# Progress Needed in Seismic Analyses from ICOLD Point of View

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## Seismic analysis of dams

**Large dams were the first civil structures designed systematically against earthquakes (worldwide).**

**Large concrete dams:** Pseudo-static analysis method developed by Westergaard in 1930s for Hoover dam; found worldwide acceptance.

- Method accounts for inertial effects of dam and hydrodynamic pressure and used **seismic coefficient of typically 0.1** **(method is obsolete today!)**.

**Large embankment dams:** First dynamic analysis by Mononobe et al. in 1936

- Pseudo-static slope stability analysis and use of **seismic coefficient of 0.10 to 0.15** **(method is obsolete today!)**.

**Engineers like these seismic analysis methods because of their simplicity, but they are obsolete today.**

## Maigrauge gravity dam, built 1872, Switzerland
### First concrete dam in Europe, still in operation!

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## Zarema May Day asphalt core rockfill dam, Ethiopia

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## Seismic hazard is 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;
- **Mass movements (rockfalls)** impulse waves, increase in reservoir level, blocking intakes, damage to gates, spillway piers, access roads, etc.
- **Other site-specific and project-specific hazards:** liquefaction, foundation deformations, seepage, etc.

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## Sharredushk Dam, Albania, after 2009 Earthquake, M=4.1, Peak Ground Acceleration = 0.07 g

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# Aratozawa Rockfill Dam (74 m high), Iwate Miyagi Earthquake, Magnitude 7.2, June 2008

- A 67 $Mm^3$ landslide at upstream end of reservoir with 1.5 $Mm^3$ sliding into reservoir with **2.4 m rise in water level**.
- PGA in foundation gallery: 1.0 g. Epicentral distance: 15 km.

## Aratozawa Rockfill Dam

Crest settlement: 40 cm, no serious damage

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## 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 (2016): Selecting seismic parameters for large dams Design Criteria**

Bulletin 52 (1986): Earthquake analysis procedures for dams (linear analysis) Clough, Zienkiewicz and Seed **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 166 (2016): Inspection of dams following earthquakes **Inspection**

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## Terms of reference 2013-2017

### ICOLD Committee on Seismic Aspects of Dam Design

- Seismic design aspects of CFRD dams, dams with asphalt core, and dams with other types of liners and internal membranes;
- Review of nonlinear seismic analysis procedures for concrete and embankment dams (in cooperation with committee on computational aspects of analysis and design of dams);
- Interpretation of seismic data obtained from dams.
- Dissemination of information on (i) seismic safety of existing dams, (ii) the updated design criteria for large dam projects, and (iii) the multiple hazards caused by strong earthquakes.

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## Seismic design criteria for large dams (ICOLD)

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

**Operating basis earthquake**, **OBE** (return period: 145 years) (**negotiable with dam owner)**

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

**Appurtenant structures (powerhouse, desander):**

**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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## Design earthquakes for large hydropower projects

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

If reservoir-triggered seismicity (RTS) is possible the DBE and OBE ground motion parameters should cover those from the RTS scenarios.

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## General seismic performance criteria of dams

**During and after the Safety Evaluation Earthquake (SEE)** the dam must be able to safely retain the reservoir. Stability of the dam must be ensured. Deformations and cracks are accepted.

**After the SEE** it must be possible to control the water level in the reservoir and it must be possible to release a moderate flood with a return period of say 200 years.

**Performance criteria:**

- **Retain reservoir**
- **Control water level in reservoir**
- **Lower reservoir for repair of damage**

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## Seismic performance criteria for large dams 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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## Main seismic failure modes of rockfill dams

**Mode 1: Overtopping of crest: Freeboard**

- Settlement (compaction due to **ground shaking**)
- Slope movements at crest due to **ground shaking**

**Mode 2: Internal erosion: Filter**

- Slope movements at crest due to **ground shaking** causing offset of filter
- Offset of filter due to **fault movements**

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## Performance criteria for embankment dams

**1. Prevention of Overtopping:**

- Elevation of top of impervious core must be above reservoir level after the earthquake.
- After the earthquake it must be possible to control the reservoir level and to prevent overtopping even for a moderate flood, i.e. bottom outlet and/or spillway must be functioning. This is mainly a problem for gated spillways.

**2. Prevention of Internal Erosion:**

- Fine filter must be functioning after the earthquake, i.e. at least 50% of fine filter width must be available.

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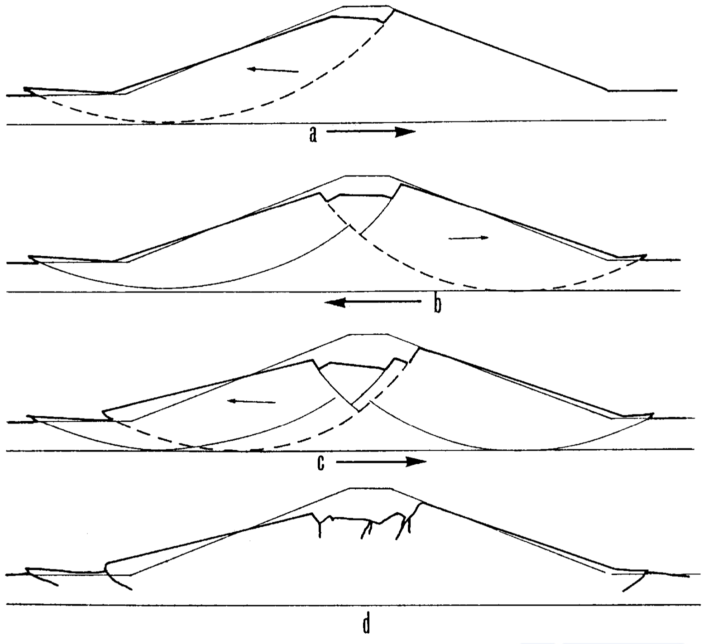
## Dynamic stability of embankment

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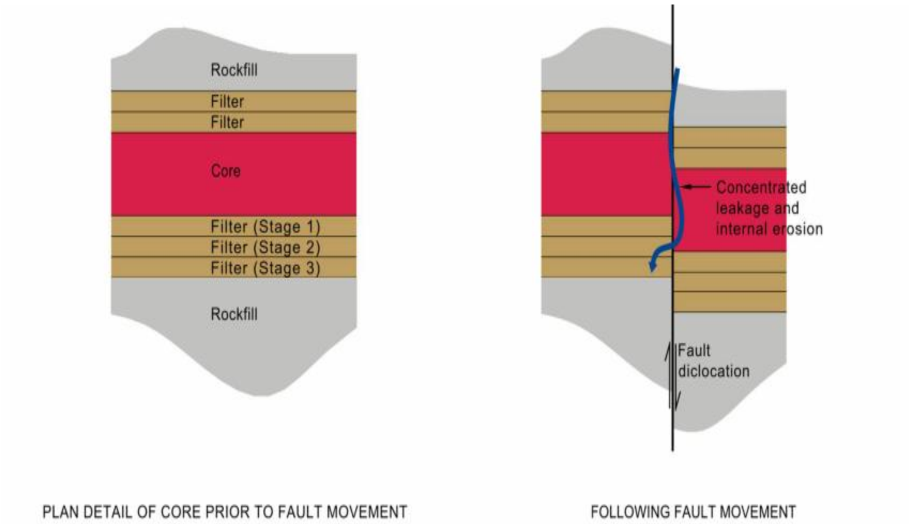
## Internal erosion: filter dislocation by slope or fault movements

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## Design and performance criteria

**Important:**

**Design and performance criteria form a unit and cannot be considered separately!**

This is very important if the design criteria of different countries or organisations are compared.

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## Need for seismic safety checks

**Seismic safety evaluations have to be carried out repeatedly during long life-span of a dam, i.e.**

- New information on seismic hazard (multi-hazard) and/or seismotectonics is available;
- Dam has been subjected to strong earthquake;
- New seismic design and performance criteria;
- New dynamic methods of analysis;
- Seismic vulnerability of dam has increased;
- Seismic risk has increased, etc.

## Seismic analysis and check of embankment dams

For embankment dams the following analyses are carried out:

1. **Static and dynamic** (ground shaking) **sliding stability analyses** using Newmark sliding block method for seismic action.
2. **Static and dynamic** (linear-equivalent or inelastic) **stress and deformation analyses** using geotechnical programs such as FLAC, Geostudio, Plaxis and others). A prerequisite is a seepage analysis (not needed for dams with surface membrane)
3. **Seismic hazard analysis results** (done by seismologist or obtained from dam authorities) are used as input for (1) and (2).
4. **Safety check**: Check of sliding safety factors or allowable sliding movement under seismic action; check loss of freeboard and filter dislocations along sliding surfaces under seismic actions. Checks are mainly based on deformations.

## Seismic safety checks

Today, for the seismic safety checks the **deformations** caused by the safety evaluation ground movement are analysed (no use of stresses or sliding safety factors, etc.).

Older dams, designed before 1989, have been designed against earthquakes using outdated seismic design criteria (mainly a seismic coefficient of 0.1 was used) and obsolete methods of dynamic analysis (pseudo-static analysis method was used), therefore the seismic safety of these dams is not known and it has to be checked, if they satisfy today's seismic safety criteria.

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# Risk Classification of Dams

## What is a large dam?

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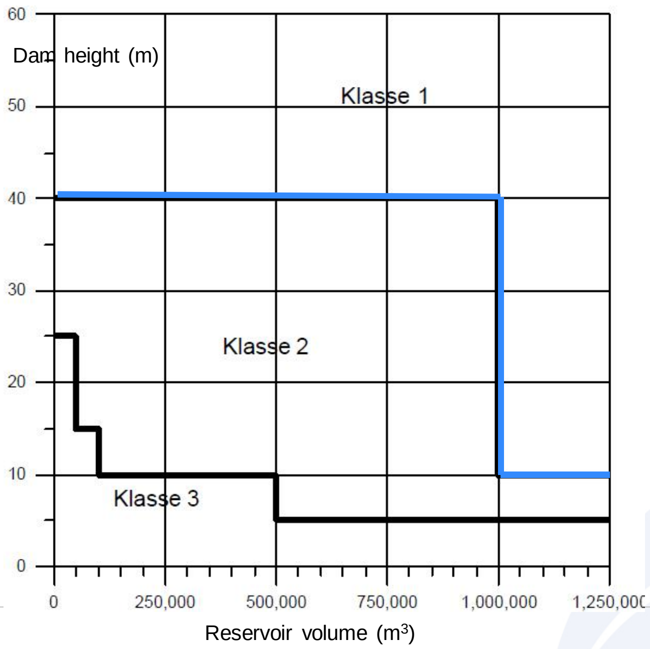
## Example: Classification of dams in Switzerland




**Return period (SEE earthquake)**

Klasse 1:
10,000 years

Klasse 2:
5,000 years

Klasse 3:
1,000 years

**Note: Flood and seismic design criteria should be consistent.**

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## Example: 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 $Mm^3$

**Note:** According to this definition less than 10 Swiss dams would fall under Class 2 and the remaining ones under Class 3, but actually some 160 large dams fall under 'Klasse 1' (highest safety class) in Switzerland.

This difference in classification of large dams has major implications on the design of dams as the return periods of the design earthquakes and floods depend on the class of the dam.

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## Requirements: Seismic analysis

- Comprehensive look at the different features of the seismic hazard (**ground shaking**, fault movements, mass movements, reservoir-triggered seismicity etc.) and their implications on the different structures and components of large storage dams.
- Seismic safety includes (i) **structural safety**, (ii) dam safety monitoring, (iii) operational safety and maintenance, and (iv) emergency planning. Seismic analysis is mainly related to (i) and (ii) and includes ground shaking only.
- Prediction of seismic behaviour of **new dam types**, which have not been subjected to strong earthquakes (RCC, CFRDs, dams with asphalt/geotextile core/surface membranes, etc.).

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## Requirements and challenges

- Use of updated **seismic design criteria** according to ICOLD Bulletin 148. Design criteria form the basis of any seismic analysis, design and safety checks. Main problem is that these guidelines are followed. Risk classification of dams is another problem as it may vary among countries and/or owners.
- Seismic safety of new and existing dams.
- Discussion of main seismic failure modes of dams and analysis of inelastic dam deformations, which govern the main failure modes.
- Development of methods for reliable inelastic deformation analysis of embankment dams.

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## Requirements

- Seismic hazard analysis for SEE ground motion. For the seismic design and safety evaluation of dams, **ground motion models** are used and **not real earthquake records**. Real earthquake records may only be used for the reanalysis of dams equipped with strong motion instruments, which have experienced strong ground shaking (these are a few special cases).
- Use of general seismic **design guidelines** for large dams before any analysis is carried out.
- Development of **"simple" methods** of inelastic seismic analysis of dams.

## 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 have been "overlooked".
- The updated ICOLD Bulletin 148 on 'Selecting seismic parameters for large dams' provides design criteria used as basis for any seismic analysis.
- Similar to design criteria, the seismic performance criteria have undergone substantial changes. The seismic safety has to be assessed based on deformations rather than stresses and slope stability safety factors.

## Conclusions

- Earthquakes affect all components of storage dams at the same time and all of them must be able to withstand different levels of earthquake shaking.
- Cracks in concrete dams are discrete cracks developing along lift and construction joints and at locations with sudden changes in stiffness and/or mass (kinks and corners form stress concentrations).
- Hydro-mechanical and electro-mechanical equipment of spillway gates and low level outlets must be capable to withstand the ground motion of the safety evaluation earthquake. Hydrodynamic pressures may damage gates.

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## Conclusions

- During the long economical life of dams, several seismic safety analyses have to be carried out.
- Experience with modern dams, which have experienced strong ground shaking, similar to that of the SEE, is still very limited.
- After a major earthquake the guidelines for seismic design and seismic safety assessment of dams may have to be revised again!

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