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Central Water Commission

The Urgent Need for the Seismic Safety Evaluation of Existing Dams

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10-12 October 2022 at Jaipur, Rajasthan (India)

Seismic analysis and design of dams

Dams were the first structures designed systematically against earthquakes.

Concrete dams: Pseudo-static method developed by Westergaard in the 1930s accounts for inertial effects of dam body and hydrodynamic pressure on upstream face.

Embankment dams: Pseudo-static slope stability analysis developed by Mononobe et al. in the 1930s.

In both methods a seismic coefficient of typically 0.1 was used.

Seismic safety of existing dams

Most existing dams were designed against earthquakes using **methods of dynamic analysis** (pseudo-static method) and **seismic design criteria** (earthquake hazard was represented by seismic coefficient of 0.1 at most dam sites), which are considered **obsolete or wrong**, today, therefore, the seismic safety of these dams is unknown, if modern seismic design criteria are used. Therefore, the seismic safety of these dams must be checked.

Important: The seismic safety of existing dams must be checked periodically during their long lifespan.

Main developments in the seismic design and safety evaluation of dams

The following are the main developments and changes that have taken place since the 1930s:

1. Change from **pseudo-static analysis** to dynamic analysis of dams.

2. Change from characterization of ground shaking by a **seismic coefficient** to Safety Evaluation Earthquake ground motion parameters.

3. Change from single hazard (**ground shaking**) to multiple seismic hazards (fault movements, mass movements etc.)

4. Change from **safety factor and allowable stress concepts** to rational seismic performance criteria (mainly based on inelastic seismic dam deformations).

5. Change from **safety of dam body alone** to safety of dam body plus safety-critical elements plus abutments and reservoir slopes (plugging of intakes and creation of impulse waves in reservoir).

6. Change in safety criteria including the **safe operation of the reservoir after strong earthquakes** and the need of **low-level outlets**.

Need for seismic safety evaluation of existing dams

- New information on seismic hazard or seismotectonics is available;
- A dam has been subjected to strong earthquake shaking;
- New seismic design criteria are introduced;
- New seismic safety criteria are introduced;
- New dynamic methods of analysis are introduced, such as nonlinear dynamic analysis methods;
- The seismic vulnerability of a dam has increased due to modifications, ageing etc.,
- Changes in risk classification of dams (new safety guidelines);
- Increase in seismic risk, i.e. increase of number of people living downstream of dam, increase of economic development etc.

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Grande Dixence Gravity Dam, Switzerland

World's highest concrete gravity dam

Dam height: 285 m

Dam volume: 6 Mm^3

Reservoir: 400 Mm^3

Crest length: 695 m

Completion date: **1961**

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Mauvoisin Arch Dam, 250 m high, completed 1957

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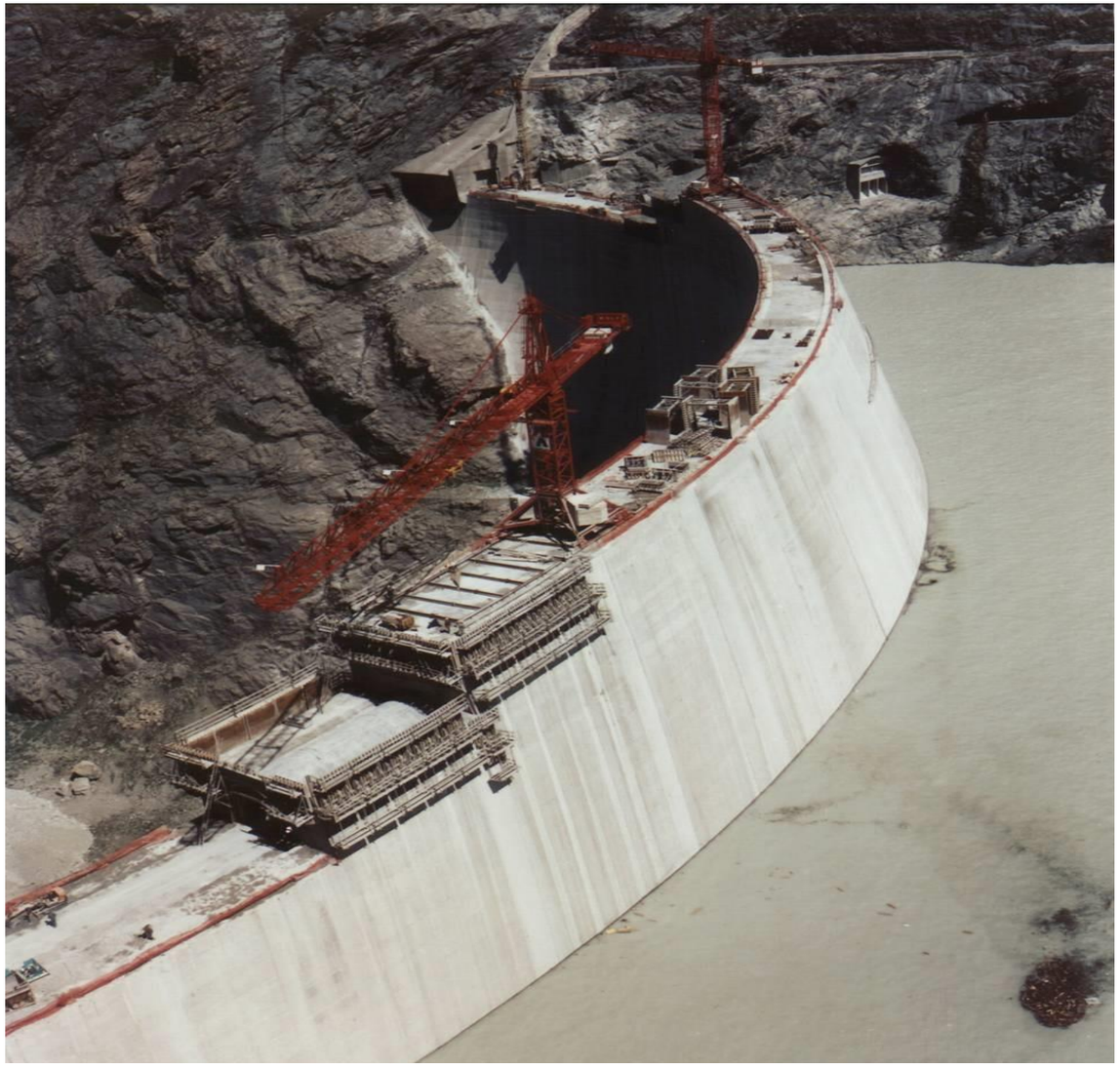

Heightening of Mauvoisin arch dam by 13.5 m to 250 m

work completed 1991

(seismic safety evaluations are required in the case of dam modifications; current design and safety criteria must be used in the case of dam modifications and rehabilitations)

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Nurek rockfill dam, Tajikistan, 300 m high

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Neelum-Jhelum HPP in Kashmir, Pakistan (dam on MBT fault)

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Seismic hazard is multi-hazard

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

(ii) Fault movements in dam foundation or discontinuities in dam foundation near major faults which can be activated causing structural distortions;

(iii) Fault movement in reservoir causing water waves in the reservoir or loss of freeboard;

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

(v) Other site-specific and project-specific hazards

Note: It is very important that all these hazards are taken into account in the seismic design and safety assessment of dams.

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Dams designed with pseudo-static method were damaged during earthquakes

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Seismic safety criteria for new and old dams

(i) **Retain the reservoir** and to protect people from the catastrophic release of water from the reservoir,

(ii) **Control the reservoir level** after an earthquake as a dam could be overtopped and destroyed if the inflowing water into the reservoir cannot be released through damaged spillways or low-level outlets, and

(iii) **Lower the reservoir level** after an earthquake (1) for repair works or (2) for increasing the safety of a damaged dam or when there are doubts about the safety of a dam.

Application of seismic safety criteria: safety checks

Safety evaluation earthquake is considered for the seismic safety check of the following:

1. **Dam body** (including saddle dams),
2. **Safety-critical elements** (spillways, low-level outlets),
3. **Dam abutments** (abutment stability is main concern for arch dams), and
4. **Reservoir slopes** (rockslides or landslides may plug intakes of safety-critical elements or may create large impulse waves in reservoir).

Seismic safety of tailings dams

Large **tailings dams** should satisfy the same design and safety criteria as **water storage dams**.

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Seismic strengthening of damaged or «unsafe» dams

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Seismic strengthening of crest spillway structure

Original Design: 0.1 g

Rehabilitation: 1.8 g

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Seismic strengthening of multiple arch dam (sliding stability)

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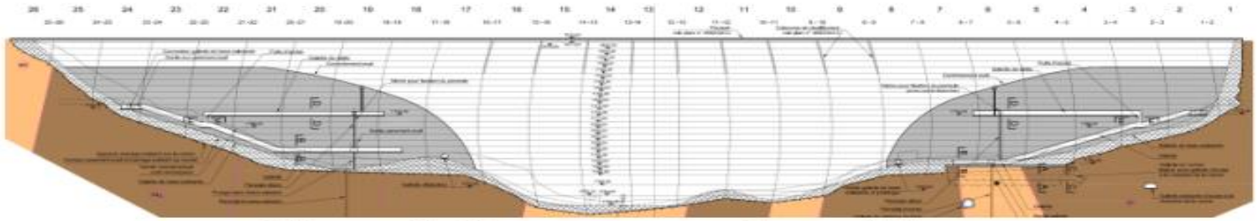
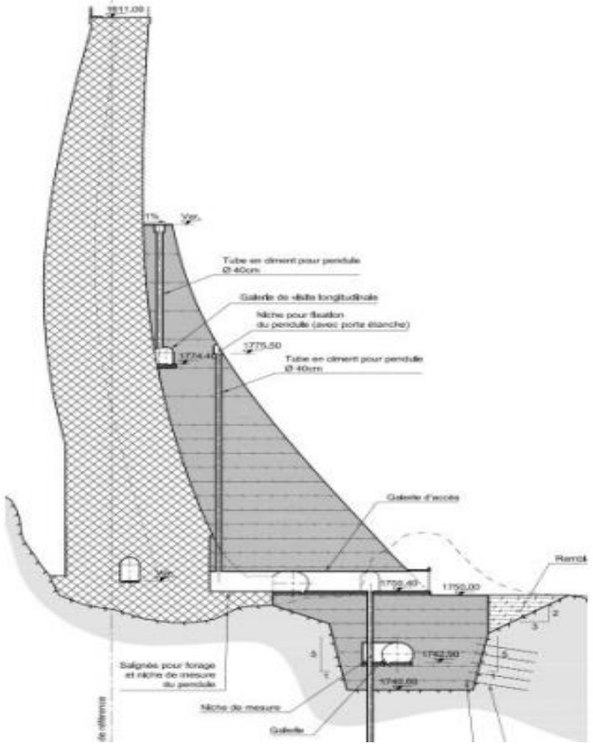
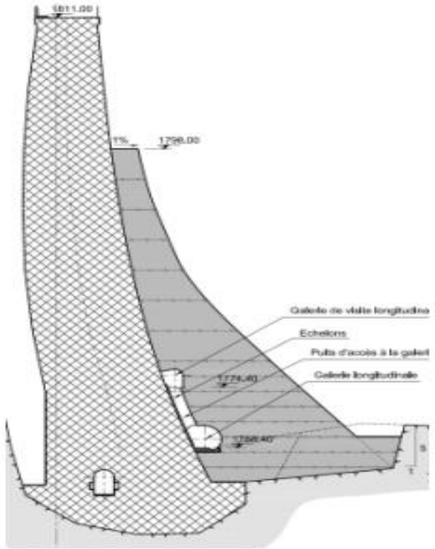


Figure 2: Downstream face of dam





Seismic strengthening of Les Toules arch dam (Switzerland)

Both abutments were modified to improve the dynamic behaviour of the very flexible dam, located in a wide valley

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Seismic rehabilitation of embankment dam (crest widening, dam heightening, downstream berm)

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Seismic safety aspects of dams

Earthquake safety includes the following items:

1. Structural Safety (Earthquake Safety)

Design of dam according to state-of-practice (codes, regulations, guidelines, i.e. earthquake design and safety criteria, methods of seismic analysis etc.)

2. Dam Safety Monitoring

Dam instrumentation (strong motion instruments, micro-seismic networks), visual inspections after earthquakes, data analysis and interpretation

3. Operational Safety

Guidelines for reservoir operation after earthquakes, qualified staff, **maintenance**

4. Emergency Planning

Emergency action plans, water alarm systems, evacuation plans, **Engineering back-up**, etc.

Conclusions

1. Old and new dams must satisfy the same safety criteria.
2. Existing dams may not satisfy today's seismic safety criteria and must be checked. This is a high priority issue.
3. Seismic safety checks must be carried out repeatedly during the long lifespan of dams.
4. In the short-term, by lowering of the reservoir, the seismic safety can be increased.
5. Earthquakes may create multiple hazards, which must be considered.
6. It must be possible to control the water level in the reservoir after strong earthquakes.
7. It is recommended to also check the ultimate seismic resistance of dams, to avoid frequent safety evaluations.