Modern Dam Safety Concepts and Seismic Safety Aspects of Sustainable Storage Dams

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SUSTAINABILITY
dam safety,
ageing,
service life,
and
environmental,
economic, and
social aspects
Maigrauge Gravity Dam, 1872, Switzerland

Augst-Wyhlen Run-of-River Power Plant at Rhine River, Swiss-German Border, 1912
Grande Dixence Gravity Dam, Switzerland

Highest concrete gravity dam in world

- Dam height: 285 m
- Dam volume: 6 million m³
- Reservoir volume: 400 million m³
- Crest length: 695 m
- Completion date: 1961
Extreme environment

DAM SAFETY
Integral Dam Safety Concept

**Structural Safety**
Design of dam according to state-of-practice (codes, regulations, guidelines, etc.)

**Dam Safety Monitoring**
Dam instrumentation, visual inspections, data analysis and interpretation, etc.

**Operational Safety**
Guidelines for reservoir operation, qualified staff, maintenance, etc.

**Emergency Planning**
Emergency action plans, water alarm systems, dam breach analysis, evacuation plans, Engineering back-up, etc.

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**STRUCTURAL SAFETY**

**FLOOD SAFETY**
Overtopping of Palagnedra dam in Switzerland in 1978 and rehabilitated dam

Avalanche
Seismic Design of Dams

Dams were the first structures to be designed systematically against earthquakes

**Concrete dams:** Method by Westergaard in the 1930s for Hoover dam; found worldwide acceptance and was used until the late 1970s.
- Method accounts for inertial effects of dam and hydrodynamic pressure and used seismic coefficient of typically 0.1.

**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.
### 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**
Dams on Faults or 'Active Discontinuities'
Rockfalls, Sefid Rud Dam

Usoy Landslide Dam, Lake Sarez, Tajikistan, Height: ca. 650 m, Landslide Triggered by 1911 M = 7.3 Earthquake
EMBANKMENT DAMS

Tohoku Earthquake, March 11, 2011
Fujinuma Dam (Japan)
Maule Earthquake: Colbun Dam, Height: 116 m, $a = 0.45 \text{ g}$, Epicentral Distance: 183 km
Bhuj Earthquake 2001, Irrigation Dams

Bhuj Earthquake 2001

PÖYRY
Bhuj Earthquake 2001
Slide in Kitayama Dam, Kobe Earthquake 1995

Sharredushk Dam, Albania, after 2009 Earthquake, M=4.1,
Peak Ground Acceleration = 0.07 g
Zipingpu CFRD with Intake Structures
Zipingpu Concrete Face Rockfill Dam (156 m)
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

CONCRETE DAMS
Chi-Chi Earthquake 1999, Shih-Kang Dam, Taiwan

Sefid Rud Buttress Dam, 105 m high, 1990
Manjil Earthquake, Iran
Critical Crack in Buttress of Sefid Rud Dam

Cracks in Sefid Rud Buttress Dam
Manjil Earthquake 1990, Repair Works

Shapai RCC Arch Dam, 2008 Wenchuan Earthquake, M=7.9, China
Pacoima Arch Dam: San Fernando (1971) and Northridge (1994) Earthquakes
Overtopping of Run-of-River Power Plant (Gates Blocked)

Damage of Pier and Retaining Wall of Run-of-river Power Plant due to Rockfall, Wenchuan Earthquake
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)*
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

Dam Safety Monitoring
Kasho Gravity Dam (49 m high), Japan, 2000
Tottori Earthquake, Mw=6.6

Acceleration Records

Gallery Dam Crest

N-S
E-W
U-D

Time (s)

Peak Acc.
0.54g
0.54g
0.49g

Dam Crest

N-S
E-W
U-D

Time (s)

2.1g
1.4g
0.9g
Free Vibration of Reservoir

- Water level in cm vs. time (h)
- Fourier spectrum
- Natural period: T = 6.5 minutes
- Damping ratio: 0.02

Operational Safety of Dams
Taum Sauk CFRD dam failure, USA, 14.12.2005
Pump Storage Reservoir, overtopping due to uncontrolled pumping (no spillway was provided)
Taum Sauk CFRD failure

Taum Sauk: CFRD dam was replaced by RCC dam
Amplified shaking on top of spillway intake tower of Zipingpu HPP (2008 Wenchuan earthquake China) damaging gate room building and vital equipment installed in building

Overturned control board at Zipingpu dam preventing operation of vital gates
Emergency Planning: Water Alarm Systems

Public Warning System: Water alarm and general alarm sirens
Evacuation Map of Zurich: Water Alarm Dam Break Sihlsee dam, 100 Mm$^3$

Seismic Rehabilitation of Existing Dams
Seismic Improvements of 116 Dams
California

- 36 Temporary storage restrictions
- 34 Buttresses added or slopes flattened on earth dams
- 27 Freeboard increased
- 21 Outlet works rehabilitations
- 12 Permanent storage restrictions
- 11 Foundation and/or embankment materials removed and replaced

Seismic Rehabilitation of Spillway on Crest Of Whakamaru Gravity Dam, New Zealand
Rehabilitation of Crest Spillway
Design: 0.1 g, Rehabilitation: 1.8 g

Seismic Rehabilitation of Multiple Arch Dam
Seismic Rehabilitation of Embankment Dam

Seismic Rehabilitation of Embankment Dam
## Economical Life of Dams

**SAFETY:** The life span of any dam is as long as it is **technically safe and operable**!

**MAINTENANCE:** This implies, that the life span is as long as **appropriate maintenance can be provided**.

### Factors Affecting Life-span of Dams

- **Changes in design criteria** (hydrology and seismic hazard) based on new information obtained since the initial design of the dam;
- **Changes in methods of analysis and new safety concepts** (e.g. n-1 rule for flood discharge facilities of embankment dams);
- **Results of risk assessments** (new risks and change in risk acceptance criteria); and
- **Ageing** of construction and foundation materials.
- **Sedimentation** (reservoir)
Mauvoisin Arch Dam, 250 m, Switzerland
Condition of dam after successful operation for 50 Years

Ageing Impact on Life-span of Concrete Dams

- **Chemical processes** (swelling due to AAR), sulphate attack, leaching, etc.,
- **Physical and mechanical processes** (thawing-freezing and drying-wetting cycles, cracking due to seismic actions etc.),
- **Biological processes** (growth of plants in cracks, mussels, etc.), and
- **Seepage in foundation and dam body** (dissolution of material, change in uplift of the dam and the foundation resulting in changes in the stability of the dam and abutment).
Rapid Safety Deterioration of 272 m high Enguri Arch Dam, Georgia

Leakage Traces in 70 Years Old Gravity Dam (high W/C ratio, effect on stability of dam)
Conclusions

- Infrastructure projects must be sustainable such that they can serve the needs of the people for a very long time. Water storage projects, however, cannot be considered sustainable if their safety according to modern standards is not assured.
- Sustainability requires a safe technology and the main factor is safety.

Conclusions

- Life-span of a dam is as long as it is safe, i.e. as long as proper maintenance can be guaranteed.
- A dam, which is safe at the time of completion, does not automatically remain safe.
- Neglecting civil maintenance will lead to a shortened life-span, which signifies an economic loss, and in a loss of confidence in the safety of dams by the affected people.