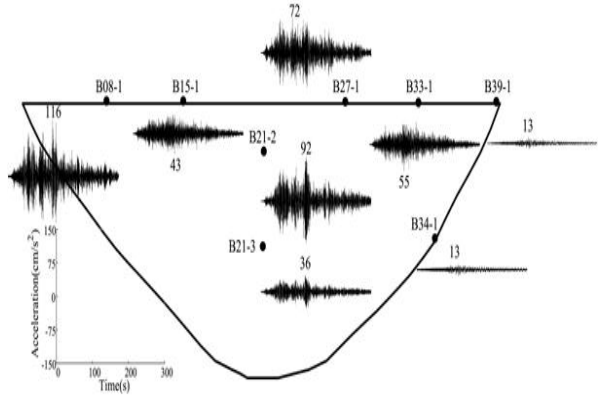
Prediction of Earthquake Ground Motions

- **Effects of source, path, local site have not been well addressed yet**



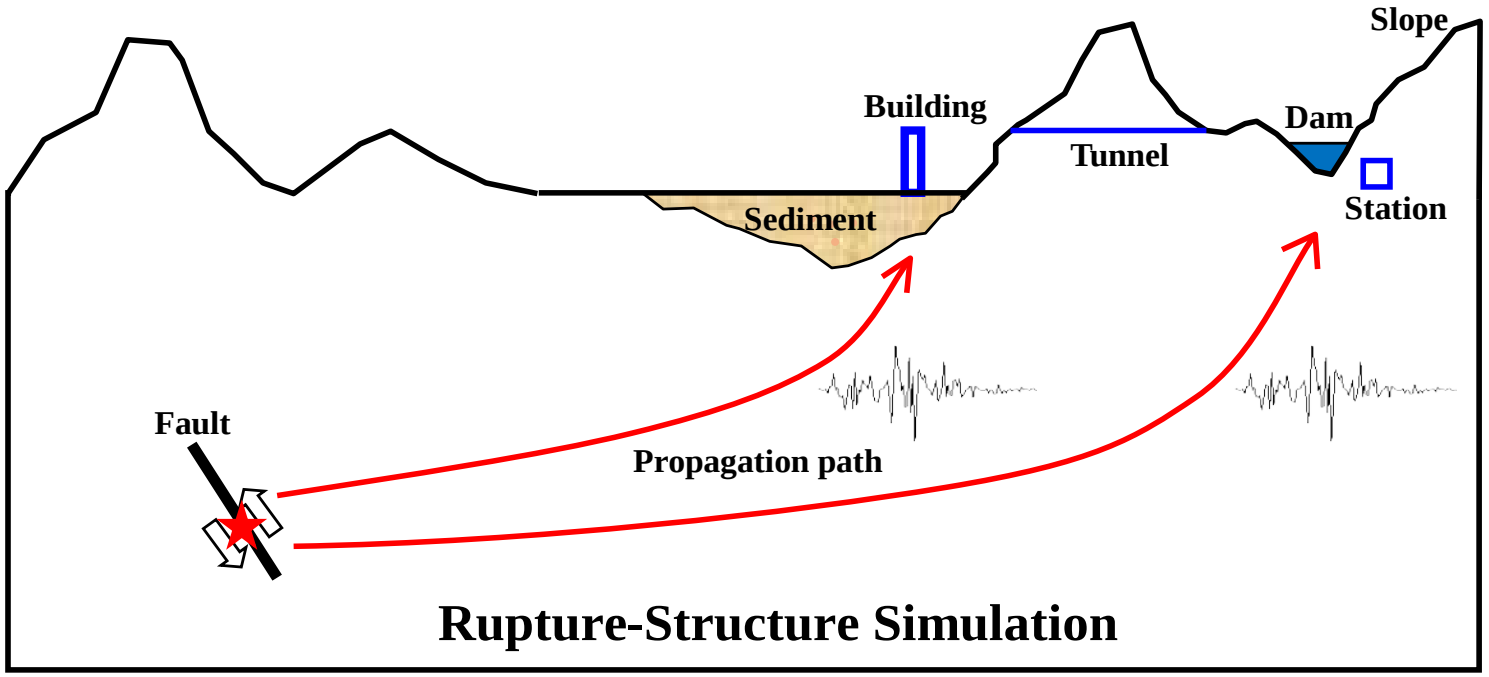


Spatially-varying ground motions are ignored in dam engineering practice

Simulation of ground motion from source to site

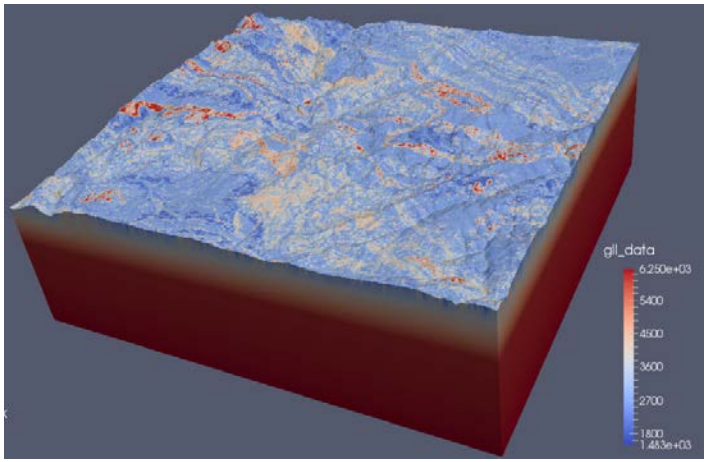
Physics-based numerical simulation: Site-specific

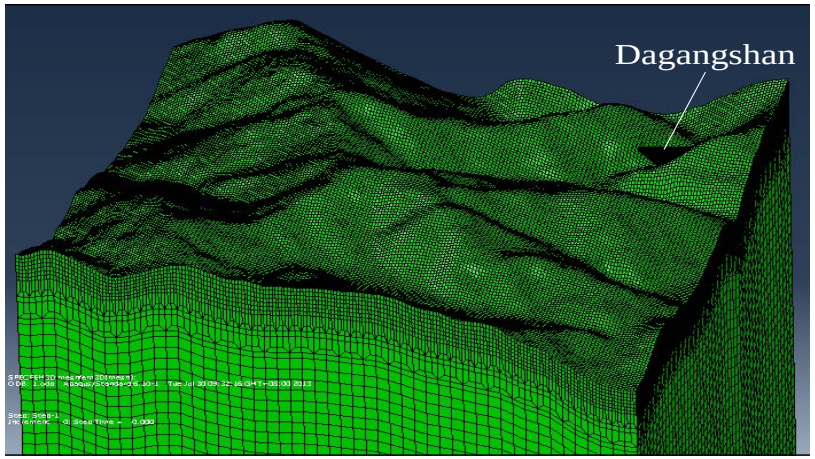
- Faulting mechanism, propagation path, site effects
- Arbitrary conditions and model parameters



Deterministic Numerical Simulation Model

- **Source:** Kinematic model
- **Topography:** Digital Elevation Model (DEM)
- **Propagation media:** Wave velocity model
- **Solution scheme:** Spectral Element Method





Numerical Simulation of Northridge Earthquake

Northridge Earthquake

Date： Jan. 17, 1994

Magnitude： Mw=6.7

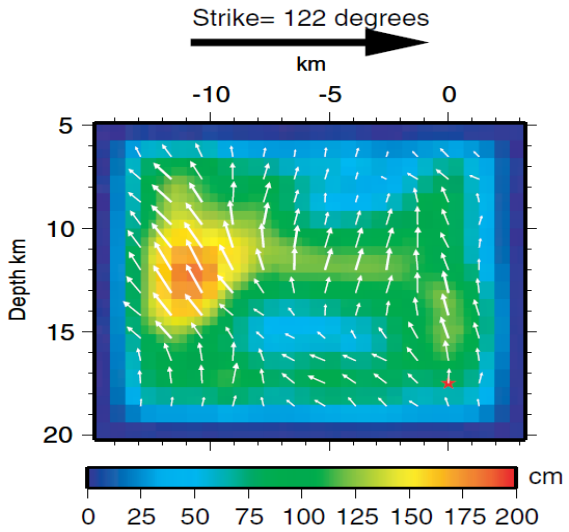
Scale： **56 × 49 × 25km**

Frequency： 0.1~8Hz

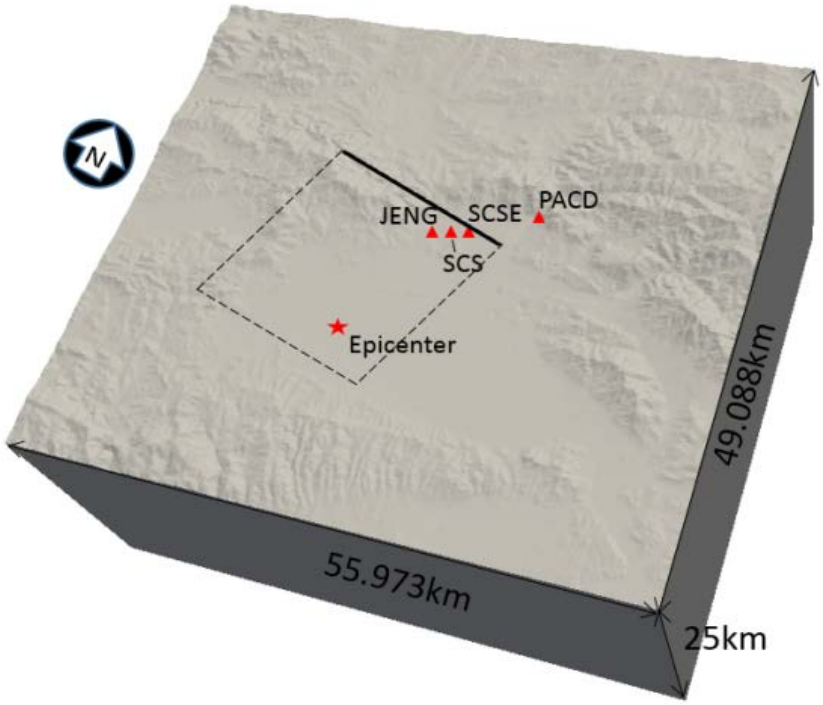
DOFs： **6.62 billion**

Cluster： Cluster System of Tsinghua University

Computation time: 54h (168 processors)

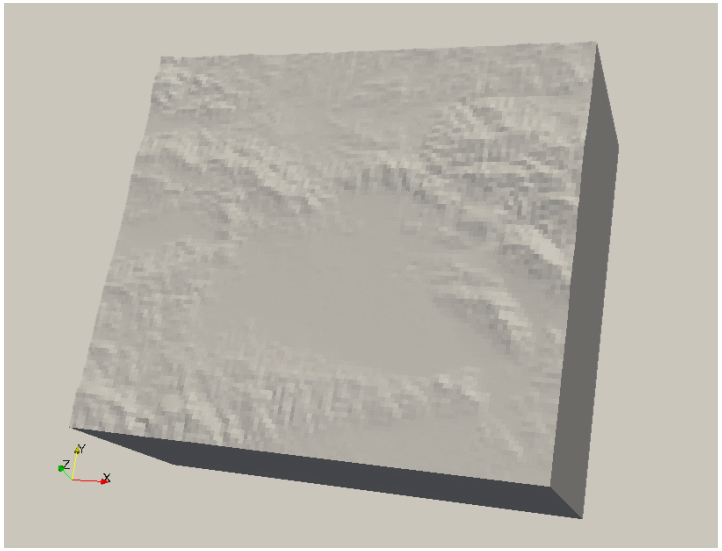


Finite fault with 42 × 42 sub-faults (Krishnan et al. 2006)

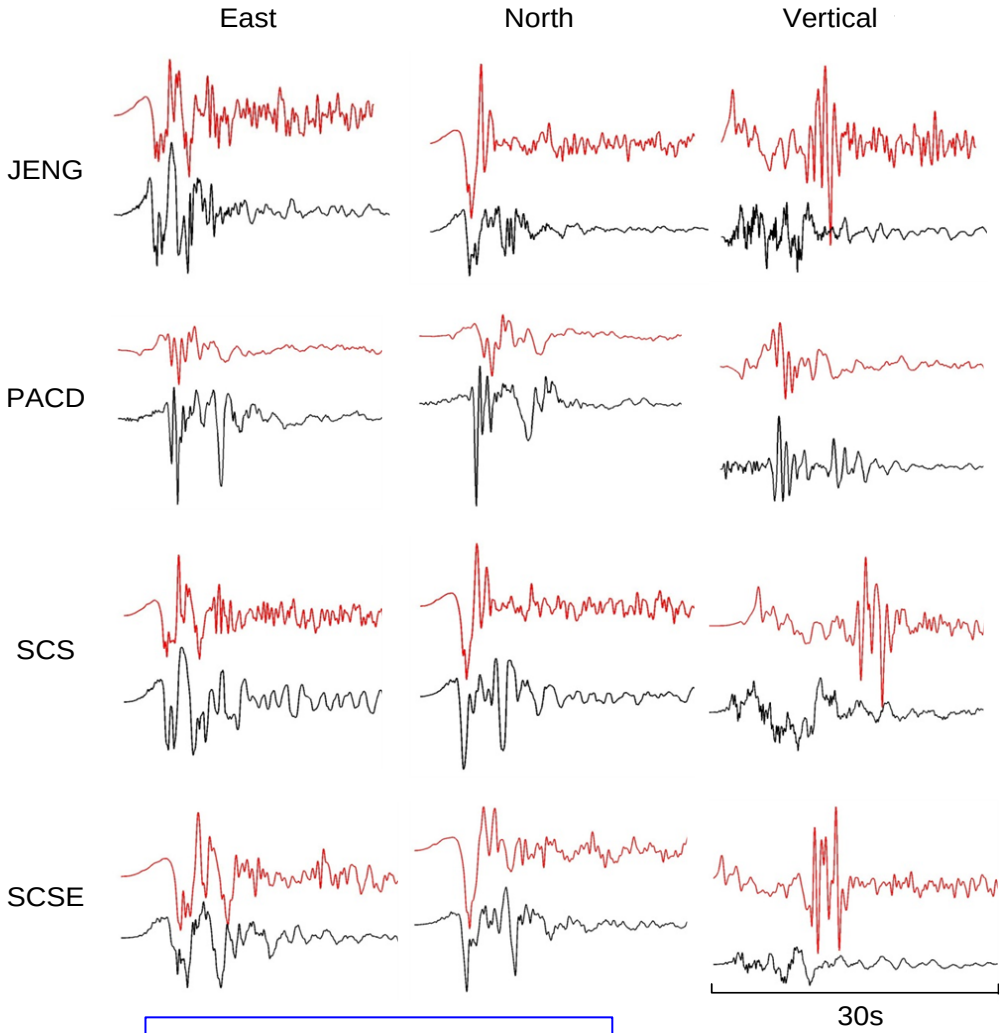


Simulation model with the locations of the fault and stations

Simulation Results—Velocity Time Histories

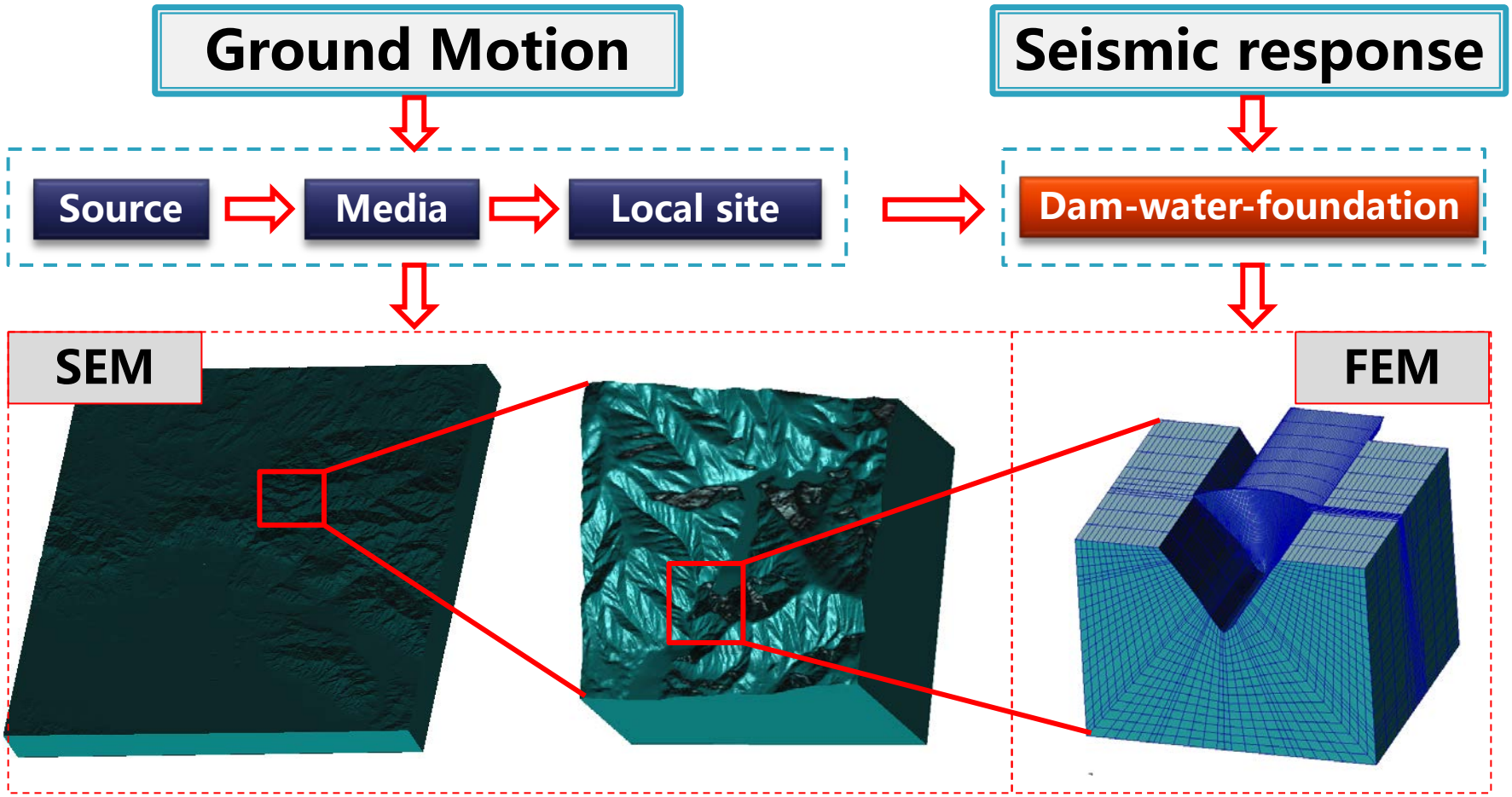


Northridge Earthquake



The synthesized velocity time histories are basically match with the records in the horizontal directions.

Ongoing Work



Conclusions

- Spatial variations in ground motions can have profound influence on the seismic response of arch dams. However, it is typically ignored in the current practice of dam engineering.

- The large-scale numerical simulation may explicitly take into account the faulting mechanism, the propagation path and the site effects, and thus may be a potential solution to define spatial ground motions at dam sites.

Personal Remarks

- It was a great fortune and honor for me having the opportunity of working with Prof. Chopra when I was a visiting scholar at Berkeley from 2007 to 2009. I was deeply impressed by his passion, drive, vision, deep knowledge, and experience.

- Prof. Chopra has been an important influence on my career. I am really grateful for his constant inspiration, support, and encouragement.

All the best wishes to Prof. Chopra for a happy and fruitful new phase of his life!