Linear Response History Analysis of Concrete Dams

Anil K. Chopra

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Complex System Geometry

- Three-dimensional system

- Reservoir: unbounded in the upstream direction

- Foundation: semi-unbounded domain
Standard Finite Element Analysis

- Ignores radiation damping into foundation rock, impounded water, and reservoir bottom sediments
Popular Finite Element Analysis

- Represent hydrodynamics by added mass, i.e., neglect water compressibility
- Assume foundation rock to be massless
- Surface ground motion applied at bottom boundary
Popular Finite Element Analysis

- Convenient to implement in commercial FE software
  - SAP 2000, ABAQUS, FLAC, LSDYNA, …
- But the problem solved is not close to the real problem
- Modeling of dam-water-foundation system inadequate
- Specification of ground motion contradicts recordings
Specification of Ground Motion

- Surface ground motion applied to bottom boundary
  - Known to be incorrect
  - Recorded motions at depth differ from surface motions
Outline

- Modeling of dam-water-foundation interaction
- Spatial variations in ground motion
- Validation of Direct Finite Element Methods
- Discussion Topics
Part I: Modeling of Dam-Water-Foundation Interaction

- Research 1980-1996
- Reclamation Investigations 1996-
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 popular finite element analysis
  - Massless foundation rock
  - Added water mass
- 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
Important to Include Foundation Rock Inertia and Damping (Material and Radiation)

Hoover Dam

Dam-foundation interaction

758 lb/in² (5226 kPa)

Massless foundation rock (flexibility only)

2204 lb/in² (15196 kPa)
Neglecting Foundation Rock Mass and Damping (Material and Radiation)

- 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 upgrading: e.g., Hoover Dam
- Analysis must include dam-foundation rock interaction
Stresses May Be Underestimated by Neglecting Water Compressibility

Monticello Dam

Water compressibility considered

1565 lb/in^2 (10790 kPa)

Water compressibility neglected

1309 lb/in^2 (9025 kPa)
Morrow Point Dam

Stresses May Be Overestimated by Neglecting Water Compressibility

Water compressibility considered

1513 lb/in\(^2\) (10431 kPa)

Water compressibility neglected

2215 lb/in\(^2\) (15272 kPa)
Part II: Spatial Variations in Ground Motion
Pacoima Dam, California, USA
113 meters high
Instrumentation at Pacoima Dam

CDMG Sensor Locations
Recorded Motions at Pacoima Dam
Northridge Earthquake, 1994
Pacoima Dam: Spatial Variations in Interface Motions Are Large
Northridge Earthquake, 1994

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

Arch stresses on upstream face in MPa

Spatially-Uniform: Base

Spatially-Varying Excitation
Pacoima Dam, California, USA
113 meters high
Pacoima Dam, Cracking Visible
Specifying Spatially Varying Ground Motions

- Waves of different types ($P$, $SV$, $SH$, Rayleigh, and Love) incident from different parts of the fault and from different directions.

- Capability to predict spatially varying motions is limited. Impractical at this time.

- Pragmatic approach: assume vertically propagating motions; models variations over height only.
Part III: Validation of Direct Finite Element Methods
Available Open Source Methods
Neither offer a fully satisfactory solution

- **Substructure method** (frequency domain)
  - Special-purpose software
    - EAGD84 / EACD-3D
  - Rigorous (analytical) treatment of unbounded domains
  - Restricted to linear analysis

- **Direct FE method** (time domain)
  - Commercial FE software
    - Abaqus, LS-DYNA, etc.
  - Nonlinear analysis
  - Modeling of unbounded domains and earthquake input not always satisfactory
Direct FE Analysis Procedure

- Finite elements used for all domains
  - Standard solid elements for dam and foundation rock
  - Fluid elements for reservoir
  - Surface elements to model reservoir bottom absorption

- Nonlinear mechanisms can be modeled
  - Concrete cracking
  - Separation and sliding at joints and interfaces
Unbounded Domains Require Special Attention

- Unbounded domains must be truncated and wave-absorbing boundaries applied at these truncations.

- Radiation condition to be satisfied at the boundary:
  - e.g., \( \frac{\partial u}{\partial x} = \frac{1}{c} \frac{\partial u}{\partial t} \) in the \( x \)-direction.
Seismic Input Must Be Specified as ‘Effective Earthquake Forces’ at All Boundaries

- Prescribing displacements at the model truncations will lead to a reflective boundary

- Instead, Effective Earthquake Forces must be applied at the boundaries or in a layer of elements inside of boundaries

- Several formulations are available using “free-field motion” as input, e.g.:
  - Traction input (Zienkiewicz, Wolf)
  - Domain Reduction Method (Bielak et. al.)
Free-Field Motion at Boundaries

Ground motion defined at a control point on foundation-rock surface

“Free-field” motion at all boundaries determined by deconvolution and convolution of surface motion

Effective earthquake forces computed from boundary motion and applied to main model
Morrow Point Dam

- Near symmetric, single centered arch dam located on Gunnison River, CO
- Forced vibration tests have measured damping of 1.5 - 3% for antisymmetric modes and around 4% for symmetric modes
- Analysis parameters chosen to be consistent with experimental data
  - Viscous damping: 1% in dam concrete and 2% in rock
  - Wave reflection coefficient, $\alpha = 0.80$
Comparison of Direct FEM with Substructure Method

Dam-water-foundation rock system: Frequency response functions

Substructure Method
- Semi-unbounded domains
- Free-field GMs at interface

Direct FEM
- Truncated domains with absorbing boundaries
- Effective earthquake forces at all boundaries
Forces on Side Boundaries Should Not Be Ignored

2D dam-foundation rock system: Frequency response functions

Observations:
- Dam response is in significant error when excluding forces at side boundaries
- Errors arise because side boundaries “drains” energy as the seismic waves propagates upward
Accuracy of Direct FEM

- Dependent on:
  - Modeling of wave absorbing boundaries
  - Computation and application of effective earthquake forces
Discussion Topics

- Mass of foundation rock should be modeled
- Compressibility of water should be included
- Spatial variations in ground motion around the canyon should be considered
- Direct FEM must be validated against independent analysis