Seismic Analysis of Concrete Dams
Workshop
2017 USSD Annual Conference
April 6-7, 2017
Session 1

Case Histories and Seismic Potential Failure Modes

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“Shaken, But Not Stirred - Earthquake Performance of Concrete Dams”

By:
Larry K. Nuss, P.E.
  Structural Engineer, Nuss Engineering (retired from Bureau of Reclamation)
Kenneth D. Hansen, P.E.
  Consulting Engineer
Norihisa Matsumoto
  Advisor, Japan Dam Engineering Center
  Executive Director, Japan Commission on Large Dams

Additional Information provided by:
Gabriela M. Lyvers
  Structural Engineer, Louisville, KY, US Army Corps of Engineers
Introduction

Highlights:

• 19 Dams Shaken More Than 0.3 g PHGA

• First two RCC dams subjected to high accelerations

• First “failure” of a concrete dam due to fault rupture below structure

• Three dams experienced greater than 2.0 g acceleration at the crest

• Two dams shaken by two significant earthquakes

• Performance of concrete dams subjected to 2011 Tohoku Earthquake
Introduction (Dams Shaken More Than 0.3 g)

Concrete Gravity Dams
- Lower Crystal Springs Dam, USA (1906 *) – curved gravity dam,
- Koyna Dam, India (1967),
- Williams Dam, USA (1989),
- Bear Valley Dam, USA (1992; 2) – straight gravity (after modification),
- Gohonmatsu Dam, Japan (1995),
- Shih Kang Dam, Taiwan (1999) – multiple-bay gravity spillway,
- Mingtan Dam, Taiwan (1999),
- Kasho and Uh Dam, Japan (2000),
- Takou and Miyatoko Dam, Japan (2011).

Concrete Arch Dams
- Gibraltar Dam, USA (1925),
- Pacoima Dam, USA (1971, 1994),
- Ambiesta Dam, Italy (1976),
- Rapel Dam, Chile (1985, 2012),
- Techi Dam, Taiwan (1999),
- Shapai Dam, China (2008) – RCC arch.

Concrete Buttress
- Hsinfengkiang Dam, China (1962),
- Sefid Rud Dam, Iran (1990)

* Earthquake date
<table>
<thead>
<tr>
<th>Dam Type</th>
<th>Number</th>
<th>Damage to Dam</th>
<th>No Damage to Dam</th>
<th>Minor Project Damage</th>
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<tbody>
<tr>
<td>A – Gravity</td>
<td>10 (1 RCC)</td>
<td>1</td>
<td>5</td>
<td>4</td>
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<tr>
<td>B – Arch</td>
<td>6 (1 RCC)</td>
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<td>2</td>
<td>3</td>
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<tr>
<td>C – Buttress</td>
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<td>0</td>
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<tr>
<td>D Spillway</td>
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<td>0</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>19</strong></td>
<td><strong>5</strong></td>
<td><strong>7</strong></td>
<td><strong>7</strong></td>
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</tbody>
</table>
Lower Crystal Springs Dam (USA)

Curved Gravity Dam
Completed 1890
Interlocking concrete blocks
20 miles south of San Francisco
Height 154 feet
Crest width 25 feet
Crest length 600 feet

San Francisco Earthquake, M 8.3
April 18, 1906

0.25 miles from San Andres Fault
Right lateral slip about 8 feet at fault

Peak acceleration
Estimated 0.52 to 0.68 g
Lower Crystal Springs Dam (USA)

“Not the slightest crack in the dam”
Koyna Dam (India)

Straight Gravity Dam
- Completed: 1963
- Height: 338 feet
- Crest width: 48.5 feet
- Crest length: 2800 feet

Koyna Earthquake, M 6.5
- Date: Dec 11, 1967
- Epicentral distance: 8 miles
- Peak Acceleration:
  - Lower gallery: 0.49 g u/s
  - 0.63 g cc
  - 0.34 g v
Koyna Dam (India)

Rehabilitation
Buttresses added to downstream face
Epoxy resin in major cracks
Taller monoliths prestressed to 70 feet below major cracks

Damage
18 horizontal cracks on upstream
7 horizontal cracks on downstream
Cracks near change in downstream slope

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Koyna Dam (India)

EAGD linear elastic analysis showed tensile stresses exceeded tensile strength
Bear Valley Dam (USA)
Gravity Dam (after modification)

- Completed: 1912
- Modified: 1988
- Location: Southern California
- Height: 92 feet
- Crest width: _ feet
- Crest length: 360 feet

Landers Earthquake, M 7.4
- Date: June 28, 1992
- Distance: 28 miles
- Peak Acceleration: 0.18 g Horiz, 0.08 g Vertical

Bear Valley Earthquake, M6.6
- Date: June 29, 1992
- Distance: 9 miles
- Peak Acceleration: 0.57 g Horiz, 0.21 g Vertical
Bear Valley Dam (1988 Modification)

No damage to the dam after earthquakes.

Only slight displacement of the girders on the highway bridge located at the crest of the dam.
Bear Valley Dam (USA)

Currently crest bridge is being removed and new bridge being built downstream.

Photographs courtesy of Mark Schultz
Gohonmatsu Dam (Japan)

Gravity Dam
Completed: 1900
Rubble concrete
Height: 108 feet
Crest width: _ feet
Crest length: 361 feet

Kobe Earthquake, M 7.2
Date: January 17, 1995
Distance: 9.3 miles
Peak Acceleration: 0.83 g

Only damage was a hairline crack in the concrete capping of the parapet on the crest of the dam.
### Shih Kang Dam (Taiwan)

**Gravity Spillway Dam (18 bays)**
- Completed: 1977
- Height: 70 feet
- Crest length: 1171 feet

**Chi Chi Earthquake, M 7.6**
- Date: Sept 21, 1999
- Distance: Zero
- Peak Acceleration:
  - Recorded 0.3 miles away
  - Horizontal: 0.51 g
  - Vertical: 0.53 g
- Displacement:
  - Uplifted left side of dam: 36 ft
  - Uplifted right side of dam: 7 ft
  - Diagonal offset: 23 ft
Shih Kang Dam (Taiwan)

Photograph compliments of Robin Charlwood
Shih Kang Dam (Taiwan)

Reservoir release of 3500 to 7000 ft³/sec

Bridge girders all came off their bearings

6 inoperable gates

Gates did not fail downstream
Cracking:
along ogee crest
along lift lines
at point of changes in geometry

Dam separated from foundation
Mingtan Dam (Taiwan)

Gravity Dam
- Completed: 1990
- Height: 269 feet

Chi Chi Earthquake, M 7.6
- Date: Sept 21, 1999
- Distance: 7.5 miles
- Peak Acceleration: PHGA (est.) 0.4 to 0.5 g

No reported damage in dam body
Kasho (Kasyo) Dam (Japan)

Gravity Dam
- Completed: 1989
- Height: 152 feet
- Crest width: _ feet
- Crest length: 571 feet

Western Tottori Earthquake, M 7.3
- Date: Oct 6, 2000
- Epicentral distance: 3 miles
- Numerous aftershocks up to M 7

Peak Acceleration
- Horizontal: 0.54 g
- Vertical: 0.49 g
- At crest: 2.09 g
- Amplification: x3.87

Relative Displacement Main Shock
- Right: 0.1 inch cc
- Upstream: 0.03 inch u/s
Kasho Dam (Japan)

- Control house cantilevered off upstream side of dam crest
- Spillway piers
- No damage in dam
- Walls cracked at base of control building at crest of dam.

Photograph compliments of Norihisa Matsumoto
Uh Dam (Japan)

Gravity Dam
- Height: 46 feet
- Crest length: 112 feet

Western Tottori Earthquake, M 7.3
- Date: Oct 6, 2000
- Epicentral distance: 3.3 miles
- Dam from fault: 0.6 miles
- Peak Acceleration
  - Horizontal: 1.16 g

Only damage was a 0.4 to 1.2 inch wide crack on the spillway chute near the base of the downstream face.
Takou Dam (Japan)

Gravity Dam
- Completed: 2007
- Location: Iwate Prefecture
- Height: 252 feet
- Crest width: _ feet
- Crest length: 1056 feet

Tohoku Earthquake, M 9.0
- Date: March 11, 2011
- Peak Acceleration
  - Estimated PHGA: 0.4 g

Aftershock M 7.1
- Date: March 17, 2011
- Distance: 70 miles
- Peak Acceleration
  - Upstream: 0.38 g
  - Cross-canyon: 0.29 g
  - Vertical: 0.27 g
- Crest Acceleration
  - Upstream: 1.79 g
  - Cross-canyon: 2.04 g
  - Vertical: 1.33 g

Photographs compliments of Norihisa Matsumoto and Gabriela Lyvers
Takou Dam (Japan)

Offset in parapet wall
No damage to main dam

Cracked wall of the gate house

Photographs compliments of Norihisa Matsumoto
Gibraltar Dam (USA)

Arch Dam
- Completed: 1920
- Rehabilitated: 1990
- Added downstream RCC
- Location: Santa Barbara, CA
- Height: 194.5 feet
- Crest width: _ feet
- Crest length: 600 feet

Santa Barbara Earthquake, M 6.3
- Date: June 29, 1925
- Distance
- Peak Acceleration
  - Estimated PHGA: 0.3 g

92,500 cu yd RCC added downstream

No damage
## Pacoima Dam (USA)

<table>
<thead>
<tr>
<th>Arch Dam</th>
<th>1929</th>
</tr>
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<tbody>
<tr>
<td>Completed</td>
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<tr>
<td>Location</td>
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</tr>
<tr>
<td>Height</td>
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<tr>
<td>Crest width</td>
<td>_ feet</td>
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<tr>
<td>Crest length</td>
<td>589 feet</td>
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</tbody>
</table>

### San Fernando Earthquake, M 6.6
- Date: Feb 9, 1971
- Epicentral distance: 4 miles
- Peak Acceleration
  - Base: 0.6 to 0.8 g
  - Left abutment: 1.25 g
  - Vertical: 0.7 g

### Northridge Earthquake, M 6.8
- Date: Jan 17, 1994
- Epicentral distance: 11.4 miles
- Peak acceleration
  - Base: 0.53 g
  - Left abutment: 1.58 g
  - Dam crest: 2.30 g
Pacoima Dam (USA)

Rock Blocks in the Left Abutment

Figures compliments of Mark Schultz
Pacoima Dam (USA)

In 1976, 35 rock anchors installed in Rock Mass B consisting of 28 half-inch diameter strands.

Post-Northridge earthquake, 8 additional anchors installed.

Figures compliments of Mark Schultz
Pacoima Dam (USA)
Pacoima Dam (USA)

Damage and conclusions from the 1971 San Fernando Earthquake
- No cracks in the main dam
- No differential movements between dam blocks
- Separation between dam and left thrust block of 0.38 inches at the crest and extending 50 feet down
- A number of engineers questioned the validity of the high accelerations

Decisions
- Installation of extensive system of seismic instruments
- Installation of 35 rock anchors in the left abutment in Block B, not in Block A

Damage and findings from 1994 Northridge Earthquake
- Accelerations from the 1971 EQ were no longer questioned
- Contraction joint opened 2 inches between dam and left thrust block
- The 35 post-tensioned anchors at the left abutment thrust block appear to have improved the performance of Pacoima Dam during the 1994 Northridge Earthquake.
- The 35 anchors helped limit the magnitude of sliding to about 0.4 inches (1 cm) along the sliding plane. By contrast, an adjacent unanchored rock mass sharing the same sliding plane moved down-slope 2.25 inches (58 cm).
Ambiesta Dam (Italy)

Cupola Arch Dam with Pulvino
- Completed: 1956
- Location: Northern Italy
- Height: 194 feet
- Crest width: 6.7 feet
- Base width: 25.5 feet
- Crest length: 475 feet

Shake Table Laboratory Tests
- Model failed with 0.95 g horizontal and 0.76 g vertical

Gemona-Friuli Earthquake, M 6.5
- Date: May 6, 1976
- Epicentral distance: 14 miles
- Peak Acceleration
  - Right abutment: 0.36 g
- Foreshocks of M 5.9 and M 6.0
Ambiesta Dam (Italy)

No Reported Damage

Pulvino Joint

maximum section

upstream elevation
Rapel Dam (Chile)

**Double Curvature Arch Dam**
- Completed: 1968
- Height: 364 feet
- Crest width: 18 feet
- Base width: 62 feet
- Crest length: 886 feet

**Santiago Earthquake, M 7.8**
- Date: March 3, 1985
- Distance: 28 miles
- Peak Acceleration:
  - Upstream: 0.14 g
  - Cross-canyon: 0.31 g
  - Vertical: 0.11 g
- Prior swarm of 300 earthquakes

**Maule Earthquake, M 8.8**
- Date: Feb 27, 2010
- Distance: 144 miles
- PHGA: 0.30 g

- No damage to arch dam
- Spillway walls were cracked
- Leakage at the wall of the right spillway
- Upper part of intake tower cracked and separated from dam
Techi Dam (Taiwan)

**Double Curvature Arch Dam**
- Completed: 1974
- Height: 607 feet
- Crest width: _ feet
- Crest length: 951 feet

**Chi Chi Earthquake, M 7.6**
- Date: Sept 21, 1999
- Epicentral distance: 53 miles
- Peak Acceleration:
  - Horizontal: 0.3 to 0.5 g
  - Crest: 0.86 g
Techi Dam (Taiwan)

PGA of 0.86 g recorded just below spillway
Techi Dam (Taiwan)

Minor cracking of the concrete curb at the crest

No damage of the dam body

No signs of movement along vertical contraction joints

Foundation seepage increased, but returned to normal within days

Typical spalling at end of deck joint

Photograph compliments of Robin Charlwood
Shapai Dam (China)

RCC Arch Dam
- Completed 2003
- Location Sichuan Province
- Height 433 feet
- Crest width _ feet
- Crest length 820 feet

Wenchuan Earthquake, M 8.0
- Date May 12, 2008
- Distance 7.8 miles
- Peak Acceleration (g)
  - Horizontal (est.) 0.25 to 0.5
- Full reservoir

- No damage of dam body
- One spillway gantry was slightly damaged
- All gates could be opened
- Power station was badly damaged from falling rocks
- Damaged elevator shaft building
Shapai Dam (China)

Damaged elevator shaft building
Hsinfengkiang Dam (China) (called Xinfengjiang Dam)

**Buttress Dam**
- Completed: 1959
- Strengthened: 1961
- Location: Guangzhou, China (was Canton, China)
- Height: 344 feet
- Crest width: 16 feet
- Crest length: 1444 feet

**Reservoir-triggered EQ M 6.1**
- Date: March 19, 1962
- Distance: 3 miles
- Peak Acceleration
  - Aftershock, M 4.5
  - Peak crest acceleration: 0.54 g

Horizontal crack 269 feet long on right side of downstream face at an abrupt change in geometry

A few smaller cracks on the left side of dam at same elevation
### Sefid Rud Dam (Iran)

**Buttress Dam**
- Completed: 1962
- Location: Northern Iran
- Height: 348 feet
- Crest length: 1368 feet

**Manjil Earthquake, M 7.7**
- Date: June 21, 1990
- Distance: Near dam
- Peak Acceleration
  - PHGA Estimate: 0.71 g

**Aftershocks**
- M 6.2, 6.5, 5.9
Sefid Rud Dam (Iran)

Horizontal cracks 59 feet below crest at change in geometry

Minor upstream to downstream displacements between a few of the 23 blocks

Leakage through some cracks

Minor damage and displacement of all gates

Repairs in 1991 included grouting of cracks and installing prestressed anchors
Observations and Conclusions

Performance
- Concrete dams have performed well in earthquakes
- RCC dams performed no differently than dams built of conventionally placed concrete.

Cracks
- Horizontal cracks high in the dam at changes of stiffness
- In features such as curbs, railings, gates, or guard or control houses.

Leakage and Seepage
- Very little in the way of increased leakage has occurred
- Some rock foundations have experienced a temporary increase in seepage.

Release of the Reservoir
- Shih Kang Dam (Taiwan) had severe damage, but the outflow was limited and not a sudden release.
Observations and Conclusions

Acceleration does amplify from the base to the crest.

- In three cases, crest acceleration in excess of 2.0 g:
  - Pacoima arch dam (USA) was 2.3 g
  - Kasho gravity dam (Japan) was 2.05 g
  - Takou gravity dam (Japan) was 2.04 g

Minor Damage Even with Multiple Shakes

- Separate major earthquakes:
  - Bear Valley Dam (USA) was one day apart
  - Pacoima Dam (USA) was 23 years apart
  - Rapel Dam (Chile) was 25 years apart

- High intensity aftershocks have not caused additional damage.
Reasons why concrete dams have performed well

• The level of shaking has been too low to cause major damage

• Massive redundant structures capable of redistributing load.

• The duration of strong shaking may be too short to cause failure.

• Many times, the dynamic tensile strength of concrete is taken up to 50 percent higher than the static tensile strength of the concrete.

• Damping mechanisms can increase in the dam during the earthquake and reduce the seismic impact on the dam.

• Natural frequency of the dam does not match the postulated frequency content of the earthquake during design.

• The three-dimensional effects of the dam help prevent failure.

• The entire potential seismic failure mode has not been fully achieved or experienced for concrete dams.
No seismic failure of arch dams

Potential failure modes are, therefore, difficult to capture

Reclamation performed shake table tests from 1999 to 2001
  • 15 tests on medium-thick arch dams
  • 1 test on thin arch dam

Scale: 1/150

Difficulties:
  • Meeting all similitude requirements
  • As a result, previous model concrete did not match real concrete behavior. This was different for these tests.
Reclamation Shake Table Tests

Medium-thick arch tests included:
- Monolithic model M1, M2, M4, and M5
- One vertical contraction joint at crown M6, M7, M8, and M11
- One horizontal unbonded lift surfaces M9 and M10
- 17 Vertical contraction joints M12 and M13
- 17 Vertical CrJs and 2 unbonded horizontal lifts M14 and M15

Thin arch test:
- Monolithic E1

Material properties:

<table>
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<tr>
<th>Property</th>
<th>Prototype</th>
<th>Scale Factor</th>
<th>Target for the Model</th>
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<td>35,000 lb/in²</td>
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<td>Compression</td>
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<td>Tension</td>
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<td>Tensile strain</td>
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</tbody>
</table>
Reclamation Shake Table Tests

Monolithic

One vertical joint

One unbonded lift joint

17 vertical joints

17 vertical joints and 2 horizontal joints

Draw predicted cracking pattern at failure
### Reclamation Shake Table Tests

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Age (Days)</th>
<th>Average Comp. (lb/in²)</th>
<th>Average Split Tens (lb/in²)</th>
<th>Average Beam Tens (lb/in²)</th>
<th>Average Modulus (lb/in²)</th>
<th>Acceleration at Initial Crack</th>
<th>Acceleration at Failure</th>
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<tbody>
<tr>
<td>M1</td>
<td>M</td>
<td>7</td>
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<td>3948</td>
<td>0.75</td>
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</table>

Ground motions were:
- Sinusoidal
- Only in the upstream to downstream direction
- Reservoir water
- At natural frequency of model (14 Hz)
Reclamation Shake Table Tests

Summary of Cracking
Reclamation Shake Table Tests

Cracking caused distinct change in acceleration
Reclamation Shake Table Tests

• All models showed the onset of sudden cracking and pronounced structural nonlinearity following cracking.

• The arch dam model demonstrated a critical acceleration of 0.70 g’s for first cracking of this specific model independent of joints in the models.

• The crack pattern in the models is dominated by the joint patterns.

• The time to full breach when converted to full scale times exceeds the duration of any recorded earthquake.

• Final failure is a push through of the dam into downstream.

• Water does pass through cracks in the model with enough duration.

• All models developed a crack along the crown cantilever.