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**

Bulletin 62 (1988/2008): Inspection of dams following earthquakes **Inspection**

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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**

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Tohoku earthquake, March 11, 2011
Failure of 18 m high Fujinuma dam (Japan)

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Bhuj earthquake 2001 (India), Damaged irrigation dam (very low reservoir level at time of earthquake)

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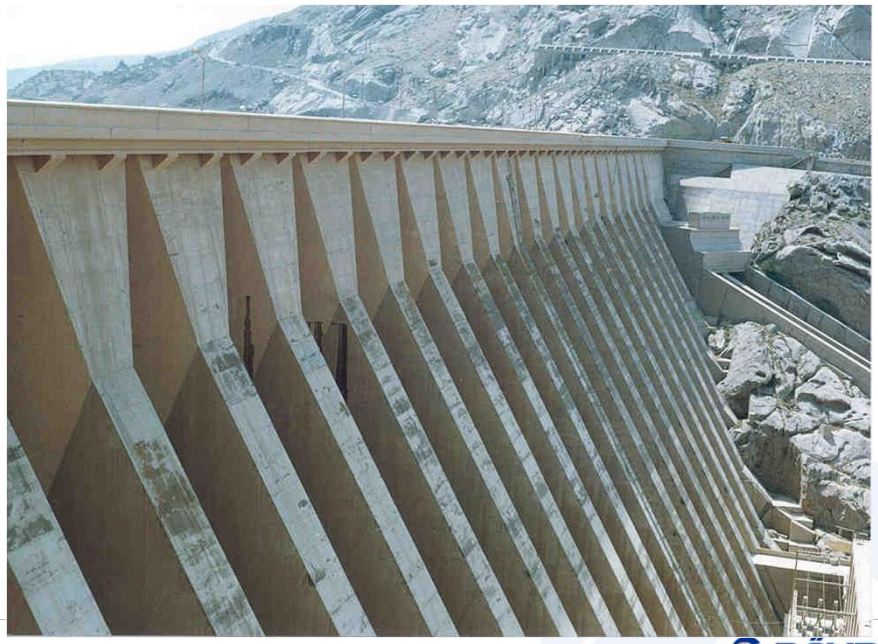
Sefid Rud buttress dam, Manjil earthquake 1990 (Iran)



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Critical crack in buttress of Sefid Rud dam

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Crack at upstream face of Sefid Rud buttress dam

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Collapsed buildings at Sefid Rud dam site

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Damaged switchyard on fill, Sefid Rud dam

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Derailed transformer, Sefid Rud dam

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Transmission tower failure due to rockfall, Sefid Rud dam

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Failure of radial gate due to rockfall, Wenchuan earthquake, 2008 (China)

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Rockfall damage of surface powerhouse and equipment, Wenchuan earthquake, 2008 (China)

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Chi-Chi earthquake 1999 (Taiwan), Shih-Kang Dam

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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)

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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

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Deriner arch dam in Turkey (spillway)

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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.

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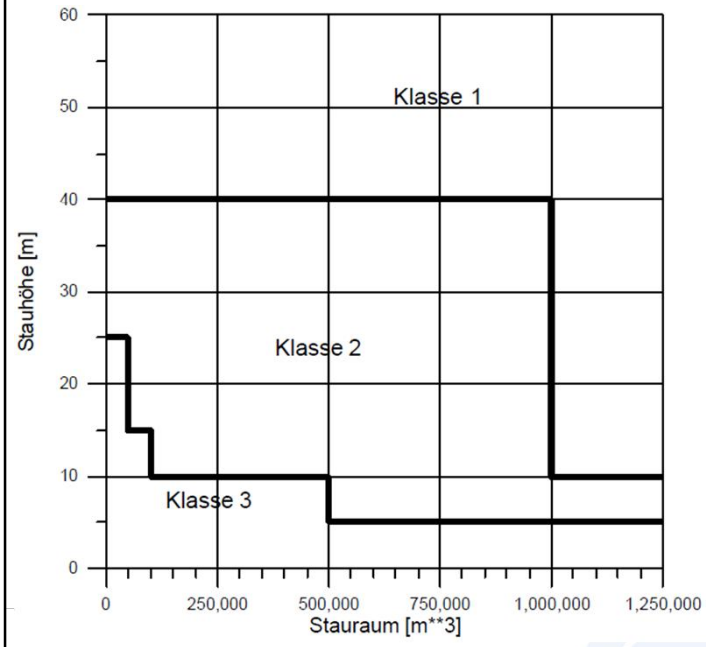
Classification of large dams in Switzerland



Return period

Klasse 1:
10,000 years

Klasse 2:
5,000 years

Klasse 3:
1,000 years

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

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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

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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.

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Typical load combinations used in dam design

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

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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.

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Title	Element / Component	Design Earthquake		
		CE	DBE	OBE/ SEE
Diversion Facilities				
- Civil	Intake/outlet structures	X		
	Tunnel, tunnel liner	X		
- Geotechnical	Rock slopes	X		
	Underground facilities	X		
	Cofferdams	X		
- Electrical/Mechanical	Gate equipment	X		
Dam: Dam Body	Dam body			X
	- Individual Blocks	OBE		
	Crest bridge		X	
	Crest spillway cantilevers		X	X
	Bottom Outlet cantilevers		X	
Foundation/Abutments	Abutment wedges		X	X
Bottom Outlet	Main gates, Valves		X	X
	Guard gate		X	
	Operating equipment		X	X
Dam: Electrical/Mechanical	Essential parts		X	

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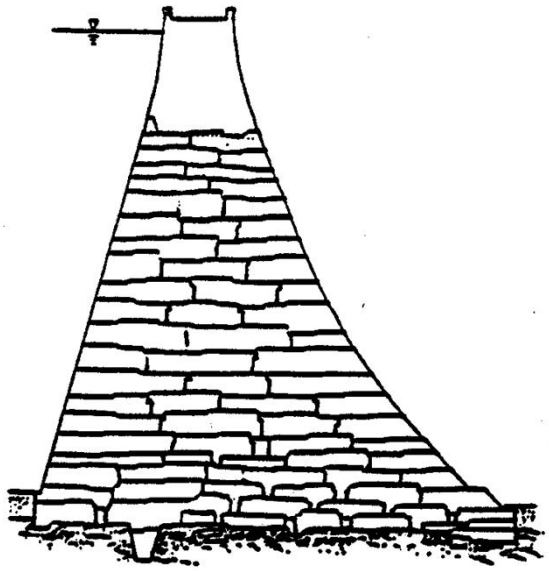
Lower Crystal Springs gravity dam (USA)

located in San Andreas fault zone, survived 1906 San Francisco earthquake undamaged



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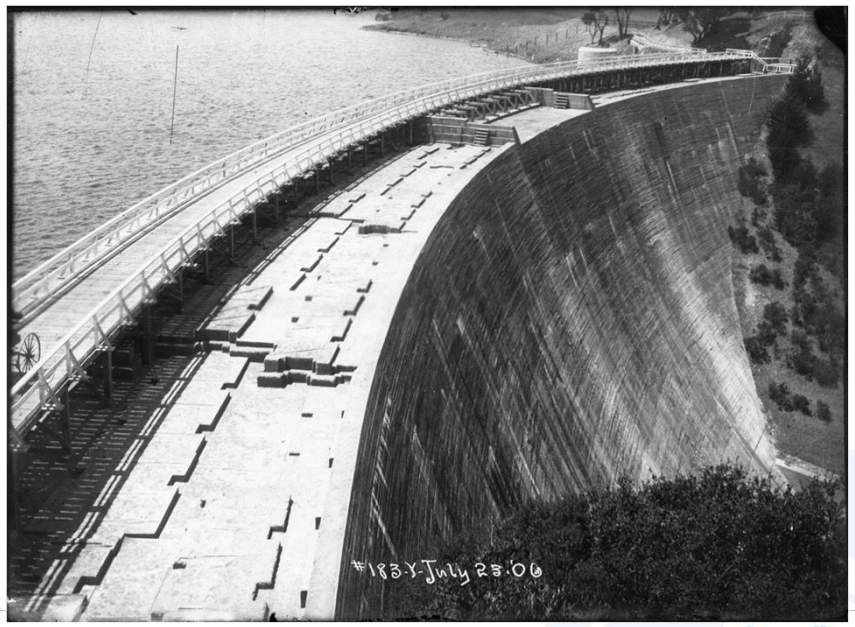
Lower Crystal Springs dam



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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!

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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.

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- 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.
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