SAFETY ASSESSMENT OF DAMS
Structural Analyses

- Linear and nonlinear analyses of embankment and concrete dams;
- Seismic fluid-structure and soil-structure interaction modeling and analyses;
- Assessment of ultimate seismic capacity of embankment and concrete dams;
- Seismic optimization of new built and seismic strengthening of existing dams;
- Probabilistic seismic hazard analyses and microzonation;
- Seismic probabilistic safety assessment of large dams
Experience in Safety Assessment of Dams

- Seismic Probabilistic Safety Assessment of *Vacha Dam*
- SPSA of *Kardjali Dam*
- SPSA of *Chaira Dam*
- SPSA of *Tsankov Kamak Dam*
Experience in Safety Assessment of Dams (2)

- Seismic Probabilistic Safety Assessment of Iskar Dam
- SPSA of Studen Kladenetz Dam
- SPSA of Beli Iskar Dam
Seismic Probabilistic Safety Assessment of Large dams

Vacha Dam
Dam Types

Arch and Double-arch Dams

All types of Gravity dams
Seismic Risk Assessment Approach

- PSA procedure used for critical facilities mainly in nuclear industry
- Codes requirements taken into account (ICOLD, USACE, FERC, FEMA)
- Realistic assessment of the seismic hazard for the region
- Statistically defined material properties
- Statistically defined loads
- Reliable numerical models
- Reliable calculation procedure
Seismic Risk Assessment Approach (2)

- **Statistical assessment of the response:**
  - Maximal and average stresses;
  - Depth of cracks;
  - Sliding and overturning forces etc.

- **Definition of damage and failure scenarios:**
  - Exceedance of the material strength;
  - Occurrence of critical cracks;
  - Loss of global and local stability;
  - Abutments failure (for arch dams);
  - Criteria based on various damage and failure parameters: strength, displacements, DI etc.;
  - Secondary risk assessment
Definition of the conditional probability of failure:

$$P_f = \int FR(x)f_L(x)dx$$

- $FR(x)$ - distribution function of the resistance
- $f_L(x)$ - density function of the loading distribution

Generation of fragility curves;

Definition of the global seismic risk;

Sensitivity analysis
Numerical Modeling

- 2D and 3D FEM models including foundation rock base and water reservoir
Rock foundation:
- Elastic massless media;
- All foundation layers and weak zones included;
- Material properties from laboratory and in-situ tests

- Size of the model depends on $Ef/Ec$ (foundation/concrete):
  - if $Ef/Ec \geq 1 \rightarrow$ 1 dam height in the three directions;
  - if $Ef/Ec = \frac{1}{2}$ or $\frac{1}{4} \rightarrow$ up to 2 dam height in the three directions.
Base Joint Modeling

- Springs or contact (interface) elements;
- Layer of finite elements representing the real geometry and base joint behavior;
- Material properties based on laboratory tests;
- Nonlinear material and reduced shear transfer after cracking;
- Decreased dynamic tensile strength - up to 30% of the concrete tensile strength;
Contraction Joints Modeling

- Contact (interface) elements;
- Coupled springs;
- Layer of finite elements with adequate behavior (intact shear stress transfer after cracking);
- Decreased dynamic tensile strength – lower than base joint: 0-15% of concrete tensile strength;
Concrete Material Properties

- Seismic tomography
- Laboratory tests
- Geological and seismic investigations
Concrete dynamic material properties:
• Linear or nonlinear material models;
• E-modulus – 15-25% higher than static;
• Compressive strength – 15-25% higher than static;
• Tensile strength – 40-60% higher than static (Raphael, 1984).
Hydrodynamic Loads

- Westergaard added masses approach;
- Fluid elements based on velocity potential;
- Min 3 layers of elements and minimum extend equal to the depth of the reservoir;
Based on Seismic Hazard Assessment

- Input records compatible with the uniform hazard response spectrum
- Excitations for various Seismic Levels with different return periods, including OBE and MCE
Temperature Load

- Air and Water Temperature curves for the dam site;
- Transient thermal analyses based on annual temperature changes;
- Displacements and stressed state from temperature loading;
Dynamic Properties of the Structure

First mode shape: 1.919 Hz

Second mode shape: 2.772 Hz
- Excess of tensile stress;
- Cracks propagated into dam’s body;
- Cracks across whole cross section and subsequent detached fragment stability;
- Zones with maximum compressive stresses;
- Abutment stresses and stability;
Deterministic Analyses

Critical Zones. Damage and Failure Scenarios

- Zones with maximum and residual contraction joint opening;
- Loss of arch action;
- Free cantilever stability in case of opened contraction joints;
- Base joint damages and possible water infiltration;
Deterministic Analyses
Post-earthquake Safety Assessment

- Post-earthquake stability assessment for static loads;
- Post-earthquake stability assessment for dynamic loads (aftershock);
- Stability of Detached Fragments
Seismic Risk Assessment

Generation of Fragility Curves for Damage and Failure scenarios

Abutment Sliding Stability

Damage scenario for Base joint
## Seismic Risk Assessment

<table>
<thead>
<tr>
<th>№</th>
<th>Damage Scenarios</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>1.</td>
<td>Downstream side cracking damages</td>
<td>4.89E-5</td>
</tr>
<tr>
<td>2.</td>
<td>Base joint cracking damage</td>
<td>4.89E-5</td>
</tr>
<tr>
<td>3.</td>
<td>Compressive Strength Exceedance</td>
<td>1.11E-5</td>
</tr>
<tr>
<td>4.</td>
<td>Contraction joints opening</td>
<td>9.33E-7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure Scenarios</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2.54E-7</td>
</tr>
<tr>
<td>2. Abutment Sliding</td>
<td>2.31E-6</td>
</tr>
<tr>
<td>3. Global Upstream failure of the Dam Structure</td>
<td>4.43E-7</td>
</tr>
<tr>
<td>4. Global Downstream failure of the Dam Structure</td>
<td>9.33E-7</td>
</tr>
</tbody>
</table>
Seismic Risk Mitigation Measures

- Dam pre-stressing;
- Seismic belt;
- Vertical reinforced concrete elements;
- etc.
Ultimate Capacity Assessment of Dam Structures

Failure Mode – Upstream Direction

Failure Mode – Downstream Direction

Graph: Displacement vs. Force

Legend:
- CRUSHED
- NORMAL
- CLOSED
- 1 CRACK
- 2 CRACKS
- 3 CRACKS
Additional Methods for Seismic Safety Assessment of Dams

- Rapid Seismic assessment and Damage prediction;
- Better understanding of Classical methods results;
- Use of displacement-based procedures;

$$DI_i = \frac{d_{r,i} - d_y}{d_u - d_y}$$
Stability Assessment of Embankment Dams

- Stability Assessment in case of Static and Dynamic Loads;
- Overall Stability Assessment;
- Seepage studies;
- Slope Stability Investigations;
- Stress and Deformation Analyses
Post-earthquake Damage Prediction Procedures

- Alerts for expected damages in the dam structure after seismic event;
- Based on various Damage Intensity Parameters (DIP);
- Multi-stage algorithms;
- Implementation in the monitoring system of the dam;
EXAMPLES

BELI ISKAR DAM

Type – concrete gravity
Height – 50.7 m
Crest length – 533 m
Crest thickness – 3.4 m
Reservoir volume – 15.3 mln. m$^3$
Type – concrete gravity
Height – 67.5 m
Crest length – 338 m
Crest thickness – 8.8 m
Reservoir volume – 380 mln. m³

EXAMPLES

STUDEN CLADENEC DAM
Type – arch gravity  
Height – 103.5 m  
Crest length – 338 m  
Crest thickness – 5.0 m  
Reservoir volume – 530 mln. m³
Completed 2010
Type – arch double curvature
Height – 130.0 m
Crest length – 468 m
Crest thickness – 9.0 m
Reservoir volume – 111 mln. m³

Tsankov Kamak HPP under construction
Type – concrete gravity dam
Height – 75.0 m
Crest length – 204 m
Crest thickness – 7.3 m
Reservoir volume – 650 mln. m³