Seismic Analysis of Concrete Dams

Workshop

2017 USSD Annual Conference

April 6-7, 2017

Session #6 – Response History Analyses of Concrete Dams with Nonlinearities

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Arch Dams
Damage/NL Threshold

DCR < 1, Minor or No Damage
• Nearly linear response

DCR < 2, Damage Acceptable If
• Overstress < 20%
• CID < 0.4 (2-DCR)

DCR > 2, CID > Threshold
• Damage is Significant
• May need nonlinear analysis or retrofit
Gravity Dams
Damage/NL Threshold

**DCR < 1, Minor or No Damage**
- Nearly linear response

**DCR < 2, Damage Acceptable If**
- Overstress < 15%
- CID < 0.3(2-DCR)

**DCR > 2, CID > Threshold**
- Damage is Significant
- May need nonlinear analysis or retrofit
Nonlinear Analysis
Purpose and Need

- Quantify damage (NL response)
  - Joint opening / cracking
  - Sliding and toppling
  - Compression and shear failure due to load redistribution
  - Coupled dam-thrust block and dam-rock wedge stability
- Assess credibility of PFMs
- Design for high seismic demands
- Reconcile numerical predictions and observed performance of dams
  - Even a minute joint opening diminishes high tensile stresses
  - Joint opening and cracking redistribute loads
  - Nonlinear response affects path, magnitude, and direction of loads
## Methods

### Explicit vs. Implicit Solution

<table>
<thead>
<tr>
<th>Explicit:</th>
<th>Implicit:</th>
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</thead>
<tbody>
<tr>
<td>• Direct solution</td>
<td>• Iterative solution</td>
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<tr>
<td>• Decoupled: efficient, fast</td>
<td>• Matrix factorization</td>
</tr>
<tr>
<td>• Conditionally stable</td>
<td>• Unconditionally stable</td>
</tr>
<tr>
<td>• Many small time steps</td>
<td>• Few large time/load steps</td>
</tr>
<tr>
<td>• Equilibrium?</td>
<td>• More demand on memory</td>
</tr>
<tr>
<td>• Energy balance!</td>
<td>• Equilibrium!</td>
</tr>
<tr>
<td><strong>Application:</strong></td>
<td>• Convergence?</td>
</tr>
<tr>
<td>• Highly nonlinear events</td>
<td></td>
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<tr>
<td>• Impact, crash, …</td>
<td></td>
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<tr>
<td>• Pressure wave propagation effects</td>
<td><strong>Application:</strong></td>
</tr>
<tr>
<td></td>
<td>• Structural static/dynamics</td>
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<td>• Low frequency response</td>
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<td>• Strength analysis</td>
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Methods
Discrete vs. Constitutive Modeling

- **Discrete**
  - Plain concrete
  - Known discontinuities
  - Lightly RC structures

- **Constitutive**
  - RC structures
  - Outlet towers
  - Spillway piers
Nonlinear Analysis of Concrete Dams
Discrete Modeling
Nonlinear Mechanisms
Discrete Modeling (local nonlinearity)

- Opening and sliding at CJ
  - Niwa & Clough’s tests
  - Pacoima Dam (1971 and 1994)

- Cracking and sliding at lift joints
  - Controlled by $f'_{t}$ of lift joints
  - Vulnerable to increased cantilever stresses
  - May lead to movements of isolated blocks

- Cracking and sliding at foundation contact
  - Usually occurs in fractured/jointed rock below interface
  - May lead to sliding of monoliths and thrust blocks (if present)

- Movements of rock wedges formed by rock discontinuities
Nonlinear Mechanisms
Discrete Modeling (local nonlinearity)

- Cracking/sliding at base
- Cracking/sliding at lift joint
- Opening/sliding at CJs
- Movements at rock wedges

Courtesy of USBR
Nonlinear Modeling

• Dam
  • Linear 3D solids
  • Nonlinear joints

• Foundation Rock
  • Linear 3D solids
  • Mass inertia and damping
  • Nonlinear joints / wedges

• Impounded Water
  • Fluid element
  • Radiation damping
Arch Dam Nonlinear Model

Nonlinear Mechanisms

• All contraction Joints
  • Gap-friction contacts

• Concrete-rock Interface
  • Tie-break contacts

• Lift Joints
  • Tie-break contacts

\[
\left( \frac{\sigma_n}{f_t'} \right)^2 + \left( \frac{\sigma_s}{c} \right)^2 \geq 1
\]
Shear Keys
Approximate Modeling

(Noble and Nuss, 2004)
Compliant Seismic Input

Seismic Analysis of Concrete Dams
Topographic Effects
Amplitude and waveform changes along canyon wall
Model Validation

• Start with linear analysis
• Use contacts to incorporate nonlinearity
• Test contacts to verify their behavior and application
• Analyze for individual static loads to check the model
• Analyze for combined static loads to correlate with existing condition / measured responses
• Analyze for seismic loads and ensure results are reasonable, logical, and explicable
• Consider independent nonlinear evaluations and parameter sensitivity studies
Acceptance Criteria
Arch dam nonlinear analyses

• Contraction joint (CJ) opening at the crest should be less than depth of shear keys
• Tensile stresses away from CJs < $f'_t$ of parent concrete
• Joint opening and cracking increase compressive stresses. Magnitude of compressive stresses < $f'_c$
• Shear keys demand-capacity ratio (DCR) < 1
• Non-recoverable movements and post-earthquake stability
Nonlinear Analysis of RC Structures
Constitutive Modeling
Reinforced Concrete Tension Response

(Adebar, 2008)
Reinforced Concrete Exhibits Distributed Crack Pattern

(a) Horizontal Cracks (b) Diagonal Cracks

(Hoshikuma and Priestly, 2000)
Factors Involved in Concrete Modeling

- Strain softening
  - Post-peak strength reduction and degradation of elastic modulus on unloading

- Stiffness degradation
  - Under cyclic loading, concrete tends to lose its stiffness

- Volume dilatation
  - Concrete tends to expand under compression load

- Tensile response
  - Tensile strength is low (≈ 10% $f'_c$) and concrete behaves in a brittle manner

- Tension stiffening
  - Refers to capacity of the intact concrete between neighboring cracks to carry a limited amount of tension
Modeling of RC Outlet Towers
Crack prediction for definitive performance assessment

Winfrith Concrete Model

Kinematic Hardening Plasticity for Steel Rebars
Concrete Principal Tensile Stresses

ChiChi

Landers

Tabas

ksi

5.000e-01
4.750e-01
4.500e-01
4.250e-01
4.000e-01
3.750e-01
3.500e-01
3.250e-01
3.000e-01
2.750e-01
2.500e-01
2.250e-01
2.000e-01
1.750e-01
1.500e-01
1.250e-01
1.000e-01
7.500e-02
5.000e-02
2.500e-02
0.000e+00
Steel Principal Tensile Stresses

ChiChi

Landers

Tabas

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Concrete crack distribution for Ci-Chi earthquake record

- All Cracks
- Cracks > 0.002 in
- Cracks > 0.006 in
- Cracks > 0.01 in But < 0.02 in
Discrete Modeling
Summary/Questions?

• Is it reasonable to assume that nonlinearities are limited to joint opening and cracking/sliding at lift joints and foundation contact?
• Should significant rock wedges impacting dam stability be modeled coupled with the dam?
• Are there other discontinuities that should be considered?
• While zero tension resistance seems reasonable for CJs, what tensile strength is appropriate for foundation contact?

• While gap-friction contact seems appropriate for CJs, do you agree more advanced contacts such as tie-break with failure criteria would be more appropriate for lift joints and foundation interface to avoid pre-mature cracking/sliding?
Is the CJ opening of less than shear key depth at the crest reasonable?

What if despite CJ opening high tensile stresses remain within the blocks. How should they be handled?

The compression-only cross beams simulating shear keys are reasonable for rectangular and steep-angle keys. How should trapezoid keys be treated, if openings are significant?
Discrete Modeling

Summary/Questions?

• What if compression and shear check do not meet the criteria?
• Is the criterion that permanent displacement should be small not to fully block drain holes reasonable?
• Are there other ways to validate a nonlinear analysis?