Seismic Design and Performance Criteria for Large Storage Dams

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Integral Dam Safety Concept

Structural Safety
Design of dam according to state-of-practice (codes, regulations, guidelines, etc.) (earthquake design criteria, methods of seismic analysis etc.)

Dam Safety Monitoring
Dam instrumentation, visual inspections, data analysis and interpretation, dam safety management system, etc.

Operational Safety
Guidelines for reservoir operation under normal and unusual conditions, qualified staff, safe software, maintenance, etc.

Emergency Planning
Emergency action plans, water alarm systems, dam breach flood wave analysis, evacuation plans, engineering back-up, etc.
International Commission on Large Dams (ICOLD)
Committee on Seismic Aspects of Dam Design since 1968

Bulletin 112 (1998): Neotectonics and dams (active faults in dam foundation) **Hazard**

Bulletin 137 (2011): Reservoirs and seismicity (reservoir-triggered seismicity) **Hazard**

**Bulletin 148 (approved 2010): Selecting seismic parameters for large dams** **Design Criteria**

Bulletin 52 (1986): Earthquake analysis procedures for dams (linear analysis) **Analysis**

Bulletin 120 (2001): Design features of dams to effectively resist seismic ground motion **Design**

Bulletin 123 (2002): Earthquake design and evaluation of structures appurtenant to dams **Design**


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**Seismic hazard a multi-hazard**

- **Ground shaking** causing vibrations in dams, appurtenant structures and equipment, and their foundations *(most earthquake regulations are concerned with this hazard only!)*

- **Fault movements in dam foundation** or discontinuities in dam foundation near major faults which can be activated causing structural distortions;

- **Fault movement in reservoir** causing water waves in the reservoir or loss of freeboard;

- **Mass movements (rockfalls)** causing damage to gates, spillway piers, retaining walls, powerhouses, electro-mechanical equipment, penstocks, transmission lines, access roads to dams, etc.

- **Other site-specific and project-specific hazards**
Tohoku earthquake, March 11, 2011
Failure of 18 m high Fujinuma dam (Japan)

Bhuj earthquake 2001 (India), Damaged irrigation dam (very low reservoir level at time of earthquake)
Sefid Rud buttress dam, Manjil earthquake 1990 (Iran)

Critical crack in buttress of Sefid Rud dam
Crack at upstream face of Sefid Rud buttress dam

Collapsed buildings at Sefid Rud dam site
Damaged switchyard on fill, Sefid Rud dam

Derailed transformer, Sefid Rud dam
Transmission tower failure due to rockfall, Sefid Rud dam

Failure of radial gate due to rockfall, Wenchuan earthquake, 2008 (China)
Rockfall damage of surface powerhouse and equipment, Wenchuan earthquake, 2008 (China)

Chi-Chi earthquake 1999 (Taiwan), Shih-Kang Dam
Seismic design criteria

Dam and safety-relevant elements (spillway, bottom outlet):

Operating basis earthquake, OBE (145 years)  
(negotiable with owner)

Safety evaluation earthquake, SEE (ca. 10,000 years)  
(non-negotiable)

Appurtenant structures (powerhouse etc.):

Design basis earthquake, DBE (ca. 475 years)

Temporary structures (coffer dams, river diversion) and critical construction stages:

Construction level earthquake, CE (> 50 years)

Seismic performance criteria for dam and safety-relevant elements

(i) Dam body:

OBE: fully functional, minor nonstructural damage accepted

SEE: reservoir can be stored safely, structural damage (cracks, deformations) accepted, stability of dam must be ensured

(ii) Safety-relevant elements (spillway, bottom outlet):

OBE: fully functional

SEE: functional so that reservoir can be operated/controlled safely and moderate (200 year return period) flood can be released after the earthquake
Deriner arch dam in Turkey (spillway)

Safety Evaluation Earthquake (SEE)

- A dam must withstand the ground motion of the SEE.

- The ground motion parameters of the SEE can be obtained from a deterministic and/or probabilistic seismic hazard analysis.

- Deterministic analysis (MCE): The ground motion parameters are represented by the 84% percentile values. The critical earthquake scenario has to be considered, which is usually independent of any return period.

- Probabilistic analysis (MDE): The ground motion parameters are represented by the mean values. For large dams the return period shall be taken as 10,000 years.

- The ground motion parameters of the SEE are taken as the maximum of the MCE and MDE.
**Classification of large dams in Switzerland**

<table>
<thead>
<tr>
<th>Klasse</th>
<th>Return period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klasse 1:</td>
<td>10,000 years</td>
</tr>
<tr>
<td>Klasse 2:</td>
<td>5,000 years</td>
</tr>
<tr>
<td>Klasse 3:</td>
<td>1,000 years</td>
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</tbody>
</table>

**Note:** The flood and earthquake safety criteria should be consistent.

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**Definition of large dams in China**

- **Class 1:** Reservoir volume > 1000 Mm$^3$
- **Class 2:** Reservoir volume 100 to 1000 Mm$^3$
- **Class 3:** Reservoir volume < 100 Mm$^3$

**Conclusion**

There may be large differences in the risk classification of large dams, which have a direct effect on the seismic (and flood) design and performance criteria.
Seismic parameters needed by dam engineer

- Peak Ground Acceleration
- Acceleration Response Spectra (5% damping)
- Acceleration time histories (structures ‘responding’ to inertial forces)
- Displacement time histories (underground structures ‘not responding’ to inertial forces (imposed deformations)) and wave propagation velocities
- Spatial variation of ground motion for special (long) structures

Ground shaking

Earthquakes affect all components of a dam project at the same time:
- dam
- foundation
- safety devices
- pressure system
- underground works
- appurtenant structures
- hydro-mechanical equipment
- electro-mechanical equipment etc.
Typical load combinations used in dam design

- Usual load combinations: no earthquake
- Unusual load combinations: OBE
- Extreme load combinations: SEE

Design earthquakes for large hydropower projects

- Safety Evaluation Earthquake (SEE)
  - Maximum Credible Earthquake (MCE)
  - Maximum Design Earthquake (MDE)
- Design Basis Earthquake (DBE)
- Operating Basis Earthquake (OBE)
- Construction Earthquake (CE)

If reservoir-triggered seismicity (RTS) is possible the DBE and OBE ground motion parameters should cover those from the RTS scenarios.
Earthquake prediction is still a research topic and not possible for strong earthquakes.
<table>
<thead>
<tr>
<th>Title</th>
<th>Element / Component</th>
<th>Design Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversion Facilities</td>
<td></td>
<td>CE DBE OBE/SEE</td>
</tr>
<tr>
<td>- Civil</td>
<td>Intake/outlet structures</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Tunnel, tunnel liner</td>
<td>X</td>
</tr>
<tr>
<td>- Geotechnical</td>
<td>Rock slopes</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Underground facilities</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Cofferdams</td>
<td>X</td>
</tr>
<tr>
<td>- Electrical/Mechanical</td>
<td>Gate equipment</td>
<td>X</td>
</tr>
<tr>
<td>Dam: Dam Body</td>
<td>Dam body</td>
<td>OBE X</td>
</tr>
<tr>
<td></td>
<td>- Individual Blocks</td>
<td></td>
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<tr>
<td></td>
<td>Crest bridge</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Crest spillway cantilevers</td>
<td>X X</td>
</tr>
<tr>
<td></td>
<td>Bottom Outlet cantilevers</td>
<td>X</td>
</tr>
<tr>
<td>Foundation/Abutments</td>
<td>Abutment wedges</td>
<td>X X</td>
</tr>
<tr>
<td>Bottom Outlet</td>
<td>Main gates, Valves</td>
<td>X X</td>
</tr>
<tr>
<td></td>
<td>Guard gate</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Operating equipment</td>
<td>X X</td>
</tr>
<tr>
<td>Dam: Electrical/Mechanical</td>
<td>Essential parts</td>
<td>X</td>
</tr>
</tbody>
</table>
Systematic application of seismic safety criteria to all structures and components of large dam projects

**Note:** Seismic design codes and recommendations are mainly concerned with new dams.

**Question:** What’s about the earthquake safety of existing (older) dams?

**Answer:** During the long lifespan of a dam several seismic safety assessments will be required!
Conclusions

- The seismic hazard is a multi-hazard for most large dam projects. Ground shaking is the main hazard considered in all earthquake guidelines for dams. The other seismic hazards are addressed less rigorously than the ground shaking or may have been ignored.

- Dams are not inherently safe against earthquakes.

- The updated ICOLD guideline on ‘Selecting seismic parameters for large dams’ covers most structures and elements of large dams.

As most dams built prior to 1989 when ICOLD has published its seismic design criteria of dams, have not been checked for the safety evaluation earthquake ground motion, the earthquake safety of these dams is not known.

Moreover, due to changes in the seismic design criteria and the design concepts it may be necessary to perform several seismic safety checks during the long economical life of a large dam.

Reservoir-triggered seismicity is not a separate load case in dam design but may be relevant for appurtenant structures and buildings and infrastructure in dam area.