Seismic response and numerical modelling of earthfill dams

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Seismic response of earthfill dams

The “Ambraseys legacy” in seismic response of dams

- Established analytically the transverse dynamic response of homogeneous dams
- Extended the shear beam method to account for truncated wedge shape, rectangular canyon and underlying elastic layer
- Sliding block analysis to calculate permanent seismically induced displacements
- Detailed investigation of numerous case studies of dam performance during earthquakes

First 2 natural transverse modes of vibration (Ambraseys 1960a, BBSA, Vol.50)

Ambraseys & Sarma (1967)
Ambraseys & Menu (1988)
Case study: La Villita dam, Mexico

Project construction: 1964-1968
Embankment construction: 1967
Reservoir Impounding: 1968

(Google Earth, 2010)

Pelecanos (2013)

US - DS cross-section
Case study: La Villita dam, Mexico

- Experienced a number of seismic events of varying intensity
- No severe damage, but suffered significant deformations
  - Crest settlement
  - Slope movements
- Available measurements:
  - settlement history
  - acceleration recordings
Case study: La Villita dam, Mexico

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Ms</th>
<th>Epicentral Distance (km)</th>
<th>PGA (g) (rock)</th>
<th>PGA (g) (crest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ1</td>
<td>11/10/1975</td>
<td>4.5</td>
<td>52</td>
<td>0.07</td>
<td>0.36</td>
</tr>
<tr>
<td>EQ2</td>
<td>15/11/1975</td>
<td>5.9</td>
<td>10</td>
<td>0.04</td>
<td>0.21</td>
</tr>
<tr>
<td>EQ3</td>
<td>14/3/1979</td>
<td>7.6</td>
<td>121</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>EQ4</td>
<td>25/10/1981</td>
<td>7.3</td>
<td>31</td>
<td>0.09</td>
<td>0.43</td>
</tr>
<tr>
<td>EQ5</td>
<td>19/11/1985</td>
<td>8.1</td>
<td>58</td>
<td>0.12</td>
<td>0.76</td>
</tr>
<tr>
<td>EQ6</td>
<td>21/11/1985</td>
<td>7.5</td>
<td>61</td>
<td>0.04</td>
<td>0.21</td>
</tr>
</tbody>
</table>

(Elgamal et al, 1992)

Bedrock motion
Case study: La Villita dam, Mexico

<table>
<thead>
<tr>
<th>Material</th>
<th>Cohesion</th>
<th>Angle of shearing resistance</th>
<th>Shear modulus</th>
<th>Stiffness degradation/damping curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Core</td>
<td>5</td>
<td>25 (degrees)</td>
<td>spatially varying</td>
<td>Vucetic &amp; Dobry (1991)</td>
</tr>
<tr>
<td>Sand Filters</td>
<td>0</td>
<td>35 (degrees)</td>
<td>spatially varying</td>
<td>Seed et al. (1986)</td>
</tr>
<tr>
<td>Rockfill</td>
<td>5</td>
<td>45 (degrees)</td>
<td>spatially varying</td>
<td>Rollins et al. (1998)</td>
</tr>
<tr>
<td>Alluvium</td>
<td>5</td>
<td>35 (degrees)</td>
<td>200 (MPa)</td>
<td>Rollins et al. (1998)</td>
</tr>
</tbody>
</table>

Stiffness variation for the clay core

Material properties based on Elgamal (1992)
Case study: La Villita dam, Mexico

Cyclic nonlinear model combined with a Mohr-Coulomb failure criterion

\[ J = E_d G_{\text{max}} \left[ 1 - \alpha \ln \left( 1 + \frac{G_{\text{max}} |E_d|}{J_L} \right)^R \right] \]

Taborda (2011)

(Puzrin & Burland 2000)
Case study: La Villita dam, Mexico

Coupled consolidation, plane strain analyses with ICFEP

Static analysis
- Layered construction
- Water impoundment
- Consolidation up to the 1st seismic event (6.5 years)

Dynamic analysis
Case study: La Villita dam, Mexico

Static analysis results: after impoundment

Flow net in the clay core

Pore water pressure distribution
Case study: La Villita dam, Mexico

Static analysis results: Crest settlement during impoundment and consolidation

![Graph showing measured and computed settlement over time.](image-url)
Case study: La Villita dam, Mexico

Dynamic analysis results: Response spectra ($\xi=5\%$) at the crest

![Graphs showing spectral acceleration vs. period for EQ2 and EQ5 earthquakes.](image)
Case study: La Villita dam, Mexico

Canyon effects? Hatanaka (1952), Ambraseys (1960)

Dams built in narrow canyons have a stiffer response than dams built in wide canyons

Dakoulas & Gazetas (1987)
Case study: La Villita dam, Mexico

Canyon effects?

Analyses with stiffer properties

Dynamic analysis results: Response spectra ($\xi=5\%$) at the crest
Case study: La Villita dam, Mexico

Canyon effects?

Analyses with stiffer properties

Dynamic analysis results: Response spectra ($\xi=5\%$) at the crest
Case study: La Villita dam, Mexico

Asymmetry in the crest response

Asymmetry observed:
- Only in the crest response (not at bedrock or toe records)
- More pronounced in the strong events, i.e. EQ3, EQ4, EQ5

Postulation:
The high positive peaks are a consequence of a localised slip
(Elgamal et al 1990)
Case study: La Villita dam, Mexico

Asymmetry in the crest response

Gazetas & Uddin (1994)

Equivalent linear FE analysis with pre-defined slip surface using interface elements
Case study: La Villita dam, Mexico

Vectors of accumulated displacement - end of EQ5

Stress level – end of EQ5

CONTOUR LEVELS
- A  0.7
- B  0.8
- C  0.9
- D  0.95
- E  1.0
Case study: La Villita dam, Mexico

Filtered recorded motion at crest for f>4HZ
Case study: La Villita dam, Mexico

Effects of hydrodynamic pressures

Interface elements with normal stiffness and nominal shear stiffness

Hydrostatic stress distribution

Pelecanos et al (2013)
COGE, Vol. 53, pp.68-82

Kw=2.2 GPa
Case study: La Villita dam, Mexico

Effects of hydrodynamic pressures

Distribution of peak hydrodynamic pressure on the upstream face

EQ2

EQ5
Case study: La Villita dam, Mexico

Effects of hydrodynamic pressures

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$F_{st}$ (kN)</th>
<th>$F_{dyn}$ (kN)</th>
<th>$F_{dyn}/F_{st}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ2</td>
<td>14303</td>
<td>618</td>
<td>4.3</td>
</tr>
<tr>
<td>EQ5</td>
<td>14303</td>
<td>1605</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Vertical profiles of max displacement & acceleration
Conclusions

- Case studies of recorded ground motion in dams are scarce and are very useful for the validation and improvement of numerical modelling procedures.

- Plane strain analyses can lead to a softer dam response in narrow canyons. In the La Villita case this led to an underestimation of the seismic response.

- The numerical model captured well the acceleration response of the dam, but did not indicate any localised failure for EQ5. This could be due to the existence of a slip surface within the downstream slope as well as the simplicity of the adopted constitutive model.

- A numerical procedure has been developed for the accurate simulation of hydrodynamic pressures. However this study suggests that their impact on the overall response is not significant.

Thank You!