The highest dam of the world in a challenging geological environment

The proposed Rogun 335m high dam, Tajikistan

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Disclaimer

The views and opinions presented here belong to the authors and do not reflect the views and opinions of the World Bank Group.
Map of Tajikistan indicating Rogun dam site
NUREK DAM, 300m high, downstream of ROGUN
Structure of the presentation

1. The project

2. The geological context

3. The site and the selection of the dam type

4. The Power House. A dangerous creep or not?

5. The salt wedge. Assessment and mitigation measures

6. The downstream strange morphology. A huge landslide or not?
Rogun dam on Vakhsh river, Amu Daria tributary

**Owner:** Government of Tajikistan

**Status:** Under construction

Construction begun in 1976

**Height:** 335m (max option)

**Reservoir:** 13.3km$^3$

**Flood:**
- PMF: 7,500 to 7,770 m$^3$/s
- 1/10,000: 5,600 to 5,700 m$^3$/s

**Power**
- Turbines 6
- Installed capacity: 3600 MW
ROGUM DAM
Government of Tajikistan
Studies started in 1963 and construction activities in 1976
Studies:
1963-1978 Hydroproject Tashkend
1992-93 Hydroproject Tashkend
2000 Hydroproject Institute Moscow (HPI)
2004-06 Lahmeyer and HPI
2009-2014 HPI
In 2007, the Government of Tajikistan requested the World Bank to assist with the Techno-Economic Assessment Study and Environmental and Social Impact Assessment Study
2011 Consultant for Techno-Economical Assessment (TEAS): Consortium Coyne et Bellier / Electroconsult / IPA
2011 Consultant Environmental and Social Impact: Poyry
And
Panel of Experts on Engineering and Dam Safety
Panel of Experts
Engineering and Dam Safety

Roger Gill, Hydropower
Ljiljana Spacic-Grill, Dam Engineering, Seismic Eng
Paul Marinos, Engineering Geology
Ezio Todini, Hydrology
Gregory Morris, Sedimentology
John Gummer, Energy

To ensure due diligence and international quality standards in studies
To provide independent advice and guidance in the assessment process
To share technical expertise and knowledge

has added significant value to the prospect of developing a sustainable project at Rogun
1. The geological context
India-Asia collision and induced deformation within Eurasia. Note that the Rogun HPP is located within the western syntax of the Himalaya, which is characterized by intensive shortening. (BRGM for TEAS, 2014)
Regional geology
Depression, decollement and thrusting structures and faults

**Principal faults**

1. Crustal faults
   - >500 km long, 50 km deep
   - Guissar-Kokshal fault,
   - Illiak-Vakhsh fault,
   - N boundary of the Tajik Depression

2. Regional faults in the TD
   - ~100 km long, rooted in Jurassic salt layer
   - Ionaksh fault in dam foundation
   - Gulizindan fault

3. Local faults
   - <5 km long
   - Fault no.35, in dam foundation

From TEAS consultant reports
2. The site
Geology and selection of the dam type
Design implications
Rogun dam
Site Geology

Alternations of sandstones and siltstones

In blue the stage I construction for early power production
Site geology – Lithology

- **Upper Jurassic evaporites**: halite, gypsum, anhydrite, 400 m thick; 20 m reddish mudstone cap
- **Lower Cretaceous continental series**: alternating sandstone, siltstone, mudstone (shales), 1100 m thick
- **Marine sedimentary series**: siltstone, shales, gypsum, dolomite, limestone; often fossiliferous; 550 m thick
Exploring the Ionakhsh fault
• The site is tight and there are several constraints, namely:
  
  o The Ionakhsh creeping fault and potential seismic movements
  o Salt wedge in the foundations
  o Fault No. 35 and potential seismic movements
  o Location of intake portal for existing diversion tunnels
Initial thoughts for an arch gravity dam avoiding the lonakhsh and other fault
**Concrete dam**: not suitable due to high heterogeneity although persistence of strong layers. Presence of active, creeping faults (creep estimated up to a few mm/year).

**Embankment dam**: can accommodate faults movements, for both earthquake associated displacement and aseismic creep. Activity of faults needs to be considered also in tunnel design.

Risk of co-seismic ground rupture causing large displacements along the Ionaksh and #35 faults is considered low. No sign of Quaternary displacements along these fault exist, as reported.
Typical cross section of the dam – TEAS Consortium
Dam site geological map with Ionakhsh Fault and other main faults; limits of Stage 1 dam are highlighted in blue for the downstream site (upstream, there are same as for the final dam, which will include the Stage 1 dam).
Surface spillway
3. Power House

A dangerous creep or not?
The machine cavern is located in a series constituted by sandstone and siltstone. It is approximately 21m wide, 69m high and 220m long.

Large amount of excavation have been already conducted, mainly in the siltstone area, where the elevation of the excavated floor is today more than 30m in height.

Time dependent deformations were exhibited since the late 80s and questions were raised about an increasing creep behavior possible to compromise its stability. This is mainly for the siltstone section.
The convergence as presented in the graph of HPI report 2012.

Significant wall closure has been recorded amounting to 600mm in the siltstone sections up to the middle of 2008 and about 750mm up to August 2102.

*Note: the scale of time is irregular and the gradient of convergence is actually lower.*
The causes

The PoE suggested, the possibility of progressive distress of the rock mass in association with the ageing of the strengthening measures applied since the late 80s, to be the reason of the time dependent deformation and not a gradual deterioration of the petrographic quality due to softening of the siltstone. Such a state can be addressed efficiently by additional support in the sidewalls.
Distressing of the siltstones after excavation, under the concrete struts

Placement of struts to face deformations
A residual GSI (from Cai et al)

Distressed siltstone in cavern
Results of the Powerhouse – Transformer Hall 2D Model

Identification of possible remedial measures and preliminary evaluation of their behaviour

- Installation of additional tendons
- Multiple Packer Sleeved Pipe System in the pillar between PH and TH
- Possibility of struts
- Installation of a suitable monitoring system

Modelling by G. Barla
4. The salt wedge
Assessing conditions and mitigation measures
A salt wedge exists under the upstream part of the dam axis along the creeping Ionakhsh fault which, if not addressed effectively to prevent dissolution by the potential hydraulic gradient, could impact the feasibility of the project.
ASSESSMENT – THE SALT WEDGE

In Nurek area
ASSESSMENT – SALT WEDGE

• The geometry of the salt body has been extensively investigated since the first studies.

• Salt body has a wedge shape with a thickness increasing with depth.

• Under the effect of orogenic forces the salt is being extruded at an estimated rate of 2.5 cm per year.

• It is being dissolved at the same rate, resulting at present stage, in a state of equilibrium.

• The impoundment of the Rogun reservoir would result in an increase in the hydraulic gradient and this increase, if not mitigated, would result in an increase in the dissolution rate and a formation of cavity.
Approach - Modelling

- Modelling,
- Following an initial modelling by the Soviet designers
  - Three interconnected sub-models have been set up by TEAS consultant
    - Groundwater flow model
    - Dissolution process model
    - Transport model

- Assess independently existing models
- Assess a number of scenarios
- Carry out sensitivity analysis on the most sensitive parameters
- Assess mitigation measures efficiency
- Carry out risk assessment
**ASSESSMENT – REMEDIAL MEASURES**

Proposed by the initial designer, 1978 and the TEAS consultant, 2013.

- Grouting of the rock all around the top of the salt wedge
- Hydraulic barrier: series of boreholes on the downstream side of the salt wedge to maintain reservoir pressure so as to minimize water gradient between the two sides of the salt wedge
- Both measure to be applied. One will cover any possible deficiency of the other.

A 3rd level of protection using a brine curtain initially considered is not further considered due to clogging of injection holes and the enormous quantities of salt required.
Grouting of the salt zone along the Ionakhsh fault
If the two mitigation measures would happen to fail or lose their efficiency, the grouting and hydraulic barrier would have to be re-implemented.

- **Stage 1:** the re-grouting and reinstallation of the hydraulic barrier can be performed from the crest of the stage 1 dam.

- **Stage 2,** the only option for re-grouting and hydraulic barrier restoration would then be to operate from the banks, above the reservoir water level. This could be implemented only using directional boring.
5. THE DOWNSTREAM STRANGE GEOMORPHOLOGY

A HUGE LANDSLIDE OR NOT?
The downstream atypical area at the right valley side
Geological setting of the Right Bank

Proposed model in previous studies
Sinks on the plateau, right valley side downstream of the dam
RIGHT VALLEY DOWNSTREAM

- Few rock debris on the surface
- Topography uphill does not suggest large scale movement
- Geophysics in 2005 anticipated shallow overburden;
- Results of 2012 geophysics show compact low specific gravity material
- New borehole revealed continuous, undisturbed, compact gypsum/anhydritic deposits in mudstone matrix, starting from shallow depth: the reason of sinks due to dissolution
The plateau (elevation about 1700) with small depressions due to dissolution

Present assessment:
A tectonic structure, due to evaporitic diapyrism not to a landslide
A tectonic structure not a landslide
Model by the Consultant of TEAS
Geology in the mood.
Design have to comprehend it
for a peaceful cohabitation
of man structures and nature

Thank you for your attention
## Seismic hazard

### Seismogenic sources

<table>
<thead>
<tr>
<th>Seismogenic source</th>
<th>Epicentral distance</th>
<th>Focal depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vakhsh / Ionakhsh / Gulizindan system</td>
<td>0 km</td>
<td>10 km</td>
</tr>
<tr>
<td>South Tienshan / Guissar system</td>
<td>5 km</td>
<td>15 km</td>
</tr>
</tbody>
</table>

### Peak Ground Accelerations

<table>
<thead>
<tr>
<th>Design earthquake</th>
<th>Return period (years)</th>
<th>PGA Vakhsh/Ionakhsh/Gulizindan</th>
<th>PGA South Tienshan/Guissar</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBE</td>
<td>150</td>
<td>0.40g</td>
<td>0.35g</td>
</tr>
<tr>
<td>MDE</td>
<td>1000</td>
<td>0.53g</td>
<td>0.47g</td>
</tr>
<tr>
<td>MCE</td>
<td>1000</td>
<td>0.63g</td>
<td>0.52g</td>
</tr>
</tbody>
</table>
CONDITIONS OF DAM ABUTMENTS

1. Rock mass permeability under the dam is not high. A conservative design in depth of the grout curtain would further reduce the hydraulic gradient against any potential impact on the salt wedge upstream.

2. Narrow saddles exist on the abutments beyond the dam axis; due to stress relaxation, rock mass is probably more permeable in these zones. Thus lateral extension of the ground curtain might be necessary, into the right abutment, depending on the position the pre-reservoir ground water table (hydraulic barrier).
Amu Daria River to the lake of Aral,
The Oxos of Alexander the Great
The portal of the diversion tunnels just downstream of the Ionakhsh fault
Several types of dams have been considered and commented by the Consultant and the PoE:

- Clay core embankment dam,
- Concrete arch dam,
- Concrete Face Rockfill dam (CFRD),
- Gravity Roller Compacted Concrete (RCC) dam,
- RCC arch gravity dam,
- RCC arch dam
RECOMMENDATIONS - MONITORING

• Accurate monitoring of the salt dome rise:
  – measurement of the displacements within the salt wedge and the embedding rock, follow-up of the deformations within the salt body by series of inclinometers.

• Monitor potential salt leaching, the following systems are proposed:
  – groundwater head monitoring, in order to check the hydraulic barrier efficiency (boreholes and pressure cells),
  – water conductivity monitoring to check the model reliability and the on-going leaching process if any (boreholes and conductivity cells),
  – microgravity in order to check the salt rising rate at Ionakhsh Fault and potential cavity generation
  – regular sonar inspection of the dam face once impounded, to detect any abnormal deformation of the upstream face.
Fig. 7. The plateau at the right side of the valley, downstream of the dam, seen from downstream (photo from Google)
Recent site investigation in the plateau area of the downstream zone

- Geological mapping 1:2000
- 3 boreholes (1 deep 300 - 500m)
- Geophysics
- Geodetic measurements
#7 refers to the salt wedge intrusion