Modern Dam Safety Concepts

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Integral dam safety concept

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

**Dam Safety Monitoring**
Dam instrumentation, visual inspections, data analysis and interpretation, annual reports, 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.
Structural Safety: Seismic Design Criteria and Flood Safety Criteria

Seismic design criteria 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

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.
<table>
<thead>
<tr>
<th>Title</th>
<th>Element / Component</th>
<th>Design Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversion Facilities</td>
<td>Intake/outlet structures</td>
<td>X</td>
</tr>
<tr>
<td>- Civil</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</td>
</tr>
<tr>
<td></td>
<td>- Individual Blocks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crest bridge</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Crest spillway cantilevers</td>
<td>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</td>
</tr>
<tr>
<td>Bottom Outlet</td>
<td>Main gates, Valves</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Guard gate</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Operating equipment</td>
<td>X</td>
</tr>
<tr>
<td>Dam: Electrical/Mechanical</td>
<td>Essential parts</td>
<td>X</td>
</tr>
</tbody>
</table>

**Typical seismic load combinations used in dam engineering**

- **Usual load combinations:** *no earthquake*
- **Unusual load combinations:** *OBE*
- **Extreme load combinations:** *SEE*
Modern flood safety concept for embankment dams

**Flood design criteria:** The rockfill dam must be able to safely release the check flood (PMF):
For checking the flood safety the following assumptions have to be made for rockfill dams with gated spillways:
1. Power plant is shut down (power intake closed).
2. The gate with the largest discharge capacity is closed. Two of the spillway gates will not be available if the number of openings exceeds 5.
3. The maximum reservoir level shall be below the top of the impervious core.

Safety features of mixed concrete-rockfill dams

- **Flood safety criteria:** Mixed concrete-rockfill dams must satisfy flood safety criteria of embankment dams.
- **Crest elevation of rockfill dam:** To prevent overtopping of the rockfill dam in case of an accident, it is recommended to have a higher crest level of the rockfill dam than that of the concrete structures (spillway). The top of the impervious core shall be higher than the spillway crest.
- **Bottom outlets:** Modern dams must have a bottom outlet or low level outlet for lowering the reservoir in an emergency. These outlets can also be used for sediment flushing.
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.

Risk Classification of Dams

What is a large dam?
Example: Classification of large 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.

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 only 4 Swiss dams would fall under Class 2 and the remaining ones under Class 3 or below, but actually some 160 large dams fall under ‘Klasse 1’ (highest safety class) in Switzerland (reservoir volume > 1 Mm$^3$).

This difference in classification of large dams is the main difference between the Chinese and international dam design codes and regulations. This 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.
Dam Safety Monitoring: Failure Modes and Strong Motion Instrumentation

Critical failure modes

The critical failure modes for embankment dams are as follows:

1. Overtopping of rockfill dam due to (i) inadequate spillway capacity, or (ii) malfunction or blockage of spillway gates

2. Excessive seismic settlements of rockfill dams causing overtopping

3. Internal erosion

4. Damage of contact between rockfill dam and concrete intake and/or spillway structure causing piping

5. Large mass movements into the reservoir causing impulse waves and overtopping of the rockfill dam
The dam monitoring system must be selected in such a way that the development of critical failure modes can be monitored.
Strong motion instrumentation of dams

Minimum System:
- Dam crest
- Dam base
- Free field
Location Map of Instruments, Kasho dam

Accelerometer in elevator shaft

Accelerometer in gallery

Tottori earthquake, Oct. 6, 2000, $M_W = 6.6$, Kasho dam

<table>
<thead>
<tr>
<th>Location</th>
<th>N-S</th>
<th>E-W</th>
<th>U-D</th>
<th>Time (s)</th>
<th>Peak Acc.</th>
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<tbody>
<tr>
<td>Gallery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.54g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.54g</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.49g</td>
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<tr>
<td>Dam Crest</td>
<td>2.1g</td>
<td>1.4g</td>
<td>0.9g</td>
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<td></td>
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</table>

Acceleration Records
Free vibration of reservoir of Kasho dam

- Fourier spectrum
- Water level in cm
- Time (h)
- Fourier spectrum
- Period (min.)

Natural period
$T = 6.5 \text{ min}$

Damping ratio
$0.02$

Tokachi-Oki earthquake, Sept. 26, 2003, peak accelerations recorded at dams

<table>
<thead>
<tr>
<th>Name of Dam</th>
<th>Height in meters</th>
<th>Type</th>
<th>Peak acc. at foundation in gals</th>
<th>Peak acc. at the crest in gals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makubetsu</td>
<td>27</td>
<td>Earthfill</td>
<td>132</td>
<td>261</td>
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<tr>
<td>Bisei</td>
<td>47</td>
<td>Composite</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Sahoro</td>
<td>47</td>
<td>Gravity</td>
<td>82</td>
<td>364</td>
</tr>
<tr>
<td>Kuttari</td>
<td>28</td>
<td>Rockfill</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Iwamatsu</td>
<td>37</td>
<td>Gravity</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tokachi</td>
<td>84</td>
<td>Rockfill</td>
<td>43</td>
<td>155</td>
</tr>
<tr>
<td>Satsumai</td>
<td>114</td>
<td>Gravity</td>
<td>51</td>
<td>677</td>
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<tr>
<td>Urakawa</td>
<td>42</td>
<td>Gravity</td>
<td>102</td>
<td>124</td>
</tr>
<tr>
<td>Sannai</td>
<td>44</td>
<td>Gravity</td>
<td>153</td>
<td>NA</td>
</tr>
<tr>
<td>Takami</td>
<td>120</td>
<td>Rockfill</td>
<td>54</td>
<td>325</td>
</tr>
<tr>
<td>Niikappu</td>
<td>103</td>
<td>Rockfill</td>
<td>156</td>
<td>276</td>
</tr>
</tbody>
</table>
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 dam was replaced by RCC dam

Emergency Planning: Water Alarm Systems for Large Dams
Consequences of dam failure

- Loss of life (top priority)
- Environmental damage
- Property damage in flood plain
- Damage of infrastructure projects
- Loss of reservoir (irrigation, water supply…)
- Loss of power plant and loss of electricity production (dam owner)
- Socio-economic impact
- Political impact

Risk reduction: Non-structural measures

- Operational guidelines for reservoir
- Emergency action plans
- Water alarm
- Training of personnel
- Lowering/restrictions of reservoir level
- Periodic safety checks
- Engineering back-up: to cope effectively with abnormal and emergency situations
- Land use planning (political decision)
- Insurance coverage, third party liability (protection from economic losses)
Risk reduction: Structural measures

- **Flood safety of dam:** Increase spillway capacity and check/improve operation of flood gates
- **Earthquake safety of dam:** Improve safety of gates; rehabilitate deficient elements
- **Geological safety:** Seepage control measures, improve grout curtain; rehabilitate and improve drainage, rehabilitate unstable slopes, grouting etc.
- **Safety of existing facilities:** Dam safety management and emergency preparedness (non-structural), **maintenance (structural)**!
Internal Emergency Action Plan (IEAP)

- The IEAP will guide dam operations, maintenance, supervisory, and owner personnel in identifying, monitoring, responding to, and mitigating emergency situations.
- The IEAP outlines “who does what, where, when, and how” in an emergency situation affecting safety of dam and powerplant.

Evacuation Map: Water Alarm
Basis: inundation map from dam breach flood wave analysis
Evacuation map of Zurich:
Water Alarm Dam
Break Sihlsee dam:
dam about 30 km away from Zurich, reservoir volume: 100 Mm³

Public warning system:
Water alarm and general alarm sirens
**Conclusions**

- Emergency planning and the installation of water alarm systems in the downstream region of large dams is a must. Even if a dam is structurally safe, there are natural or man-made events that could cause failure.
- For emergency planning to be effective, the population affected must be involved and informed about what to do in an emergency.
- The first water alarm systems for dams were installed in Switzerland some 50 years ago and Swiss engineers have been at the forefront of emergency planning ever since.

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**Dam Safety Management**
## Dam safety inspections: 4 levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Responsibility</th>
<th>Activities</th>
<th>Reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Owner (dam safety engineer, technical staff)</td>
<td>Regular inspection of condition (by visual observations) and behaviour (by measurements). Tests of spillway and bottom outlet gates.</td>
<td>Monitoring records and test protocols</td>
</tr>
<tr>
<td>2</td>
<td>Experienced engineer (civil engineer)</td>
<td>Analysis of the measured data and observations. Annual inspection of the dam.</td>
<td>Yearly report on condition and on measured behaviour. Yearly report on condition and on measured behaviour.</td>
</tr>
<tr>
<td>3</td>
<td>Experts (civil engineer and geologist)</td>
<td>Inspection and appraisal of the dam safety every five years.</td>
<td>Report on condition and long-term behaviour. Analysis of special safety related questions. Interventions if measures have to be implemented.</td>
</tr>
<tr>
<td>4</td>
<td>Dam Safety Authority</td>
<td>On-site inspection. Review of the annual reports and the expert’s appraisal. Verification of the implementation of the necessary measures.</td>
<td></td>
</tr>
</tbody>
</table>

### Need for periodic seismic safety checks

Seismic safety evaluations of existing dams have to be carried out repeatedly during the 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 shaking;
- New seismic design criteria are introduced;
- New seismic performance criteria are introduced;
- New dynamic methods of analysis are introduced;
- Seismic vulnerability of dam has increased;
- Seismic risk has increased, etc.
Earthquake Safety, Sustainability and Life-span of Dams

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. Maintenance slows down ageing.
Factors Affecting Life-span of Dams

- **Changes in design criteria** (hydrology and seismic hazard, seismic design criteria) based on new information obtained since the initial design of dam;

- **Changes in methods of analysis and new safety concepts** (e.g. n-1 rule for flood discharge facilities of embankment dams; dynamic analysis methods – inelastic behaviour);

- **Results of risk assessments** (new risks and change in risk acceptance criteria, seismic vulnerability of dams);

- **Ageing** of construction and foundation materials (decrease in seismic safety), and

- **Sedimentation in reservoir** (change in dynamic interaction with reservoir).

Life-span of concrete

- Extrapolation of concrete performance to 150 or 200 years is rather difficult as no reference dam projects exist.

- Studies (temples, storage of radioactive waste) have shown that service lives of up to 500 - 1000 years would be possible if no reinforcement is employed and special (low-heat) cements and stable aggregates are used.

- Under ideal environmental conditions (temperature, humidity etc.) the service life of a concrete dam can be very long.
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).
Leakage traces in 70 years old gravity dam
(high water-cement ratio, effect of pore pressure on dam stability)

Conclusions

For dam safety to be credible an integral dam safety concept has to be used, which includes the following:

- Structural safety
- Dam safety monitoring (dam safety management)
- Operational safety
- Emergency planning

All elements are equally important.