OSHPC BARKI TOJIK

TECHNO-ECONOMIC ASSESSMENT STUDY
FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

Phase 0 Report – Geological and Geotechnical Investigation of the Salt Wedge in the Dam Foundation and Reservoir

Summary

COYNE ET BELLIER
Ingénieurs Conseils

ELC
ELECTROCONSULT

IPA
Energy + Water Economics

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Summary

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1 OBJECTIVES OF THE REPORT

The Phase 0 Report examines the potential impact on dam safety of the wedge of salt that exists along the Ionakhsh Fault, which cuts across the Rogun dam site in a roughly NE-SW direction, in the upstream part of the dam axis (cf. Figure 1-1).

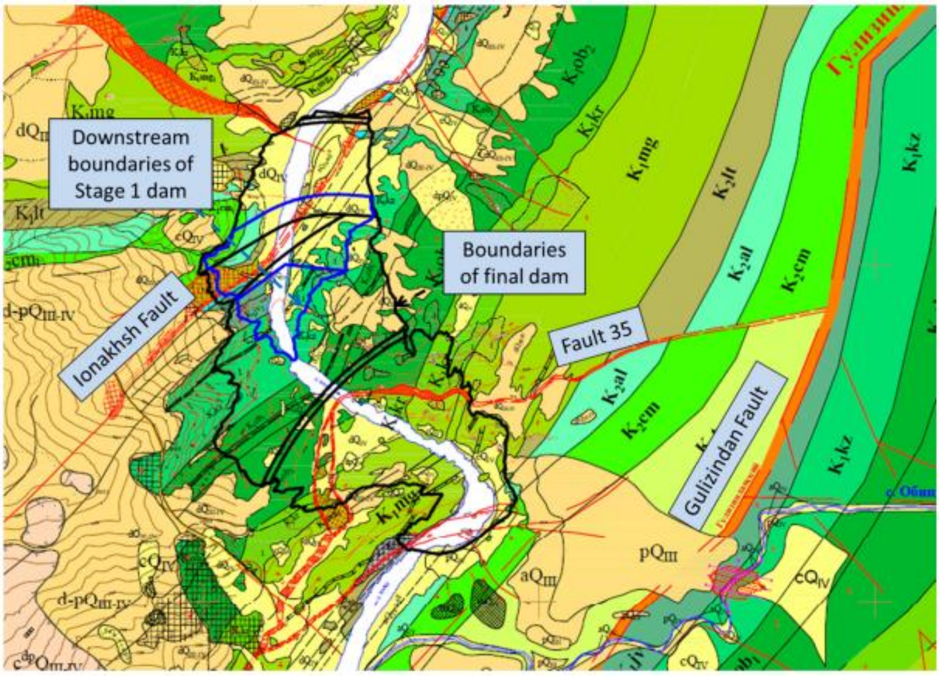

Figure 1-1: Dam site geological map with Ionakhsh Fault and other main faults; limits of Stage 1 dam are highlighted (in blue), limits of final dam (in black) for the El. 1290 Full Supply Level Alternative

The geometry of the salt body within the Ionakhsh Fault has been extensively investigated since the first studies were conducted on the proposed Rogun project. The investigations have shown that the salt body has a wedge shape, the top of which, at the maximum elevation, has a variable width from 1.5-2 m within the left bank to up to 12 m within the right bank. The thickness of the salt wedge increases with depth, with an average 15 m increase every 100 m depth.

Under the effect of orogenic forces (i.e. the folding and faulting of the earth’s crust), the wedge of salt is being extruded along the Ionakhsh Fault at an estimated rate of 2.5 cm per year. In the vicinity of the Vakhsh River, it is being dissolved at a similar rate, resulting 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 possible formation of a cavity.

This summary presents the potential salt dissolution scenarios analysed by the Consultants, and the proposed mitigation, monitoring and remedial measures to be undertaken during Rogun's operation. This assessment has been reviewed by the Government of Tajikistan, the independent Panel of Experts and the World Bank technical team. The Phase 0 Report will be finalized after comments received from riparian and civil society stakeholders on this summary are reviewed and appropriately taken into account.

2 SCOPE OF THE ANALYSES PERFORMED

A thorough analysis of the hydrogeological phenomena has been carried out, and the existing numerical models that have been used in previous studies have been reviewed. New models have been developed by the TEAS Consultants to independently assess the results of the previous studies.

Specific hydrogeological conditions at the Ionakhsh Fault were assessed in the context of the overall site hydrogeological conditions, with special focus over prevailing conditions in the cap aquifer (i.e. the aquifer created above the top of the salt wedge in the space filled with the residues of the salt dissolution). A pumping test was carried out by the Consultants to determine the in-situ hydraulic conductivity and effective porosity of the cap aquifer.

The mitigation measures proposed in previous studies to control the dissolution process were assessed. New mitigation measures have been proposed by the Consultants utilizing up-to-date technologies. The efficiency of the recommended mitigation measures to reduce dissolution has been assessed in sensitivity analyses and the Consultants have proposed monitoring of the performance of the mitigation measures through the use of predictive modelling. The estimated costs of the proposed mitigation measures have been derived to be included in the overall estimated cost of the proposed project.

3 SITE HYDROGEOLOGICAL CONDITIONS

The general site hydrogeological conditions have been assessed based on a complete review of available investigations and a field survey carried out by the TEAS Consultants. The different aquifers were identified and their natural conditions and attributes assessed. The different physical characteristics to be used in the hydrogeological modelling were derived from the results of tests from previous investigations. Where previous investigations were deemed insufficient, new, complementary tests were conducted in 2012 under the supervision of the TEAS Consultants. For example, 18 boreholes at the dam site were equipped in observation wells and monitored by the TEAS Consultants. This was to ensure that the key inputs of the hydrogeological modelling are representative of the real site conditions.

4 DISSOLUTION PHENOMENA AND MODELLING PRINCIPLES

4.1 Dissolution processes characterization

Dissolution is the process by which water forms a solution in contact with a soluble material acting as solute. Each main component of the phenomenon is analysed, namely the soluble material characteristics, the solvent (water) characteristics and the different transport phenomena of the solute to be envisaged (advection/convection, diffusion, gravitational convection). The Péclet number (a dimensionless number relevant in the study of transport phenomena in fluid flows) has been evaluated for the different scenarios envisaged to understand which transport process is predominant in the dissolution of the salt, and this was used to assess potential dissolution rates.

4.2 Geometry and characteristics of Ionakhsh Fault

The model developed for the analysis is based on a thorough evaluation of all documentation available since the original 1978 design and up to 2012, when a new pumping dissolution test was conducted by the TEAS Consultants. This gives an accurate location and delimitation of the salt wedge within the Ionakhsh fault, detailed lithological composition of the hemming rock, detailed nature and composition of the dissolved rock residues around the salt wedge (mostly made of halite and anhydrite), the hydraulic conductivity, and the solubility of the studied material.

The Ionakhsh Fault is bordered with salt extruded from a deep evaporitic layer. It is capped on its top with clay and gypsum. The width of the salt zone increases with depth from 1 to 8 m at the top to 40-60 m at a depth of 200 m. Further down to a depth of 2-3 km, the thickness of the salt increases by about 15 m, every 100 m depth. The top of the salt wedge in the banks is located at elevation 956 m to 970 m. There is no salt above this elevation; it has been dissolved.

Under the compressive horizontal tectonic forces the salt is creeping, resulting in a salt wedge rise that was estimated at about 2.5 cm/year in previous studies. As no recent records have been found on this rate of rising, a sensitivity analysis was conducted on this crucial parameter in the model.

All previous studies of the salt wedge assumed that the depth of the un-dissolved top of the salt wedge below the Vakhsh River does not vary with time, which means that there is equilibrium between dissolution and salt wedge rising. This is a fundamental assumption in model calibration, and has been carefully reviewed by the Consultants. The Consultants have concluded that this assumption is valid. However, sensitivity analyses have been carried out for the case when the assumption of equilibrium is not considered valid.

Lithological conditions around the salt wedge are presented in the following figure. The hemming rock is gypsum coated argillite of Gaurdak Formation on the downstream side and sandstone interbedded with aleurolites on the upstream side. This figure shows the typical sequence as evidenced by boreholes and investigations.

Figure 4-1: Lithological conditions above the salt wedge

4.3 Pumping dissolution test of end 2012, results interpretation

A pumping test was performed from November 16 to December 10, 2012, for which a 48 m deep borehole was drilled with a 10” diameter. This borehole was drilled in the limited portion of the bank where the fault has not yet been grouted. During the test, the following parameters were measured: discharge, drawdown, electric conductivity of water, total mineral content at the well itself. In addition, drawdown at a neighbouring piezometer was measured.

This large-scale pumping dissolution test allowed deriving transmissivity and hydraulic conductivity values of the cap aquifer that are fundamental inputs for the different models. Analysis of the results allowed a better understanding of the aquifer’s attributes under the present conditions. This pumping dissolution test confirmed the order of magnitude of the salt wedge rate of rise, based on an analysis of the salt content over time.

The hydraulic conductivity derived from this test was used to derive the Péclet number for the different conditions considered, showing that **the transport process is slow and diffusion contributes moderately to the process in the present conditions**.

The fact that diffusion is an intervening transport process is corroborated by the observation of a significant salt content inside the hemming formations upstream as well as downstream. In case of pure advective/convective or dominant advective/convective transport, the higher concentrations would only be observed within the downstream part of the hemming rock.

5 MATHEMATICAL MODELLING OF THE DISSOLUTION PROCESS

5.1 Assessment of current HPI model

The model developed by HPI (Hydroproject Institute Moscow) is calibrated on the natural conditions before the grouting of Ionakhsh Fault, which now extends almost all along the dam site, except for the Vakhsh River bed and part of the left bank.

The calibration process is based on the equilibrium between the assumed 2.5 cm/year rate of uplift of the salt wedge, and the dissolution of the salt at the same rate. The model resulted in acceptably similar levels between the calculated and observed salt concentration distributions inside the Ionakhsh Fault hemming rock.

The transport laws used in the model, including the gravity convection process, represent as best as possible the reality. Unfortunately, the input value for the hydraulic conductivity, which is one of the most crucial parameters, is not conservative. An overestimation of the kinematic porosity seems not conservative, because it slows down the transport process. The adopted value resulted from the consideration of several water tests performed in the vicinity of the wedge cap, but no pumping test allowing determination of realistic values for the hydraulic conductivity of the wedge cap aquifer was performed.

Using the parameters deduced from the 2012 pumping test, with the 50% to 75% of clay coating of the HPI model, would lead to a simulated dissolution that could be significantly higher than assessed by the HPI model, requiring a 25 cm salt dome yearly rise for equilibrium in the actual conditions. There has been no field evidence of such a high rising rate of the salt wedge within the Ionakhsh Fault, thereby showing the limitations of the calibration of the present model.

All the scenarios were analysed with parameterization of the hydraulic conductivity of the grouted cap, assuming the wedge cap is covered by clay over 50% and 75% of its surface.

The whole model reliability is very sensitive depending upon:

- The percentage of the surface of the top of the salt wedge assumed to be clay-coated.
- The effective natural rising rate of the salt wedge within Ionakhsh Fault.

The HPI model needs to be enhanced and recalibrated.

5.2 TEAS Models

The TEAS Consultants have built their own model in order to assess independently the model prepared by HPI, but they haves also used a parametric analysis to assess scenarios and extreme conditions which were not considered in the previous studies. This provides a wider range of sensitivity analyses for the overall risk assessment of the dissolution phenomenon.

The Consultant's model is less sophisticated than the HPI model and is meant to be a tool for overall assessment and decision making at the assessment stage.

The whole dissolution process is simulated by three separate sub-models which are used sequentially:

- **Sub-model 1 - Groundwater flow model:** It simulates the groundwater flow around the salt wedge for various natural conditions, different project stages, mitigation works and different levels of mitigation efficiencies.
- **Sub-model 2 - Dissolution process model**: It models the maximum dissolution ability inside the part of the salt wedge subject to dissolution. It takes into consideration: the whole chemical process, dissolution kinetics and concentrations at equilibrium, and composition of the evaporite. The results are the dissolution rates of the salt for different scenarios. The gradient at the salt wedge is obtained from Sub-model 1.
- **Sub-model 3 - Transport model**: It models the transport processes: diffusion and advection/convection. The gravity convection is not modelled. In this model, the appropriate analytical formula (advection, diffusion) are used. The results from the pumping test (hydraulic conductivity and kinematic porosity) are used. The groundwater gradients are obtained from Sub-model 1. The model is calibrated on the observation that the dissolution is equal to the salt wedge rise.

Sensitivity analyses indicate that the most sensitive parameters are the hydraulic conductivity, the groundwater gradient, the wedge uplift and the clay coating. There is no or only limited uncertainty regarding the hydraulic conductivity, but this could be significant for the clay coating and the rate of rise of the wedge.

Different scenarios for various wedge rising rates are considered for Stage 1 and 2 conditions, taking into consideration the period of exposure of each situation.

A study was carried out to determine the maximum cavity size that would not damage the core and filters of the dam as a consequence of cavity-induced embankment movements. A conservative assessment shows that cavity generation generated by salt dissolution might be critical only if larger than 25 m. For the purpose of this study, a factor of safety of 3 was used, and an 8 m cavity threshold was used to ascertain the acceptability of the results of different scenarios.

Mitigation measures considered were:

- Cap grouting, or grouting of the rock all around the top of the salt wedge,

- Implementation of a hydraulic barrier, which consists of a series of holes on the downstream side of the salt wedge to maintain the reservoir pressure, so as to minimise the water gradient between the two sides of the salt wedge.

The following scenarios were therefore analysed:

- Existing conditions prior to any mitigation work, for the model calibration based on an observed natural equilibrium between salt dissolution and salt wedge rising;

- The “No remedial measures” option after the construction of the Stage 1 dam, *i.e. no mitigation measures is implemented*.

- Each of the following mitigation measures implemented for the three different dam height alternatives:

    - Grouting of the cap alone;

    - Reduced efficiency of the grouting of the cap alone (i.e. long term loss of efficiency of grouting);

    - Hydraulic barrier alone;

    - Hydraulic barrier and cap grouting;

    - Hydraulic barrier and reduced efficiency of the cap grouting.

In all cases, the size of the generated cavity is always less than 3 m, or the salt wedge penetrates the dam body.

The consequences of the salt wedge penetrating the dam body are negligible. The dam fill above the Ionakhsh Fault has a porosity of about 10%. The salt intrusion will happen very slowly; it will begin to fill the voids in the dam body and be dissolved by the impounded water in the upstream part of the dam fill until a new equilibrium is reached. In the worst case, this new equilibrium will be a return back to the initial conditions, which would be controlled by the proposed mitigation measures.
One specific “worst case” scenario has been studied: considering reduced hydraulic barrier efficiency, reduced efficiency of the grouting and loss of clay coating of the salt wedge, for a 40-year delay in construction after the Stage 1 dam. In this case, the cavity generation might exceed 5 m.

There is no significant groundwater gradient difference at the salt wedge for the three dam alternatives for Stage 2.

6 MAIN MODEL CONCLUSIONS

The conclusions arrived at from the various analyses performed are as follows:

- “No remedial measures” option at Ionakhsh Fault, i.e. dam constructed without any mitigation measure against salt dissolution. This is not acceptable for scenarios with high wedge rising rates or an extended duration before the completion of Stage 2, because with time dissolution could lead to large cavities that could affect the water retaining function or even dam integrity.

- The most effective combination of mitigating actions is grouting and a hydraulic barrier. In that case, and even considering the most pessimistic values of porosity and hydraulic conductivity, no significant dissolution or cavity formations are observed. In most cases, with time, the salt wedge will intrude the dam body.

- A brine curtain (brine injection into the cap aquifer) would theoretically further reduce the dissolution process. Unfortunately, previous trials proved the brine curtain technique to be unreliable because of clogging phenomena and because of the enormous quantities of salt required for its operation. The model shows that the brine curtain appears to be superfluous.

- All results are dependent on the part of the wedge cap surface covered with clay; the clay-coating is very favourable because it inhibits the dissolution process. It is certain that the top of the salt wedge is coated with clay because the evaporites have a significant clay content, the clay coating has been observed in boreholes at the site, and this clay-coating is generally observed worldwide on extruding diapirs.

- The combination of hydraulic barrier and grouting should lead to an acceptable dissolution rate that remains lower than the rate of salt wedge rise. The grouting operations at the top of the salt wedge should be sufficient to reduce the dissolution rate to an acceptable level, even if the achieved hydraulic conductivity is less than 10 LU (Lugeon Units, an approximate hydraulic conductivity of 10^{-6} m/s);

- Using only a hydraulic barrier could be sufficient, but in case of significant loss of efficiency, the situation would turn into the “no remedial measures” scenario, which is unsafe. The same conclusion is drawn in case of only cap rock grouting. **It is therefore required to implement both of these mitigation methods: grouting of the cap rock and inserting a hydraulic barrier**.

Taking into consideration the possible inaccuracy of some input parameters (the rate of salt wedge rising being the most crucial), the scenarios results have to be considered with a safety factor of 3. Except for one scenario, they all show that there is no risk that the dissolution could generate unacceptable cavities.

The only critical scenario is that of a 40-year delay before the completion of the Stage 2 dam, because the hydraulic barrier could degrade, the efficiency of the grouting could be reduced, and the clay cap could be removed. However, this scenario implies that during that time no monitoring and/or maintenance of the mitigation measures would be implemented.

Given the experience of the Tajik authorities in monitoring the downstream Nurek dam over several decades, the risk of monitoring failure or/and maintenance abandonment is expected to be low but shall be still considered in the overall risk analysis of the project.

7 RECOMMENDATIONS

7.1 Monitoring

Accurate monitoring of the salt dome rise has to begin immediately. This value is crucial for confirming the dissolution rate prediction and models' reliability. It should consist of:

- measurement of the displacements within the salt wedge and the embedding rock, and
- follow-up of the deformations within the salt body by a series of clinometers.

In order to monitor potential salt dissolution, 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 dissolution process if any (boreholes and conductivity cells);
- microgravity in order to check the salt rising rate at Ionakhsh Fault and potential cavity generation (one campaign every six months during the Stage 1 construction phase); and
- regular sonar inspection of the dam face once impounded, to detect any abnormal deformation of the upstream face.

7.2 Follow-up and maintenance

The dissolution numerical model made by HPI needs to be enhanced and recalibrated with more accurate values of hydraulic conductivity and kinematic porosity of the cap aquifer. Further investigations may still improve understanding of the input parameters. The rate of salt rise within the fault needs to be thoroughly assessed and measurements should resume as soon as possible. This model would be a useful predictive tool that should benefit from regular feedback of data from the work site, and should be kept operational during the entire life of the dam.

If large cavities were to happen, (which would be detected by microgravity monitoring for example), intervention must be ensured in a timely manner.

If either of the two mitigation measures would lose their efficiency, the relevant mitigation measure would have to be re-implemented. Appropriate arrangements shall be foreseen to intervene and restore these two processes.

During or at the end of Stage 1, which is the stage with the highest risk, the re-grouting and reinstallation of the hydraulic barrier can be performed from the crest of the Stage 1 dam.

At Stage 2, the only option for re-grouting and hydraulic barrier restoration, while keeping the reservoir full, would be to operate from the banks, above the reservoir water level. This can be implemented using directional boring. This supports the implementation of a sub-horizontal hydraulic barrier through directional drilling.

8 CONCLUSIONS

From these assumptions and the TEAS Consultants' models, it is clear that both efficient grouting and an efficient hydraulic barrier are necessary to prevent excessive salt dissolution. Both mitigation measures are required to cover the risk that one of the two mitigation measures might lose part of their effectiveness.

Even if the results of the analysis show that an efficient hydraulic barrier alone, or efficient grouting alone would be acceptable, both of these two mitigation measures should remain operational throughout the lifetime of the dam.

In order to check the efficiency of the design mitigation measures, adequate monitoring is required, so that timely remedial measures can be implemented as soon as possible. Detailed monitoring measures have been proposed.

With the implementation of the hydraulic and grouting barriers, the related monitoring system, and the design of feasible remedial works in case of the loss of efficiency of the mitigation measures, the Consultants conclude that these measures are sufficient to ensure that the dissolution potential of the salt wedge does not affect the safety of the proposed dam.