OSHPC BARKI TOJIK

TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

PHASE 0: GEOLOGICAL AND GEOTECHNICAL INVESTIGATION OF THE SALT DOME IN THE DAM FOUNDATION AND RESERVOIR

RP 38

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1.1.1 Preamble: the salt body within Ionakhsh Fault

This Phase 0 report deals with the specific issues created by the detected presence of salt within the Ionakhsh Fault, which is cutting Rogun dam site in a roughly NE-SW direction, in the upstream part of the dam axis (cf. Figure 1-1).

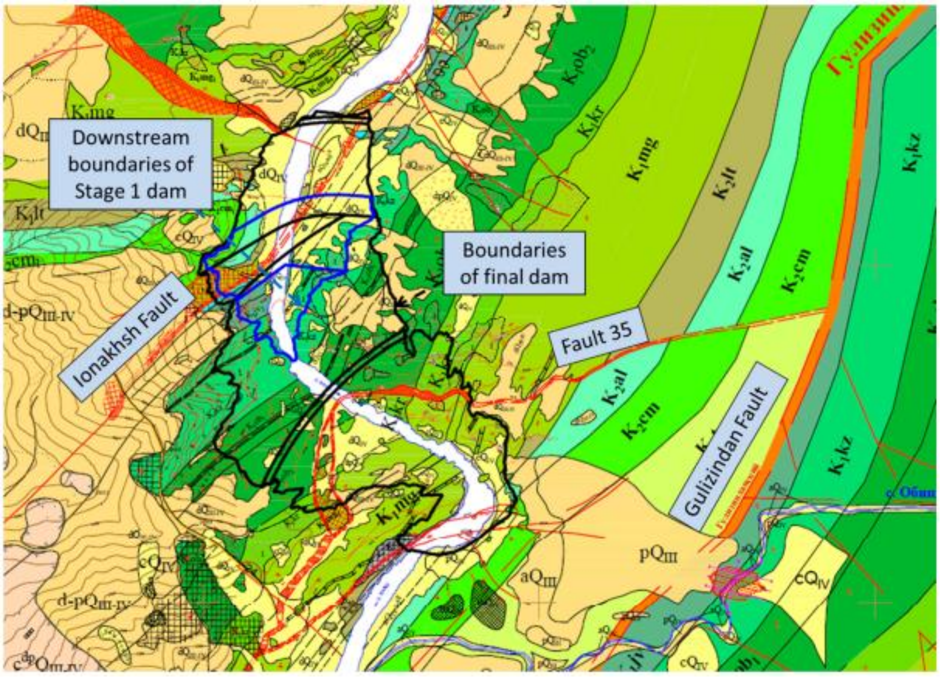

Figure 1-1: Dam site geological map with Ionakhsh Fault and other main faults; limits of Stage 1 dam are highlighted (in blue), limits of final dam (in black).

The geometry of the salt body within the Ionakhsh Fault has been extensively investigated since the first studies carried out on Rogun project. From the investigation campaigns, it appears that the salt body has a wedge shape, the top of which having, at the maximum elevation, a variable width from 1.5-2 m within the left bank to up to 12 m in the right bank. It was also evidenced that the thickness of the salt wedge is increasing with depth, with an average 15 m increase every 100 m depth. Considering these features, we will refer in continuation to the salt wedge of Ionakhsh Fault.

1.1.2 Objectives of the report

This chapter is the outcome of the thorough analysis of the hydrogeological phenomena, and an assessment of the existing numerical models. Independent models have been carried out by TEAS consultant to properly assess the reliability of existing studies.

Specific hydrogeological conditions at Ionakhsh Fault are put in the more general context of the site hydrogeological conditions, with special focus over prevailing conditions around the top of the salt wedge, in the so-called cap aquifer. Results and interpretation of a pumping test in the cap aquifer recommended by TEAS Consultant in 2012 are analysed to feed the overall assessment.

This report also encloses the description of mitigation measures proposed by previous designers. New alternatives are also recommended by TEAS consultant based on up to date technologies. The efficiency of the recommended mitigation measures to reduce leaching is assessed in a sensitivity analysis and the Consultant indicates recommendations for monitoring of the project by predictive modelling. Cost of the corresponding works is derived to be included in the overall cost of the project.

1.2 Site hydrogeological conditions

The general site hydrogeological conditions are described based on a complete review of available investigations works and a field survey carried out by the Consultant. The different aquifers are identified, their natural behaviour described. The different physical characteristics to be inserted in the model are derived from the results of tests from previous campaigns, and where found insufficient, have been complemented by new tests carried out in 2012 under the supervision of TEAS Consultant. For example, at the dam site itself 18 boreholes were equipped in observation wells and monitored in 2012 by TEAS Consultant. This was to ensure that the key inputs of the hydrogeological modeling are representative of the real site conditions, by using reliable records.

1.3 Dissolution phenomena and Modeling Principles

1.3.1 Dissolution processes characterization

Dissolution is the process by which water forms a solution in contact with a soluble material acting as solute. This complex process is described in details by analysing each main component of the phenomenon, 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 has been evaluated for the different scenarios envisaged to understand which transport process is predominant.

1.3.2 Geometry and characteristics of Ionakhsh Fault:

The model is based on a thorough evaluation of all documentation available since 1978 design up to 2012, when a new pumping dissolution test was carried out by TEAS. This gives accurate location and delimitation of the salt wedge within 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, hydraulic conductivity, 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 to 970. There is no salt above this elevation; it has been leached.

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 has been carried out on this crucial parameter in the model.

All previous studies assume 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.

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.

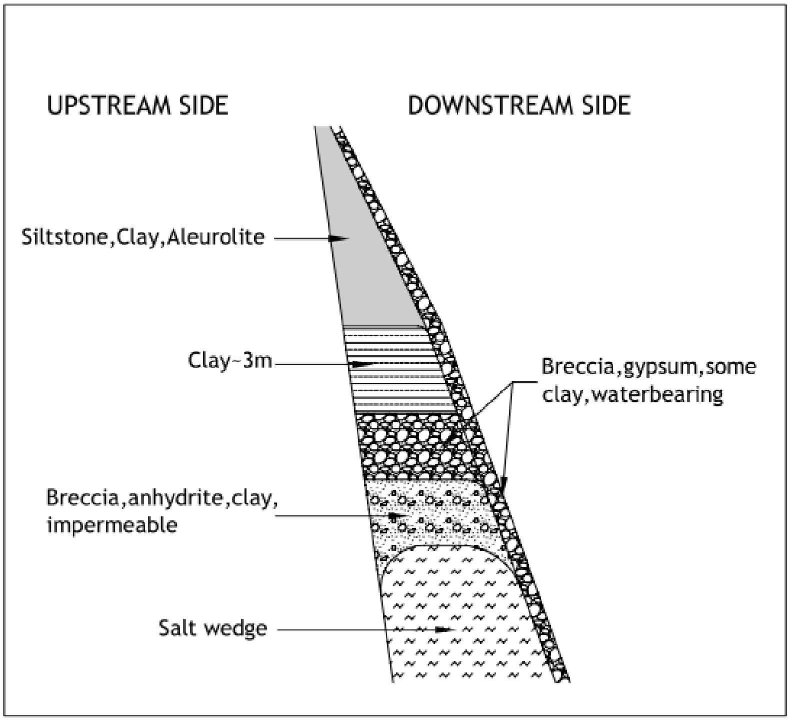

Figure 1-2: Lithological conditions above the salt wedge

1.3.3 Pumping dissolution test of end 2012, results interpretation

A pumping test has been performed from November 16th to December 10th 2012 for which a 48 m deep borehole has been 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 have been measured: discharge, drawdown, electric conductivity of water, total mineral content at the well itself. In addition drawdown at a neighboring piezometer was followed.

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 better understanding of the aquifer behavior in the present conditions. This pumping dissolution test allowed to some extent to confirm the order of magnitude of the salt dome rising rate, 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.

1.4 Mathematical modelling of the dissolution process; analysis

1.4.1 Assessment of current HPI model

The model 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 a 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 process leaching the salt at the same rate. The model results give a similarity at an acceptable level between the observed salt concentration distribution inside the Ionakhsh Fault hemming rock and the calculated one.

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, since it slows down the transport process. The adopted value results 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 leaching that could be ten times higher than assessed by the HPI model, requiring a 25 cm salt dome yearly rise for equilibrium in the actual conditions. There are until now no field evidences 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 liability 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.

HPI model seems likely to be reliable, but the choice of the input parameters has to be enhanced following the results of tests and observation data (in particular the recent pumping-dissolution test carried out).

1.4.2 TEAS Models

The Consultant has built its own model in order to assess independently the model prepared by HPI, but has also used a parametric analysis to assess scenarios and extreme conditions which were not considered by the existing models. This provides a wider range of sensitivity analysis to be included in the overall risk assessment of the dissolution phenomenon.

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

The whole leaching process is simulated by three separated sub-models which are used sequentially:

- **Sub-model 1 - Groundwater flow model:** that 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 - Leaching process model**: it models the maximum leaching ability inside the part of the salt wedge subject to dissolution. A salt wedge thickness subject to leaching has to be introduced, the introduced gradient at the salt wedge results from submodel1,

- **Sub-model 3 - Transport model**: it represents the transport processes: diffusion and advection/convection. The gravity convection is not modelled. In this model the exact analytical formula (advection, diffusion) are used. The results of the pumping test: hydraulic conductivity and kinematic porosity are introduced. The introduced groundwater gradients are the results of sub-model 1. The model is calibrated on the observation that the leaching is equal to the salt wedge rise.

Sensitivity analyses indicate that the most sensible 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 could be significant for the clay coating and the rate of rising 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.

It was considered that the maximal geometrical size of cavity to be generated without damage to the dam, considering quite conservative assumptions is estimated to 25 m. This is basically a theoretical value, based on geometric considerations. Immediate interpretation of data from the planned monitoring is to be performed to enable timely rectification measures if needed.

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 in maintaining in a series of holes on the downstream side of the salt wedge the reservoir pressure, such as to minimise the water gradient between both sides of the salt wedge.

The following scenarios were therefore considered:

- Conditions before any work, for the model calibration based on an observed natural equilibrium between salt leaching and salt wedge rising,

- The “No remedial measures” option after construction of Stage 1 dam: no mitigation measures are implemented.

In such a case, the calculations results are:

- 10 year duration for the stage 1 dam: decametric cavity generation for large wedge rising rates, or in case of a leaching rate larger than the wedge rise, appearing as early as Stage 1,
- In case of Stage 1 dam lasting 40 years: in almost all cases, decametric cavity generation in stage 1 and stage 2,

- The following mitigation measures were modeled for the three different elevations:
  - Grouting of the cap alone,
  - Harmed 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 harmed cap grouting.

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

One specific “worst case” scenario, considering a reduced hydraulic barrier efficiency, harmed grouting and loss of clay coating of the salt wedge, for a 40 year stage 1 duration has been studied. 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.

1.5 Main Model Conclusions

The Consortium model conclusions are:

- “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 rate or an extended duration before the completion of stage 2, since with time, leaching could lead to large cavities which could affect the water retaining function or even dam integrity,
- The most effective combination of mitigating actions is grouting, and hydraulic barrier. In that case, and even considering the most pessimistic values of porosity and hydraulic conductivity, no significant leaching or cavity formations are observed. In most cases, with time, the salt wedge will intrude the dam body,
- The brine curtain (brine injection into the cap aquifer) would still reduce the leaching process. Unfortunately, previous trials proved the brine curtain technique to be not reliable, 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 closely depending upon the part of the wedge cap surface covered with clay. The clay-coating is very favorable, since it inhibits the dissolution process. There is no doubt that the top of the salt wedge is coated with clay, since evaporites have a significant clay content and this clay-coating is generally observed worldwide on extruding diapirs,

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

- 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 not safe. The same conclusion is drawn in case of only cap rock grouting. It is therefore required to implement these two mitigation methods, grouting of the cap rock and hydraulic barrier.

Taking into consideration the 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 to 5. The safety factor corresponds to the ratio of size of the cavity for each scenario (less than 8 m) divided by the maximum size of the cavity acceptable (25 m). The safety factor of 3 relates to standard engineering practice. Except for one scenario, they all show that there is no risk that the leaching could generate unacceptable cavities.

The only critical scenario is that of a 40 years delay before the completion of stage 2 dam, with degradation of the hydraulic barrier, loss of efficiency of grouting and removal of the clay cap. This would imply that during that time, no monitoring and/or no maintenance of the barriers were implemented.

Given the experience of the Tajik competent authorities in the monitoring of the downstream located Nurek dam during 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.

1.6 Recommendations

1.6.1 Monitoring

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

- measurement of the displacements within the salt wedge and the embedding rock,

- follow-up of the deformations within the salt body by series of clinometers.

For this purpose, we would recommend five profiles made each one of three boreholes of at least 100 m depth, penetrating into the salt rock and distributed along the whole of the grouted Ionakhsh Fault.

In order to 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 (one campaign every six months during stage 1 phase),
- regular sonar inspection of the dam face once impounded, to detect any abnormal deformation of the upstream face.

1.6.2 Follow-up and maintenance

The dissolution numerical model made by HPI is to be enhanced and recalibrated with more accurate values of hydraulic conductivity and kinematic porosity of the cap aquifer. Further investigations may still improve our knowledge on the input parameters. Especially the rate of salt rising within the fault is required to be thoroughly assessed and measurements shall resume at the earliest. This model would be a useful predictive tool which is to be permanently fed back by data from the work site, and be maintained operational during the whole life of the scheme.

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

If the two mitigation measures would happen to fail or lose their efficiency, the grouting and hydraulic barrier would have to be re-implemented. Some measures 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 then be to operate from the banks, above the reservoir water level. This could be implemented only using directional boring. This goes in favor of implementing a sub-horizontal hydraulic barrier through directional drilling.

1.7 Conclusions

From the here above different assumptions, and because the risk of failure of one of these two mitigation measures exists – especially in the case of grouting, it is clear that both efficient grouting and efficient hydraulic barrier are by far necessary to prevent salt leaching.

Moreover, the results evidence the fact that even if efficient hydraulic barrier alone, as well as efficient grouting alone is acceptable, it is clear that at least one of these two mitigation measures shall be maintained operational throughout the lifetime of the scheme. Both mitigation measures can be repeated over time during the most critical period after the end of stage 1, as can be the hydraulic barrier in the later stages, so that the sustainability of the dissolution prevention process can be ensured.

In order to follow the efficiency of the design mitigation measures, an adequate monitoring is required, so that in-time reaction and repair works can be carried out as soon as possible. Suggestions for this monitoring are given in this report and the set of drawings.

With the implementation of the hydraulic and grouting barriers, the related monitoring system, and the design of remedial works in case of the failure of mitigation measures, the thorough analysis of the scenarios shows that the leaching issue at the Ionakhsh Fault does not affect the project feasibility.

2 LIST OF MAIN ABBREVIATIONS AND DEFINITIONS

For convenience, this paragraph presents a list of the most commonly used abbreviations and essential definitions used in this report.

HPI: Hydroproject (Gidroproyekt) Institute

LU: Lugeon Units (measurement unit for permeability)

Salt tectonics: in this report, the term corresponds to the deformation resulting from extrusion, doming, creeping of evaporitic rocks such as salt, anhydrite or gypsum

Salt wedge: extruded evaporite along the Ionakhsh Fault, mainly constituted of halite and anhydrite.

Salt wedge cap: cap of rock located above the salt wedge; it is the interface between the top part of the intact impermeable salt dome and the space located above and filled with the residues left after dissolution of the salt,

Cap aquifer: designates the aquifer within the space filled with residues left after salt dissolution

Hydraulic conductivity: symbolically represented as K, is a property of a material that describes the ease with which water moves through pore spaces or fractures. It is related to the intrinsic permeability of the material, on the degree of saturation, and on the water density and viscosity.

Stage 1 dam: means the first-stage dam at elevation 1110 masl for alternative of main dam at FSL 1290, its axis is close to Ionakhsh Fault.

Stage 2 dam: means the final dam, the dam axis is located 300 m downstream of Ionakhsh Fault.

3 MAIN REFERENCE DOCUMENTS.

Hereafter the list of the main documents and data files used for this chapter.

[1] LEKHOV A.V., 2009: Simulation modelling of salt layer dissolution during construction of the Rogun HPP on the Vakhsh River in the Republic of Tajikistan, Moscow

[2] HYDROPROJECT, 1174-T15, Central Asian Branch: Rogun HPP on Vakhsh River, Technical Project, Part I, Volume 3, Engineering-geological conditions, Tashkent, 1978, No. 1174-T15

[3] LAHMEYER INTERNATIONAL, 2006, Rogun Hydroelectrical Plant in the Republic of Tajikistan. Bankable Feasibility study for stage 1. Construction completion. Geology, Geotechnics and Seismic characteristics Part 3.

[4] OREKHOV. V.V. International Institute of Geomechanics & Hydraulic works. 2005. Mathematical modelling of salt dissolution, while creating Rogun HEP reservoir. Stage1.

[5] ROGUN GEOLOGICAL ARCHIVES. 1979. Borehole logs, results of water tests.

[6] ROGUN. GEOLOGICAL ARCHIVES.2012. Groundwater level measurements, springs discharge measurements, Pumping / dissolution test.

[7] RUSAL 2005 Construction of the Rogun HEP Engineering and Geological Conditions

[8] KOLICHKO. 2012. Replies to experts.

[9] PFANKUSH, H.O. 1963. Contribution to miscible fluids in a porous medium (in French). Revue de l'Institut du Pétrole.

[10] HPI, 2012. Rogun HPP on Vakhsh River.Development of geo-filtration model of the site of the main constructions of Rogun HPP.

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[12] LOGAN, J 1964. Estimating transmissivity from routine production tests of water wells. Groundwater, 2:35 – 37

4 PREAMBLE AND OBJECTIVES OF THE REPORT

4.1 Preamble: the salt body within Ionakhsh Fault

This Phase 0 report deals with the specific issues created by the detected presence of salt within the Ionakhsh Fault, which is cutting Rogun dam site in a roughly NE-SW direction, in the upstream part of the dam axis.

From the early beginning of the studies of Rogun dam, presence of salt rock has been a matter of study, with respect to the potential dissolution of this salt once the Stage 1 dam is constructed and impounded, as well as for the final Stage 2 dam.

The present location of the dam has been selected such as to be positioned in the gorge made by a bend towards south of the Vakhsh River, between Ionakhsh Fault to the North, and Fault 35 to the South.

The area is tectonically very active, and geodetic measurements carried out before 1978 demonstrated that both Ionakhsh Fault and Fault 35 were creeping at a rate of about 1.5 to 2 mm per year.

Therefore, the dam location was selected such as the dam axis, as well the core of the dam, is to be located on the block between those two faults, where no movement were assumed to occur.

Figure 4.1 shows the overall arrangement of the site, with Ionakhsh Thrust Fault, which will be located beneath the Stage 1 dam, and beneath the upstream shell of the stage 2 dam.

Gulizindan Fault, located farther south, sub-parallel to the Ionakhsh Fault, is also a thrust fault, where salt has also been detected, but without direct interference with the project components.

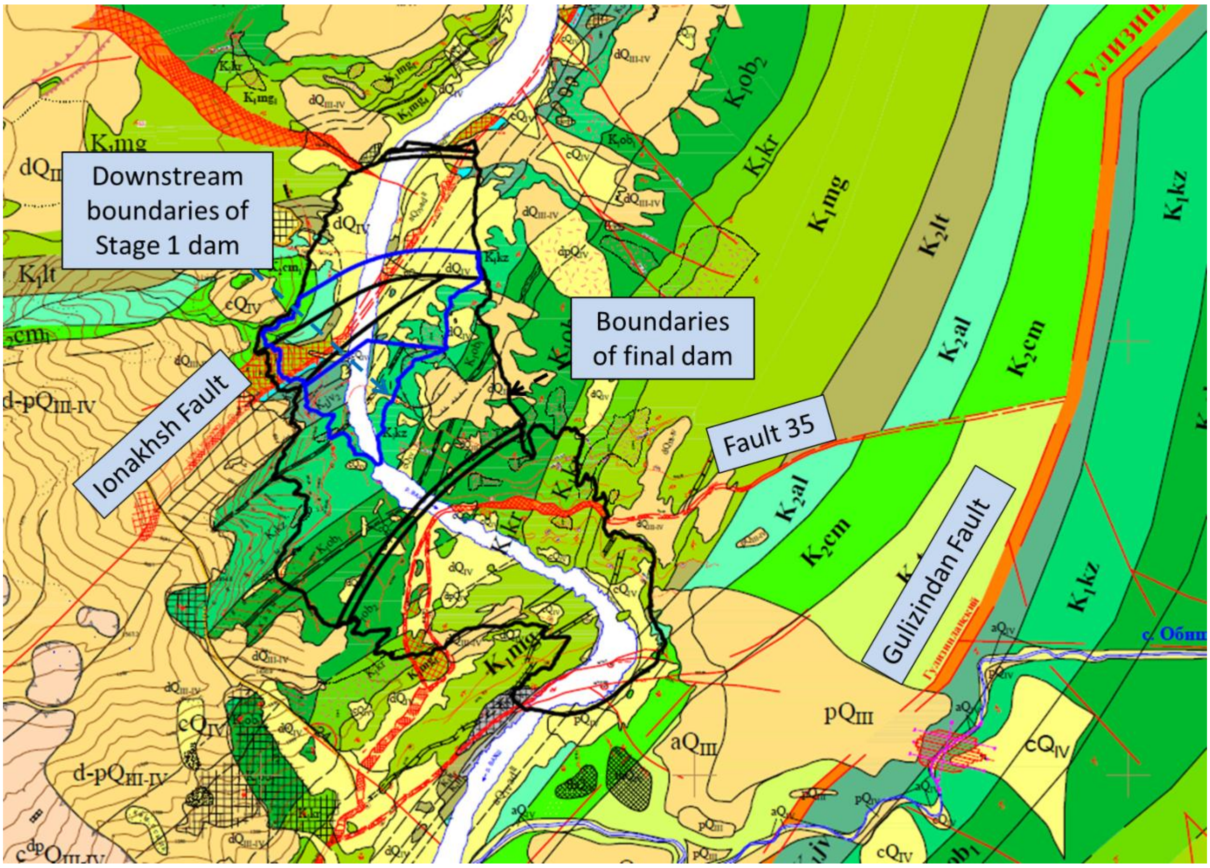


Figure 4.1: Dam site geological map with Ionakhsh Fault and other main faults; limits of Stage 1 dam are highlighted in blue for the downstream site (upstream, there are same as for the final dam, which will include the Stage 1 dam)

The geometry of the salt body within the Ionakhsh Fault has been extensively investigated before issuance of the 1978 Design Report (Ref [2] where the results of these investigations are presented in details). Boreholes and investigation adits allowed observing the salt body over an approximate length of 450 m along the fault on each of the two banks.

Along this roughly 1 km stretch of fault, centered on the river, it came out that the elevation of the top of the salt body was identified up to 970 masl in the left bank, at about 950 masl under the river bed and up within the right bank, from 956 to 964 masl (the latest point being the farther reached within the right bank).

From the boreholes campaign, it appears that the salt body has a wedge shape, the top of which having, at the maximum elevation, a variable width from 1.5-2 m within the left bank to up to 12 m in the right bank. It was evidenced that the thickness of the salt wedge is increasing with depth, with an average 15 m increase every 100 m depth.

Considering these features, we will refer in continuation to the salt wedge of Ionakhsh Fault.

The specific features of the rocks surrounding the salt body will be detailed progressively in the course of the report.

Orogenic forces extrude the salt rock of the Jurassic Gaurdak Formation along the Ionakhsh Fault at an estimated rate of 2.5 cm/year. At the same time the salt is leached, so that the cap depth does not change with time. After impoundment of the reservoir, and more specifically for stage 1, the groundwater gradient along the Ionakhsh Fault might increase significantly.

The dissolution or leaching phenomena are complex and combine several distinct processes. The first being the salt dome dissolution itself, leaving residual clay that covers partially the salt cap. Besides the halite, which is the dominating component of the salt dome, the anhydrite part is about 25%. Anhydrite, when in contact with un-saturated water is transformed primilarly before leaking, into gypsum which is an anhydrite hydrate. This transformation leads to volume increase filling partially the void left concurrently by halite dissolution. After water saturation the salt is evacuated following several transport processes.

4.2 Objectives of the report

The objectives of this study are to evaluate the potential risk of leaching rate increase and to determine to what extend cavities in the dam foundation could be created and endanger the overall integrity of the structure. This matter has been subject to specific studies and design (including design of mitigation measures) since the start of the project design in the 70's.

In order to establish the risk of leaching and the efficiency of the mitigation techniques, several models were established in the past: an analogical model (1978) (ref [8]) and more recently in 2005 and 2009: numerical models (ref [1] and [4]). This chapter is the outcome of the thorough analysis of the hydrogeological phenomena, and an assessment of the existing numerical models. Independent models have been carried out to compare their results to the proposed models.

Specific hydrogeological conditions at Ionakhsh Fault are put in the more general context of the site hydrogeological conditions. Results and interpretation of a pumping test in the cap aquifer recommended by TEAS Consultant in 2012 are analyzed to feed the overall assessment.

This report also encloses the description of mitigation measures proposed by previous designers namely:

- Grouting the cap aquifer,
- Creating a hydraulic barrier to reduce the gradients over the salt wedge,
- Implementing a brine curtain to annihilate the leaching process, by injection of brines (saline solutions).

The report includes recommended new alternatives for mitigation measures with their corresponding cost estimate. Their efficiency to reduce leaching is assessed in a sensitivity analysis and the Consultant indicates recommendations for monitoring of the project by predictive modeling.

5 SITE HYDROGEOLOGICAL CONDITIONS

5.1 Site aquifers subdivision

The aquifers related to the projected works: dams at two stages, caverns, tunnels and spillway have a limited extent. They are ruled by the Vakhsh River which is the main draining axis. Subsequently there are two main independent aquifers, one on the right bank and the other on the left bank. Both are subdivided into sub-aquifers behaving also independently on each side of the Ionakhsh Fault (see Figure 5.1).

On the left bank, the aquifer is limited at the east by the Gulizindan Fault about 1.1 km from the Vakhsh River, which is highly compressed under the SE-NW compression acting forces (15Mpa). It is impervious and acts as a natural barrier.

To the south it is limited by the Obishur River while the northern boundary cannot be well defined.

Fault 35 is filled with clay (ref [7]), it splits the left bank aquifer into two sub-aquifers: “left bank north” and “left bank south”. Sub-aquifer left bank north also includes a part of the Ionakhsh Fault which is draining and a small alluvial aquifer, consisting of coarse (gravel) alluvial deposits.

The host rock of the aquifer is made of alternating layers of aleurolites (Figure 5.3 and Figure 5.2, ref.[3]), very fine grained sandstone and argillites. The layers are dipping to the south-east with an angle of 60°. The host rock is poorly permeable and as evidenced in most rock aquifers, the hydraulic conductivity (permeability) is decreasing with depth.

As a rule in aquifers within sedimentary formations, a strong anisotropy is usually observed, of one to two orders of magnitude, the highest hydraulic conductivity being in the direction parallel to the bedding while the lowest is directed perpendicular to the bedding. In the case of Rogun site the hydraulic conductivity is the highest parallel to the layers dip which is 60°. But on the other hand strong horizontal forces are acting, closing the nearly vertical bedding as well. It may be expected that the degree of anisotropy is not that significant. However, at the left bank one observes at the outcrop some water leaking through the bedding planes. Leaking is observed along the bedding planes inside the galleries, too.

From water tests previously performed in several directions around the galleries, no anisotropy could be measured (ref [8]).

From field observation it can be concluded that some anisotropy exists, but locally concentrated and not exceeding one order of magnitude difference.

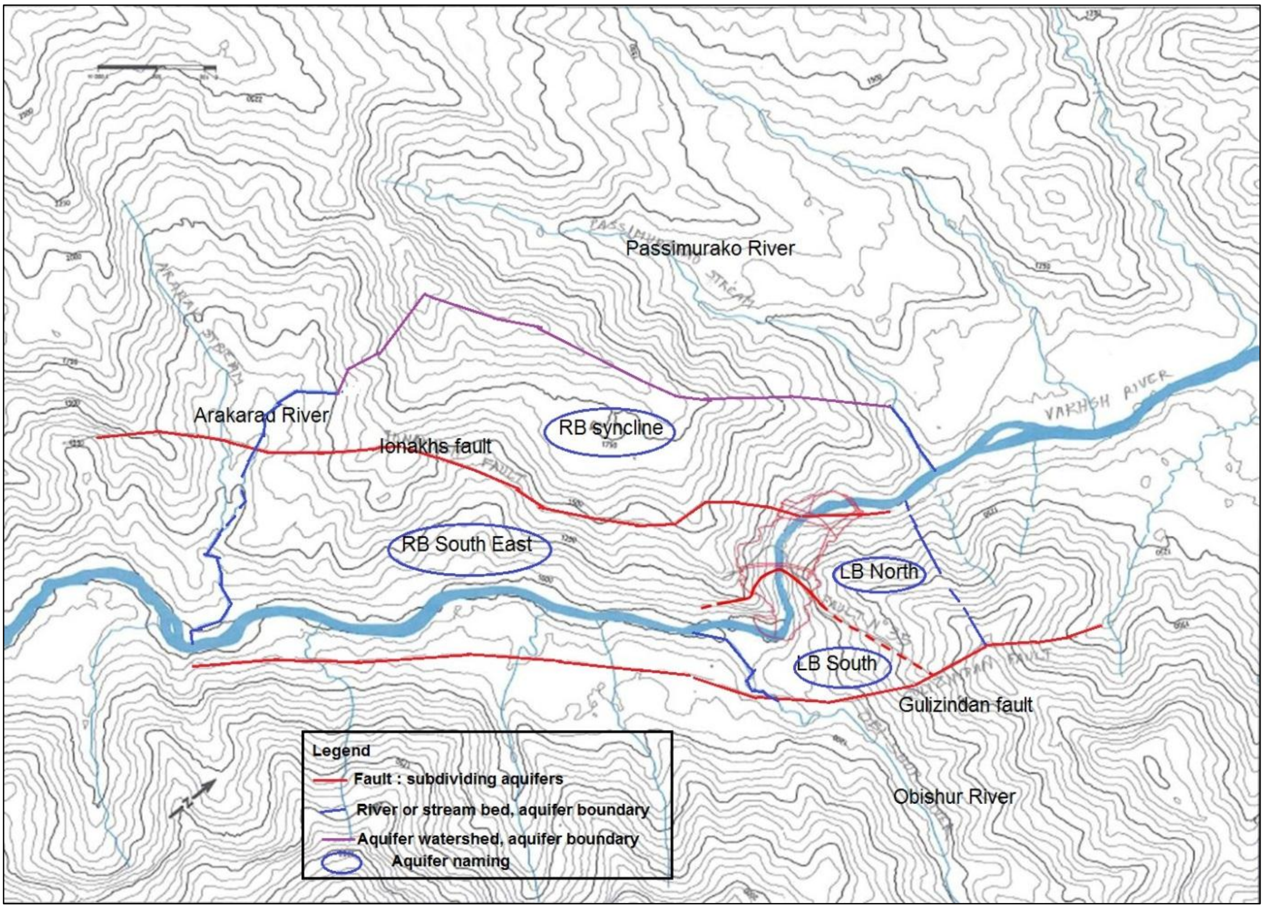


Figure 5.1 Aquifers delimitation.

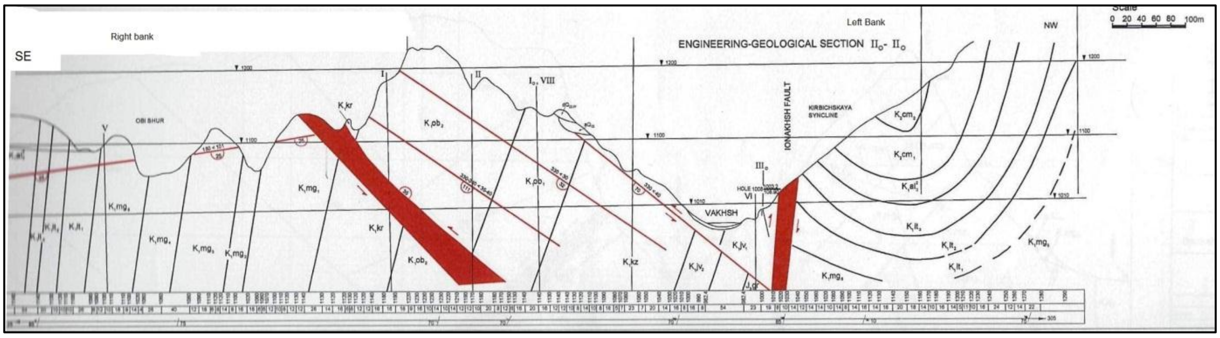


Figure 5.2. Cross section

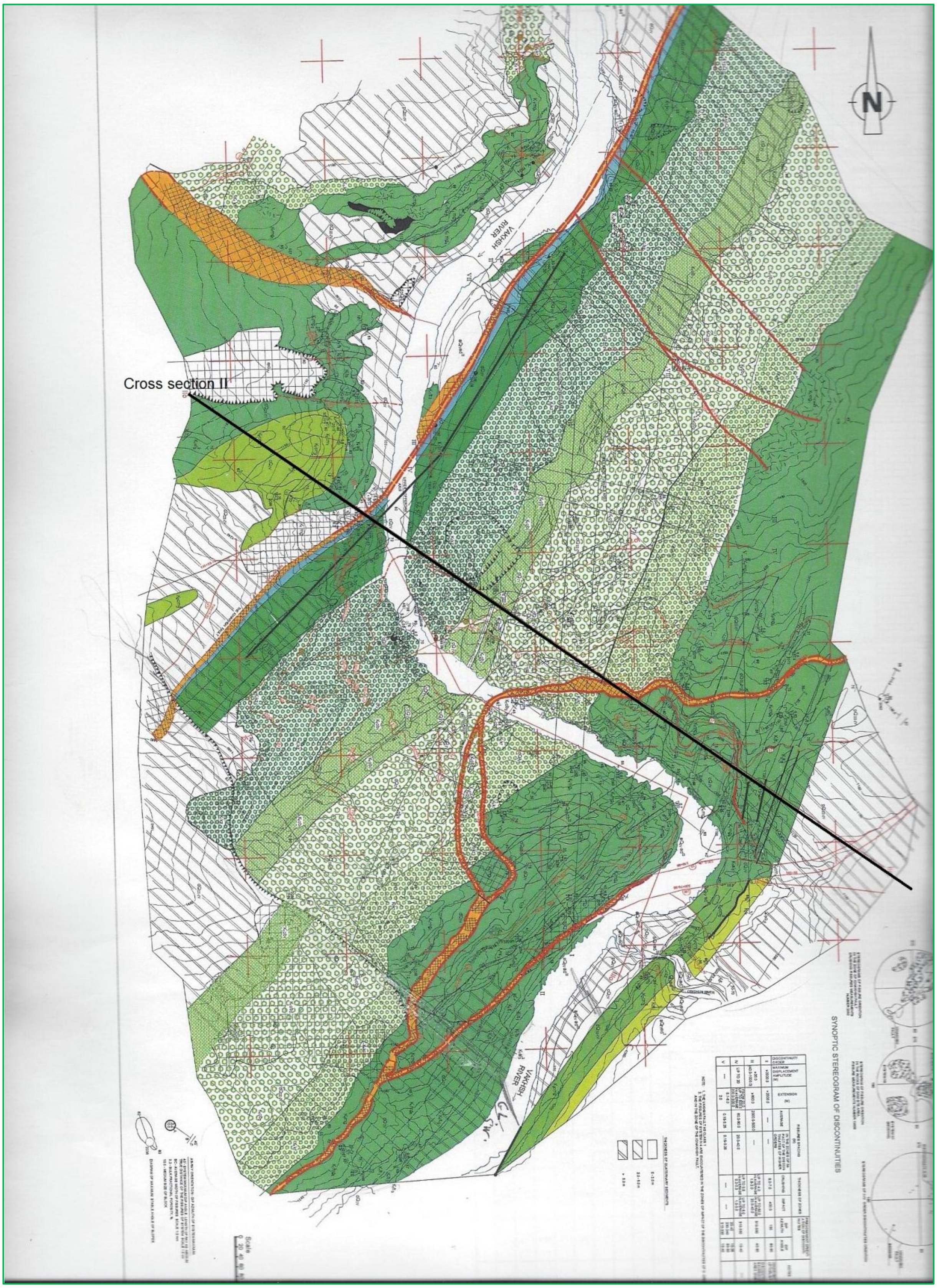


Figure 5.3. Detailed geological map. Cross section location.

As an average the groundwater of the aquifer is flowing to the Vakhsh River and the aquifer is recharged by infiltrated water. Since the slopes are high, the rock poorly permeable, the runoff is huge and the infiltration ratio might not exceed 10% of the rainfall (15% according to Ref [10]).

During the Vakhsh River high water time (summer season as it is a glacier fed regime), the River level may rise up to 7 meter. At that time, the Vakhsh River is recharging the aquifer and the groundwater flow goes from the River to the banks. A series of 11 observation wells have been performed in August and September 2012, they were monitored since that time thus at Vakhsh River high water, showing the Vakhsh water is flowing towards the land with a groundwater gradient of 3% at the left bank and 3.5% at the right bank.

The hydraulic conductivity is derived from several hundred water tests (ref. [5] and [8]).

The hydraulic conductivities distribution estimated on this basis, are presented in ref.[10] and summarized in Table 5.1.

		Undisturbed rock at 45 to 90m depth. K (10^{-5} m/s)	Slightly distressed rock 20 to 40m thickness K (10^{-5} m/s)	Distressed rock 20 to 40m thickness K(10^{-5}m/s)	Very distressed rock, 5 to 20 m thickness K(10^{-5}m/s)
Valanginian Hauterivian	Argillite, aleurolite	0.001	0.01	0.12	1.5
Valanginian Hauterivian	Argillite, aleurolite, sandstone	0.001 to 0.002	0.02 to 0.05	0.15	2
Hauterivian Albian	Aleurolite, gypsum	0	0.02	0.1	1.5
Hauterivian Albian	Aleurolite, sandstone, argillite	0.0025	0.07	0.25	2

Table 5.1: Distribution of hydraulic conductivities in the main geological formations of the left bank, as deduced from the water tests performed on site

The higher hydraulic conductivity observed in the upper part brings a skin effect limiting the flow in the upper thin layer of the aquifer. It could be misleading and thought in contradiction to seepage observations deeper in the existing galleries and caverns.

On the right bank, the aquifer has also to be subdivided in two sub-aquifers. We refer to Figure 5.1 and Figure 5.2. Their mutual boundary is the Ionakhsh Fault. They are referred to as the Right Bank South-east aquifer and the Right Bank Syncline aquifer.

The south-eastern aquifer is limited at the north by the Vakhsh River and the Ionakhsh Fault, at the east by the Vakhsh River and at the west by the Ionakhsh Fault. It is extending to the south, including the “disturbed zone”, to the Ararak River or its northern tributary. The

Ionakhsh Fault is also draining, but with respect to the rather low hydraulic conductivities, the drained discharge is very low.

All characteristics close to the dam site (infiltration, hydraulic conductivity, groundwater gradient) are similar to the aquifers of the left bank.

The Right Bank Syncline aquifer shows a structural difference. The syncline axis is dipping to the north with an almost unique outflow: a series of springs located on its axis. The total discharge is about 18 l/s (September 2012). This value, related to the recharge basin, corresponds to at least 110 mm infiltration (taking into account that the measurements were made at low water period and less than the average discharge).

The lithological and hydraulic parameters characteristics are the same as for the above mentioned aquifers.

Other lithological formations are observed with slightly different characteristics. Since there is only a few number of water tests in those formations, the hydraulic conductivities are a best estimate; they are presented in Table 5.2.

		Uncompressed rock at 45 to 90m depth. K (10^{-5} m/s)	Slightly distressed rock 20 to 40m thickness K (10^{-5} m/s)	Distressed rock 20 to 40m thickness K(10^{-5}m/s)	Very distressed rock, 5 to 20m thickness K(10^{-5}m/s)
Albian	Sandstone, argillite, aleurolite	0.002	0.04	0.2	2
Albian	sandstone aleurolite, argillite,	0.003	0.06	0.3	2.1
Albian	Sandstone,chalk, aleurolite, argillite,gypsum	0.002	0.04	0.3	2.
Albian	Sandstone, aleurolite,gypsum	0.003	0.03	0.2	2.3

Table 5.2: Distribution of hydraulic conductivities in the main geological formations of the right bank

The hydraulic conductivities are slightly higher than for the other aquifers or sub-aquifers conferring a more pervious character to the right bank.

5.2 Ground water flow of the different aquifers and sub-aquifers.

Before 2012, there was a serious lack of observation wells in the aquifers/sub-aquifers. Except along the Ionakhsh Fault, only few observation wells had been performed at the dam site area and no discharge measurements on the long term of the inventoried springs. At the dam site itself 18 boreholes were equipped in observation wells and monitored in 2012. The observed groundwater levels only involved the Left Bank north sub-aquifer and a limited part of the Right Bank south-east sub-aquifer. As previously mentioned they show the recharge phenomenon of the aquifers by the Vakhsh River.

Discharge measurements were performed at the end of the summer 2012 (in this case is at low water) of the right bank tributaries of the Vakhsh River .

The following values were recorded:

- at Ararak River the flow leaving the Right Bank south east aquifer is about 0.5 litre/sec.
- at Passimurakho, leaving the right Bank syncline aquifer about 30 litre/sec.

In the present conditions, assumed groundwater flow lines at Vakhsh River low water season are given hereafter (Figure 5.4). During the summer, the flow to the Vakhsh River is reversed and the flow goes from Vakhsh River to the banks.

5.3 Ionakhsh Fault specific aquifer.

The space filled with the residues of the evaporite dissolution above the top of the salt wedge, connected with breccia at the contact with the surrounding rock forms a draining aquifer. The surrounding rock is only slightly permeable and the recharge area by infiltration very small. Subsequently, the discharge of this aquifer (referred to in the following as "cap aquifer") is very limited. As we further will see (results of the long duration pumping test) the hydraulic conductivity is very high: 10^{-4} m/s. The low discharge combined with the high hydraulic conductivity explains that the groundwater gradient is very low (Ref.[6]).

This cap aquifer is connected with the Vakhsh River with a dual regime, flowing toward the Vakhsh River at low Vakhsh River water level (winter time) and flowing towards the land at Vakhsh River high water level (summer time).

This aquifer is specific and works almost independently of the other dam site aquifers.

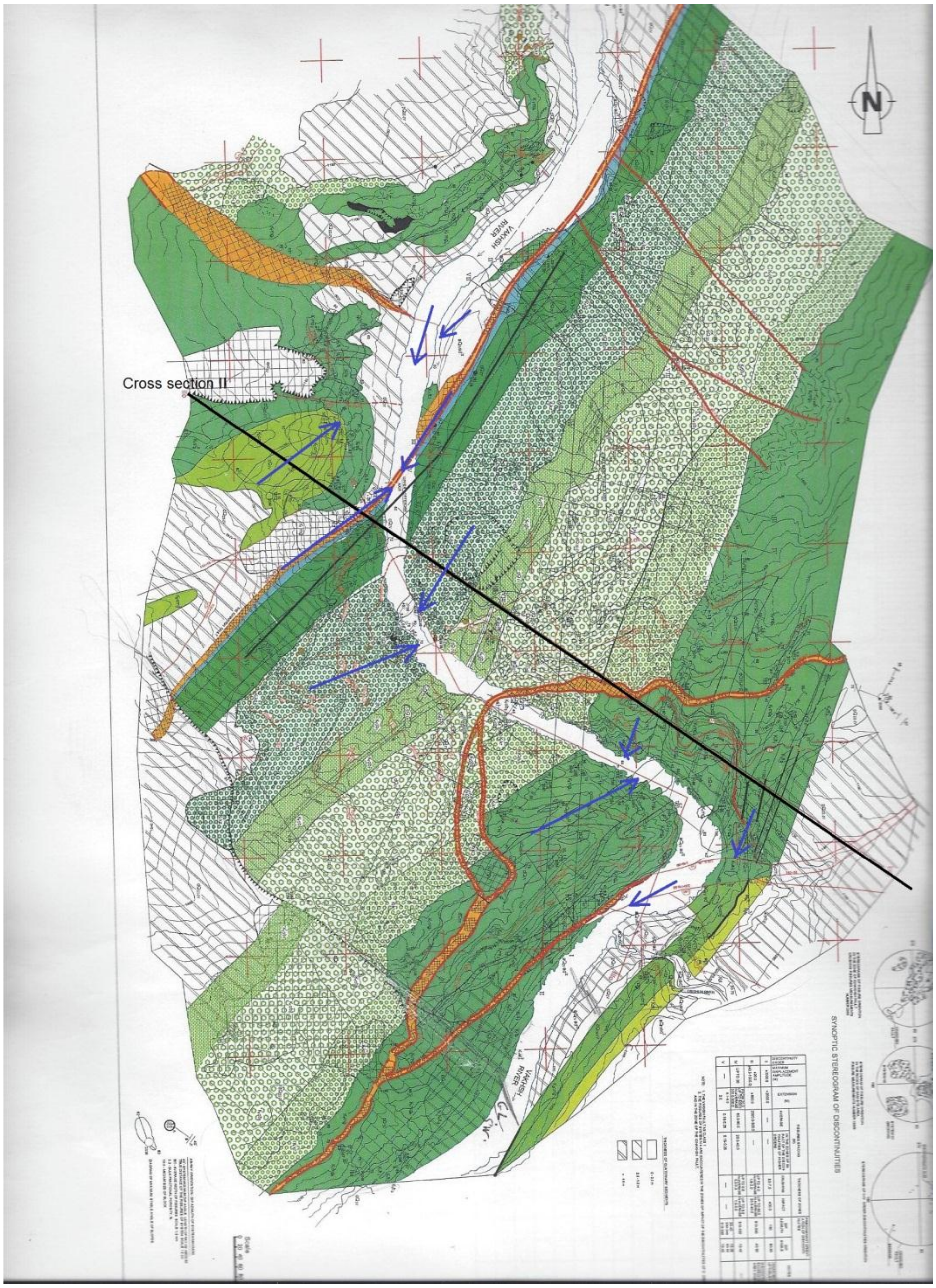


Figure 5.4: Presumed groundwater flow direction at Vakhsh River low water, as presently observed

5.4 Conclusion

The overall understanding of the aquifers behavior and characteristics has been established by means of a thorough analysis of existing investigations, site visits and on site water discharge measurements. This overall understanding of the site conditions is a fundamental pre-requisite to assess the existing models, their assumptions for boundary conditions and the input parameters. This analysis was also used to build the three independent sub-models described in the following sections.

6 DISSOLUTION PHENOMENA AND MODELLING PRINCIPLES

6.1 Dissolution processes characterization

Dissolution is the process by which water forms a solution in contact with a soluble material.

The different phenomena leading to dissolution are various and complex. They are described in details hereinafter:

- *Soluble material characteristics*

The material subject to dissolution is a blend of halite, anhydrite and various insoluble components. The evaporite content has been established, and it is reported as follows: 60.5% of halite, 25% anhydrite and 14.5% of insoluble components (ref.[1]).

It is however worth to note that this composition is reported in Ref.[1] to be the results of tests performed by the Scientific Research Institute (SRI) of Hydroproject in 1985, which were not directly available to the Consortium but quoted in existing reports. The 1978 Design Report (Ref.[2]) had formerly assigned to the rock salt an average percentage of 79.3%, actually ranging between 76 to 92%.

- **Halite** (NaCl) is fully soluble and the solubility kinetics is high, so that it is considered to be instantaneously dissolved.

- **Anhydrite**'s ($CaSO_4$) solubility is slower and its solubility product is lower than that of halite. Before to be solved, anhydrite is hydrated and following this process transformed into gypsum which is soluble, but less than halite. The anhydrite-gypsum transformation goes together with a volume increase of 162% (ref.1). This volume increase will plug the pores and subsequently reduce the exchange surface. Since the dissolution process is proportional to the surface exchange, the dissolution process will be reduced with the transformation of the anhydrite into gypsum counterbalancing partly the pore increase related to the halite dissolution : 1.62 x 25%= 40,5% pore plugging and 60,5% pore generation by halite dissolution.

- **Less soluble components**, made of gypsum from hydration of the anhydrite mixed with the 14.5% insoluble compounds (mainly pieces of embedding rocks) are further filling the new pores (40.5% + 14.5%= 55%) after dissolution; they settle covering the evaporites dome, and partially protecting it from further dissolution.

- **After dissolution of gypsum,** which may be leached as well (at a much lower rate than halite) where exchange surface allows it, the insoluble compounds are remaining, and the long-term dissolution process produces a clay-coating over the top of the evaporites, which is typically observed over evaporites.

Exchange surface. As mentioned above, the dissolution is proportional to the evaporites surface exposed to water circulation. The interface surface is proportional to the kinematic porosity (kinematic porosity is the part of the voids through which the groundwater is moving). Some empirical relationships have been defined depending on the shape of the apertures to determine the exchange surface.

Conclusion 1 The dissolution rate and velocity are dependent on the composition of the evaporites dome. This composition is known and even taking into consideration the volume increase, due to the transformation of anhydrite into gypsum, there is an increase of porosity and, subsequently, other things remaining constant, initiation of a leaching process. Some insoluble components cover the evaporites dome. This may reduce significantly the exchange surface. As typically observed over evaporites body, the settlement of insoluble compounds after dissolution leaves a clay-coating covering its surface, counter balancing the dissolution process.

As it will become more evident later, the percentage of the surface of the salt dome which is coated with residual clay is a major parameter of the whole dissolution process.

- *Solvent characteristics*

The dissolution processes are only acting as long as the solvent (water) is not saturated with the dissolved components. It means that still water “water without any movement”, would dissolve the evaporite wedge as long as water is not saturated with the soluble components[1].

Conclusion 2 The outcome is that the dissolution process is proportional to the underground flow and inversely proportional to its dissolved salt content.

- *Transport process of the dissolved components*

Three processes are considered for the transport of the dissolved components of the evaporite dome.

Transport by advection/convection. This transport is the most intuitive, since it is transport by a fluid in movement. According to Darcy’s law, and for a given hydraulic conductivity of the rock mass, the real velocity within the pores is inversely proportional to the kinematic porosity. Pore geometry also introduces differences in the travel time of the particles (those travelling through a shorter way), and delayed particles (travelling through a longer way). This latter phenomenon is the dispersion. The driving force is the water head difference. The analytical formulas are well defined.

The analytical formula (combined with diffusion process) for one dimension is presented in Figure 6.1. Numerical modelling of this process is common.

Transport by diffusion. The physical phenomenon is the Brownian motion dragging solved particles from places with their highest concentration to places with the lowest concentrations. The driving force in this case is the concentration difference. Here again analytical formulas are well defined (Fick’s law formula). Numerical modelling of transport by diffusion is common.

1 *In case of still water, the various salt ions will be evacuated by diffusion processes, but such processes are very slow.*

$$D\frac{\partial^2 C}{\partial x^2} - U\frac{\partial C}{\partial x} = \omega\frac{\partial C}{\partial t}$$

Dispersion, diffusion equation:

$$D\frac{\partial^2 C}{\partial x^2} - U\frac{\partial C}{\partial x} = \omega R\frac{\partial C}{\partial t}$$

With $D = d + \frac{\alpha}{\omega}U$ dispersion (L^2/T)

d diffusion (L^2/T)

α dispersion coefficient (L)

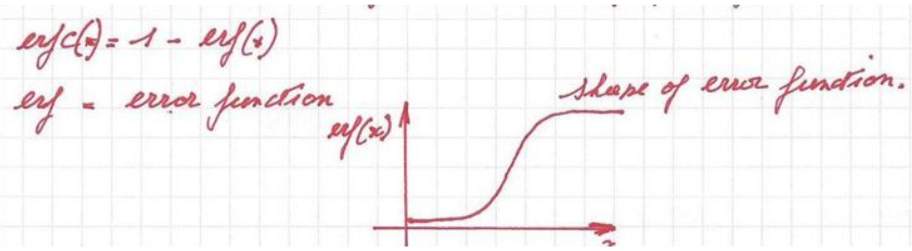
U Darcy velocity (L/T)

R Retardation (delay factor)

t time (T)

ω kinematic porosity (or total porosity for diffusion)

$erfc(x) = 1 - erf(x)$ where erf is the error function (see below)



Analytical solution of the dispersion diffusion equation:

$$C(x,t) = \frac{C_0}{2}\left[erfc\left(\frac{x - \frac{U}{\omega R}t}{2\sqrt{\frac{Dt}{\omega R}}}\right) + exp\left(\frac{Ux}{D}\right)erfc\left(\frac{x + \frac{U}{\omega R}t}{2\sqrt{\frac{Dt}{\omega R}}}\right)\right]$$

Where:

x distance between source and receiver

t time

C_0 Concentration at the source

C Concentration

Figure 6.1: Equations for convection, diffusion, dispersion

It is usual to check which of these transport processes is predominant: advection/convection or diffusion. For this purpose the Péclet number: P_e is determined by the following formula:

$$P_e = \frac{v_r l}{d_0}$$

where v_r is the real velocity (m/s), l the dimension of the particles (m) and d_0 the diffusion coefficient (m²/s).

From laboratory test when lower than 10 one has pure diffusion and when higher than 500 pure advection (Ref.[9]). It is common that the Péclet number determination is introduced in the numerical models.

Transport by gravitational convection. . It is the convection (carriage) of contents of a fluid, such as mass by means of currents induced in the fluid by buoyancy forces which are dependent on gravity acting upon density differences within the fluid. When the water circulation is low, the salt content might be close to the saturation. The water become brine with a density of 1.2 (sea water is only 1.03). Thus, the evaporite dissolution increases the brine density, resulting in an unstable situation in which more-dense brine overlies less-dense brine. This gravitational instability gives rise to density-driven convection of the fluid, which enhances the dissolution process. Water /salt exchanges by this way have been modeled. The driving force in this case is the density difference. The gravity convection formulas have been developed and detailed (Ref.[1]).The gravitational convection is depending of course of the density differences but also of the kinematic porosity and the hydraulic conductivity. It is noteworthy to mention that the hydraulic conductivity is diminishing with salt content increase. The hydraulic conductivity is related to the real velocity within the pores, and the latter is reversely proportional to the viscosity. Viscosity is proportional to density and density to salt content. The hydraulic conductivity of an aquifer with salt saturated water is 40% less than the hydraulic conductivity of the same aquifer at the same temperature with fresh water (Ref.[1]).

Conclusion 3: Three main processes of solute transport in aquifers are therefore taken into consideration: advection/convection, diffusion and gravitational convection.

Further taking into consideration the real field conditions:

- previous to any work,
- 2012 current conditions,
- at construction stages 1 and 2.

Based on the available observations, tests and hydraulic parameters will be analyzed to identify which phenomenon or combination of phenomena is predominant in each case.

6.2 Existing data, observations tests results at Ionakhsh Fault.

- Before 1979 : 13 numbers boreholes between 80 and 100 m depth were realized in the vicinity of the Ionakhsh Fault, for the following purposes:

- accurate location and delimitation of the salt wedge within Ionakhsh Fault,
- detailed lithological composition of the hemming rock,
- detailed nature and composition of the dissolved rock residues around the halite-anhydrite dome,
- water tests (rather similar to Lugeon tests) for hydraulic conductivity appraisal,
- Equipment of boreholes into piezometers (Ref. [5]).

➢ Before 1979: Laboratory tests on samples for the evaporite composition, bench mark to determine its solubility (Ref. [5]),

➢ Groundwater level measurements of the observation wells, until their grouting which prevented further measurements (Ref.[6]),

➢ 1979: large in situ test of a hydraulic curtain and brine injection (Ref.[1], and [5]),

➢ 2012: pumping and dissolution test as recommended by TEAS Consultant (Ref.[6]).

6.3 Ionakhsh Fault, geometry and characteristics

The Ionakhsh Fault crosses the bed of the Vakhsh River just at the entrance of the gorge, 0.5 km upstream of the dam site area. It strikes in North-East direction, sub-parallel to the Vakhsh River upstream of the dam site, then penetrating into the right bank as the river bends towards South to enter the gorge (see Figure 5.3). The fault plane is dipping 75 to 80° to the south east, i.e. towards downstream.

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 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. The top of the salt wedge in the banks is located at elevation 956 to 970. There is no salt above this elevation; it has been leached.

Under the horizontal forces the salt is creeping, resulting in a salt dome rise that was estimated to 2-3 mm per year in 1978 (Ref [2]) and 2 cm per year in 2005 (Ref [7]). It is assessed to be currently between 1 and 2 cm (Ref [7] and [8]), and more recently between 2 and 5 cm per year; even 12 cm/year could be envisaged (Ref.[1]), as discussed here after.

It is worth to notice that the rising movement has not been monitored in the frame of the general geodesic survey, from 1969 to 1992. Some experts believe it could be currently higher than 2 cm. As observed for very similar orogenic conditions in Iran and Israel, 5 to 12 cm per year could be expected (Ref [1]) and more specifically 12 cm in mountainous areas.

Logs of some boreholes executed for grouting above the salt wedge in 2012 seem to have encountered the salt wedge at elevation 945, hence more than 5 m lower than the minimal elevations predicted by the boreholes made during the investigations for the 1978 Design Project. But it is thought to be the consequence of the natural irregularities of the top of the salt wedge, depending upon nature of the embedding rock, its discontinuity distribution, etc.

A leaching rate exceeding the rising rate of the salt wedge by as much as 15 cm/y (5 m in 3' years) would have indeed resulted in unstable conditions which would have been evidenced on field. Therefore such a high rising rate can derived from this observation on site.

Ms Lekhov and Kolichko from HPI finally consider 2.5 cm/year in their assessment (Ref [1]). This value seems the most realistic for the TEAS Consultant. However given the uncertainties and the lack of recent measurements of this dome rising rate, it was thought important to keep in the overall risk assessment a sensitivity analysis on the rate of rising.

All previous studies assume 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 rise (Ref [1], [3]).

Although this assumption seems the most probable based on site observations, it should be further evidenced as this is a fundamental assumption in the overall understanding of the phenomenon. It is also linked to the estimate of the rising rate adopted in the calculations. If the salt wedge rise was higher than the leaching, one should observe extruding salt on both River banks.

The leaching which might have started after the last ice age and after glaciers melt at the site. The most probable explanation is that the top of the salt wedge then deepened until the level where equilibrium was found between the leaching rate and the salt wedge rising rate. This equilibrium is depending on the groundwater gradient which is decreasing with the salt cap depth.

The clay cap above the salt wedge is residual clay remaining after leaching of the salt, which contains some clay impurities. Taking into consideration the clay content of the salt wedge, and the thickness of residual clay over the top of the salt wedge (as per borehole investigations), the time necessary to dissolve a volume of salt sufficient for producing the said amount of clay has been deduced. Assuming the leaching conditions are same as today, this would mean that leaching has started some 300 years ago. A longer duration is however plausible, since the salt leaching rate cannot actually be considered as constant over all this period, and should have been higher earlier, when the salt was more close to the surface than now. Considering the end of the last ice age, and depending upon melting of the glacier at Rogun site, an expected overall 0.5 cm/year or even less over all over this period is plausible.

It is to be noted that the assumption that the equilibrium is not entirely achieved in natural conditions is considered in the scenario: no or negligible rise. This scenario combined with all other worst conditions is the most critical.

The movement of the top of the salt body is therefore a crucial parameter for the calibration of the dissolution models.

Lithological conditions around the salt dome are presented in Figure 6.2 (Ref.[3]. The hemming rock is gypsum coated argillite of Gaurdak Formation on the downstream side and sandstone interbedded with aleurolites on the upstream side.

Above the salt wedge, and from investigation boreholes, the following typical sequence has been derived (see Figure 6.3, Ref [1]) from bottom to top:

- Intact salt wedge: halite and anhydrite, impermeable. Since in the valley floor the salt has been leached down to elevation 953, the intact salt wedge is found at this elevation (about 40m depth).

- Above: one to three meters of almost watertight transition of clay-breccia-anhydrite to breccia-clay. It is further called clay coating. The area of the wedge coated with clay is not known, but estimated between 50 to 75% by HPI (Ref [1]). From core observations and analysis of the dissolution processes, this part could reach, and even exceed 95%.

- 1 to 3 meters pebbles, debris of dissolution with an assumed high porosity and hydraulic conductivity. Only one water test could be performed in order to test that horizon and it gave a value of discharge up to 10 l/min (roughly 1,000 LU). On the other hand, numerous tests were performed in the neighbouring rock, and finally, 0.85×10^{-5} m/s have been considered in the HPI model. Other tentative tests inside the cap aquifer itself were not successful, probably because it was technically not possible to tight up the packers in the borehole for a test with reliable results. We further will see that this hydraulic conductivity value has been determined by the large-scale pumping test recommended by TEAS Consultant.

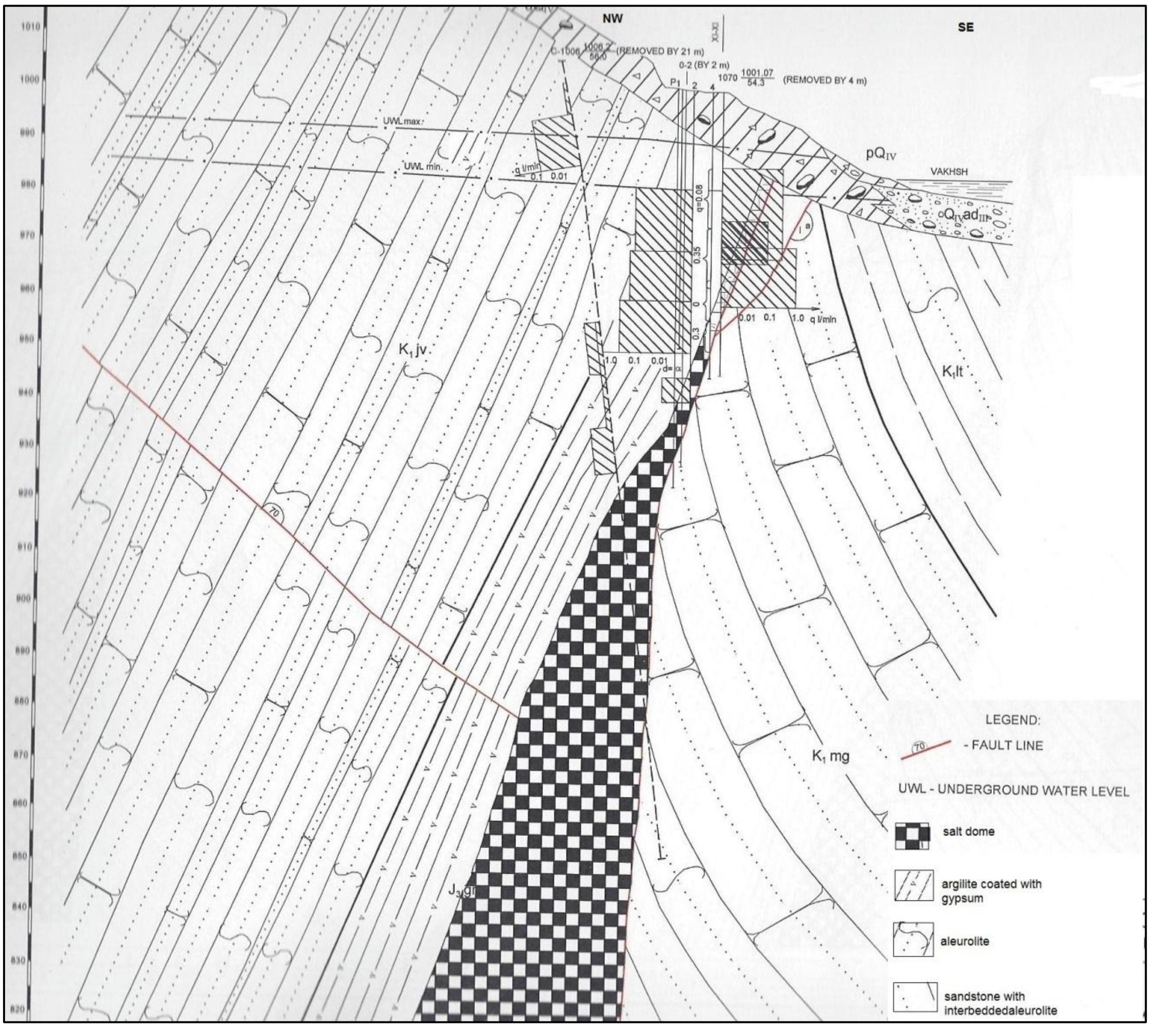


Figure 6.2. Left Bank NW-SE cross section of the salt wedge of Ionakhsh Fault.

- From elevation ~957 to the surface (or Vakhsh River bed) a refilled void with mainly the upstream hemming rock: gypsum coated argillite. One would expect this clay to be impermeable. But previous observations and the 2012 pumping test pumping test showed that there is a direct connection between the Vakhsh River and the lower permeable layer above the dome cap. This connection may also result from the brecciated part of the upstream "sandstone" hemming rock.

- Farther inside the banks, the elevation of the top of the salt wedge is assumed to rise slowly, and above the salt cap aquifer, it has been observed in grouting galleries that a stiff breccia mainly made of aleurolites with remaining inclusions of gypsum, consolidated by the compressive tectonic forces was overlying this zone of cap wedge.

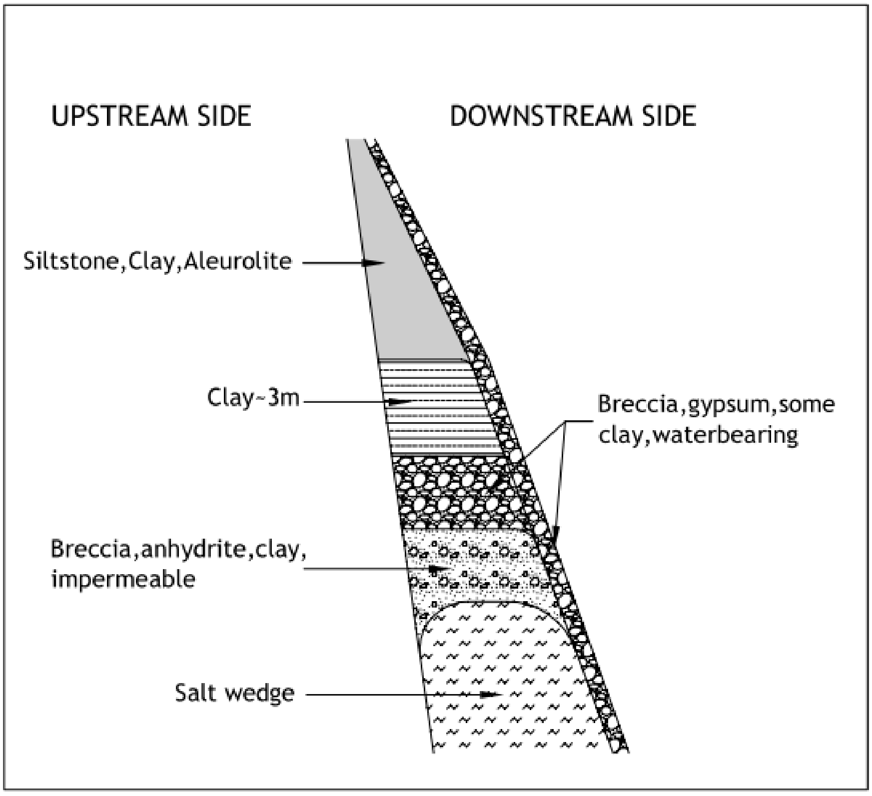


Figure 6.3: Dissolved material above the salt dome.

6.4 Pumping dissolution test of end 2012; results interpretation

A pumping test has been performed from November 16th to December 10th 2012 for which a 48 m deep borehole (HG1) has been drilled with a 10” diameter (see location on Figure 6.4 and Ref [6]).

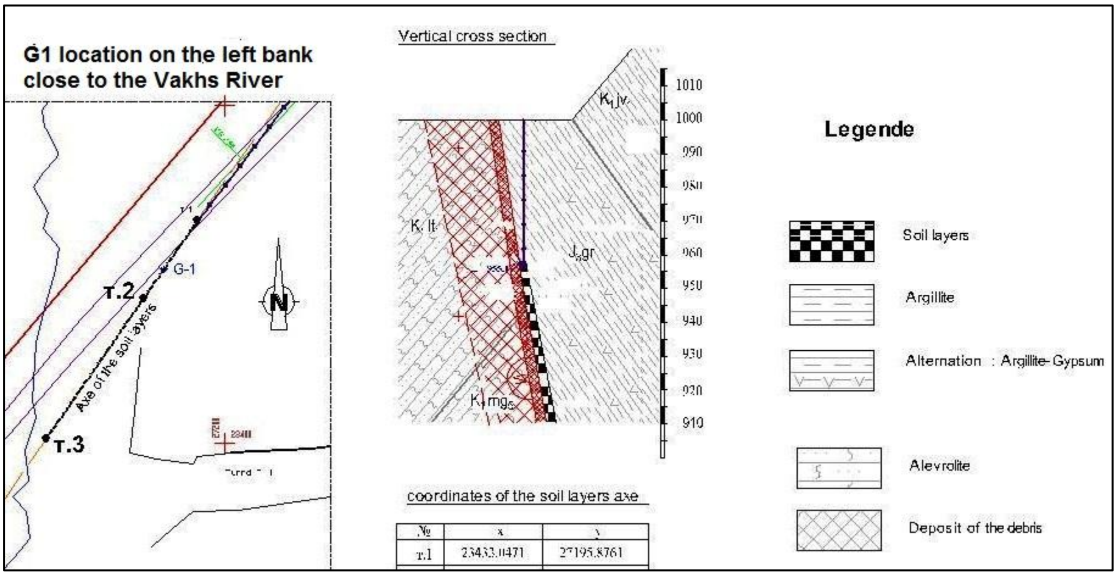


Figure 6.4 : Pumping test borehole location and cross section.

The borehole log and detail of well equipment are presented in Figure 6.5.

Scale 1:200	Depth interval layer from-to, m	Name of species	The well design for drilling	NOTES:
2				0-14m, drilling diameter 426mm
4				
6				
8				
10				
12				
14				
16				0-39.5m, steel casing diameter 219mm
18	0-19,5	Embankment (debris and boulders of sandstones)		
20	19,5-21,0	Gravel		
22				
24				
26				
28	21,0-28,0	Injection gallery -16 A		
30		interbedded mudstone and siltstone		
32	28,0-32,4			
34	32,8-34,2	Clay		
36	34,2-35,4	interbedded mudstone and siltstone		
38	35,4-38,0	Reddish-brown clay		37.75-45.0m, steel casing diameter 127mm Slotted casing between 42.5 and 45 meter depth
40				
42				
44	38,0-43,5	Interbedded siltstone and mudstone. Siltstone and mudstone with gypsum veins. 43,5-44,0 interbedded siltstone anhydrite with gypsum veins		
46	44,0-45,5	Breccia fragments of mudstone and aleurolit on clay		
48	45,5-48,5	Salt inclusions debris siltstone and mudstone		

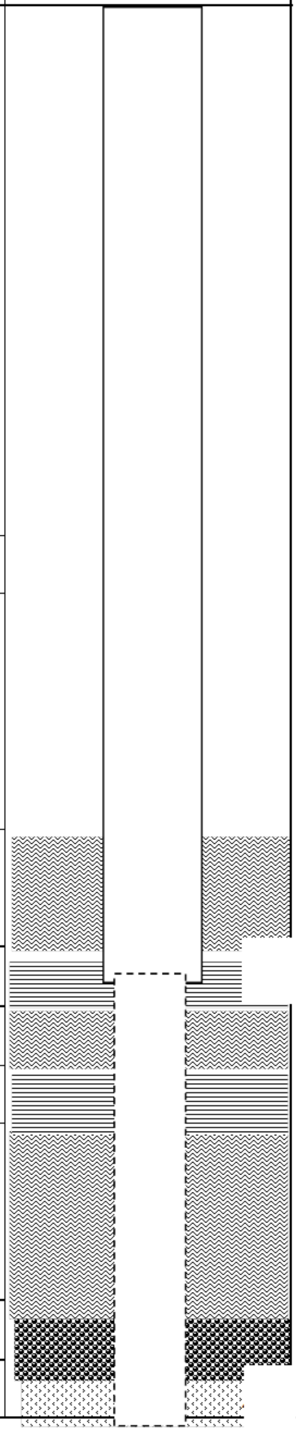


Figure 6.5: Borehole log and equipment of HG1, where pumping / dissolution test was performed

During the test the following parameters have been measured: discharge, drawdown, electric conductivity of water, total mineral content at the well itself. In addition drawdown at the neighboring piezometer P31A was followed.

It is to be reminded that grouting works have been performed along the fault in the cap of the dome on both river banks except for a roughly 180 m long section including the river bed and part of the left bank. Below the river bed, the salt is therefore intact of any treatment. The grout used is a blend of cement and bentonite in order to enhance the imperviousness and to allow some deformations induced by creeping.

The results of the pumping/dissolution test are given hereafter in Figure 6.6, Figure 6.7 and Figure 6.8.

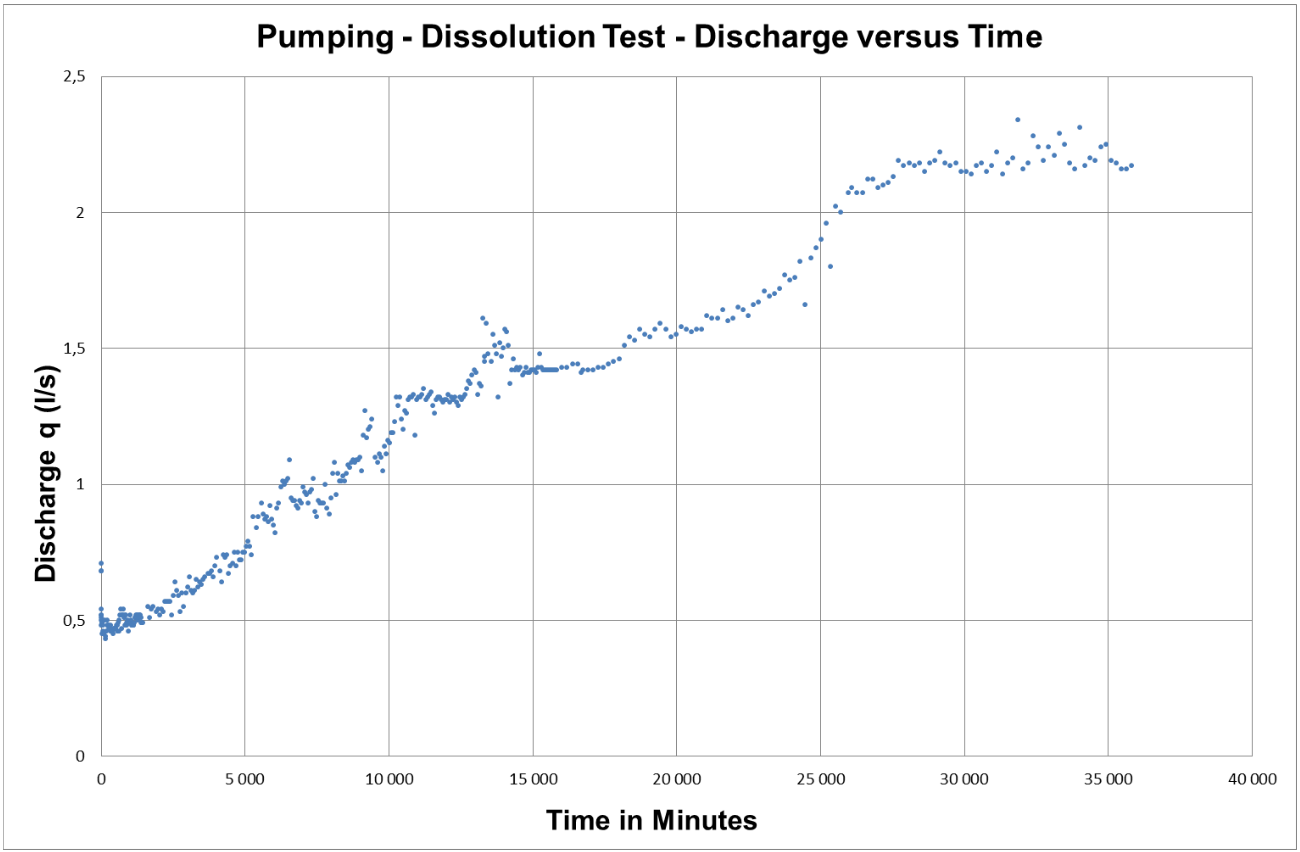


Figure 6.6. Pumping/dissolution test - Discharge versus time

The following main conclusions can be drawn from these results:

The discharge is gradually but significantly increasing with time, 0.5 l/s at the beginning of the test to reach 2.3 l/s after 34000 minutes (23.6 day). Considering that the pumping test was performed at the maximum well capacity, discharge increase is in general the result of well development.

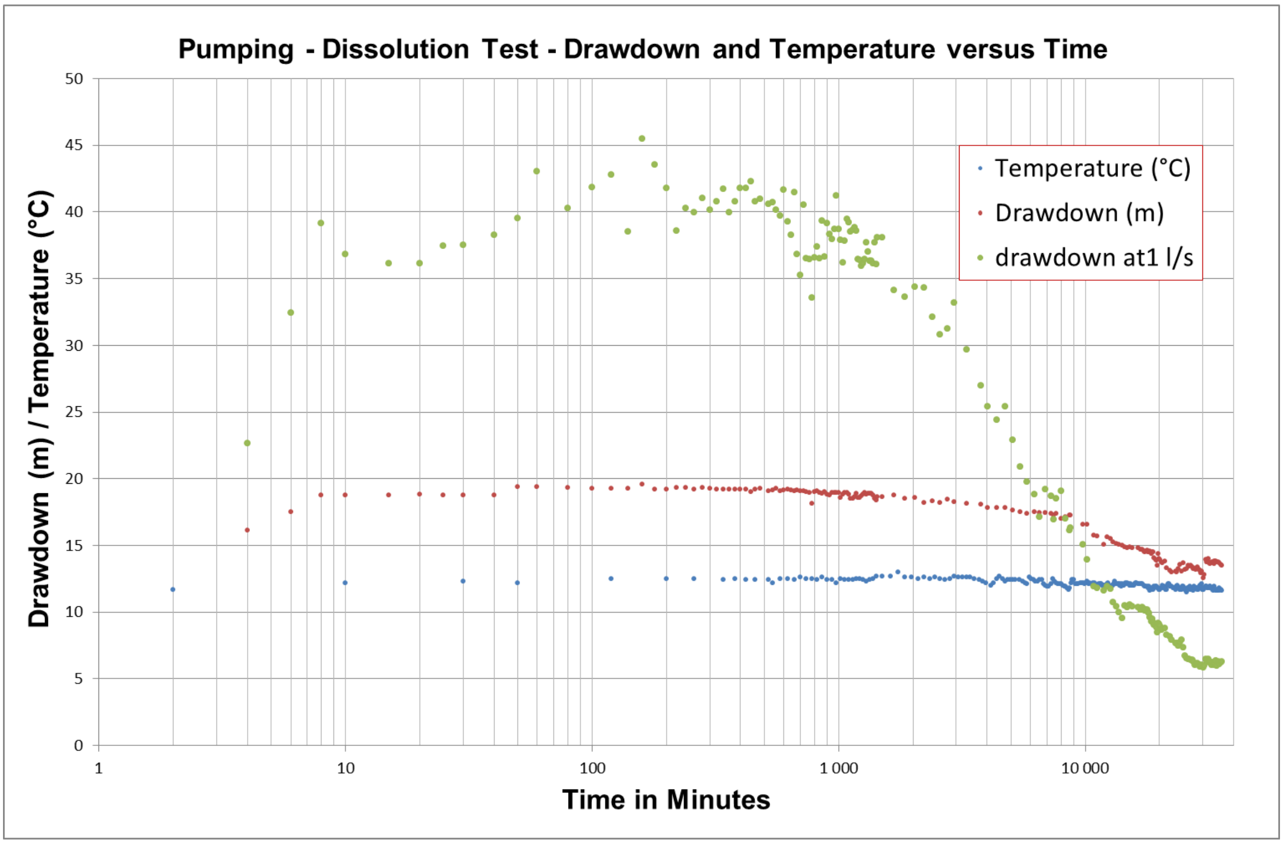


Figure 6.7: Drawdown (m), calculated drawdown at constant discharge (m) and temperature versus log of time (minutes)

A well development is the progressive removal of fines from the vicinity of the well screen, a phenomenon which allows free flow of water from the rock into the well and also reduces the turbidity (fine particles may damage the pump). If the well is not well developed, its development is taking place during the pumping, most of the time with turbidity, or at least with fine particles deposits observed at the bottom of the sampling bucket. This was not observed during the test. In the particular case of the cap aquifer of the Ionakhsh Fault, the well capacity increase may also result from a significant effective porosity increase which should be predominantly the consequence of leaching.

The results of a pumping test are presented as a plot at constant discharge of the drawdown versus the logarithm of time, and for normal conditions, one or two straight lines are observed, from which using Theis law, the transmissivity is determined.

In our particular case, since the discharge was not constant, the observed drawdown values were converted into drawdown at constant discharge of 1 litre/sec. The Logan empirical formula is used: T=1.22 x q/s (where q is the discharge and s the drawdown). The corresponding calculated drawdown is plotted in green on Figure 6.7. The drawdown, versus logarithm of time is decreasing which, as above mentioned, is unusual and show an increase of the transmissivity around the well and an improved contact with a better transmissive aquifer. A standard “Theis” interpretation of the pumping test is therefore not reliable. Using Logan’s empirical rules (Ref [12]), which is considered reliable as it is based on a very large number of recorded pumping tests; the following results of Table 6.1 are obtained:

	Transmissivity	Hydraulic conductivity
Start of the test	3.10^{-5} m²/s	$1.2\ 10^{-5}$ m/s
End of the test	$2.4\ 10^{-4}$ m²/s	$1.\ 10^{-4}$ m/s

Table 6.1: Transmissivity and hydraulic conductivity of the cap aquifer as measured from the pumping test, at the beginning and the end of the test

Once again, the huge increase of hydraulic conductivity can hardly be explained only by removal of fine particles. This is the evidence that significant dissolution happened with respect to the low discharge imposed.

During the pumping test, the drawdown at piezometer P31A was recorded, and results are presented in Figure 6.8. As a rule, the interpretation from a piezometer drawdown is more reliable than the one based on the drawdown measured at the pumping well itself.

The plot of piezometer P31A drawdown shows a gradual decrease, with a small increase between 16 days (24000 minutes) and 19 days (28000 minutes) after the start of the pumping test. This increase shows an improved connection with a more transmissive aquifer.

Drawdown measurements from a piezometer allow the determination of the transmissivity and storativity (or storage coefficient) of the aquifer.

Omitting the observed small rise and using Theis method, the obtained transmissivity (hydraulic conductivity) is $3\ 10^{-4}$ m²/s (K= $1.2\ 10^{-4}$ m/s) and the storativity is 13%. This transmissivity value is close to that calculated from the pumping well drawdown at the end of the test, and is therefore the best estimate of the cap aquifer hydraulic conductivity. In this case and due to the fact that the pumping test is a long time pumping test, the so-called cap aquifer integrates the cap aquifer itself, but also the aquifer located inside the brecciated column over it, connecting the latter with the Vakhsh River.

The obtained value of hydraulic conductivity through the pumping test may be compared with the “absorption” reported to have been observed during a test made in the caprock prior to 1978, which gave an “absorption” of 10 litre/min, hence some 10^{-4} m/s.

The storage coefficient, or storativity, is the volume of water released from storage with respect to the change in head (water level) and surface area of the aquifer. The value of the storage coefficient is dependent upon whether the aquifer is unconfined or confined. In an unconfined aquifer, the predominant source of water is from gravity drainage as the aquifer materials are dewatered during pumping. The storage coefficient is approximately the same as the effective porosity.

The storage coefficient for an unconfined aquifer ranges from 1% to 30%.

Water released from storage in a confined aquifer is from compression of the aquifer and expansion of the water when pumped.

During pumping, the pressure is reduced in a confined aquifer, but the aquifer is not dewatered. The storage coefficient is related to the compressibility of the solid material within the aquifer and water compressibility and ranges from 1 x 10^{-5} to 1 x 10^{-3}.

With respect to the determined storativity values higher than 0.1%, the aquifer where water is pumped is unconfined and its effective porosity is ~13%.

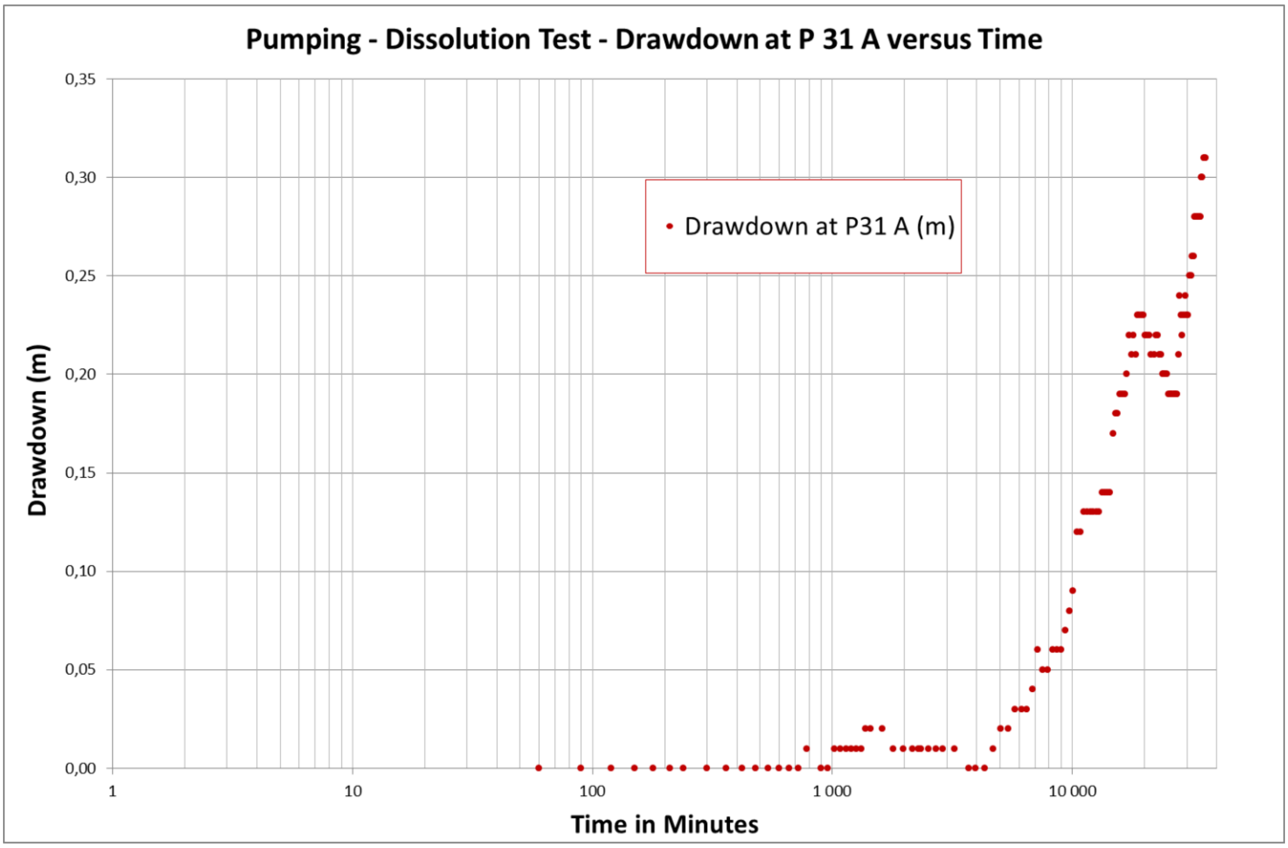


Figure 6.8. Drawdown at P31A observation well, versus log of time (minutes)

The fact that the part above the salt dome cap aquifer is unconfined shows that there is, despite the presence of aleurolite and clay layer of several meter thickness, a direct connection with the Vakhsh River. This feature is confirmed by the groundwater levels observations made in the piezometers along the Ionakhsh Fault, which respond instantaneously to the Vakhsh River water level fluctuations (Ref.[1] and [6]).

The salt content curve, presented in Figure 6.9, shows a decrease of salinity of the pumped water from 31 g/l to 6 g/l after 24,000 minutes (400 hours) followed by an increase of salinity to 8.9 g/l after 35,900 minutes (~600 hours).

Vakhsh River water salt content is between 0.3 and 0.6 g/l (Ref. [5] and [6]). From measurements and from the investigation boreholes along Ionakhsh Fault, groundwater before pumping has a salinity of 7 to 17 g/l at 10m depth. Between 10 and 44 m depth, the salt content is increasing to 35 g/l. Deeper, from 44 to 47 m depth the salt content may reach 314 g/l (Ref [1]) which corresponds to brine.

With respect to the above considerations a possible interpretation of the salt content versus time curve is as follows: initial mineralized groundwater is pumped (31 g/l) immediately followed by abstraction of fresh Vakhsh River water blended with groundwater. Progressively groundwater in the aquifer is replaced by fresh Vakhsh River water. Later after 400 hours, the salinity increases. At this moment the hydraulic conductivity is significantly increased, probably related to dissolution of remnant gypsum, halite in the residual formations above the cap. The final increase of salt content seems to be related to salt dome dissolution. In that case, it means that at an average discharge of 2.12 l/s for the timespan of the last 15,900 minutes, 4,4 t of salt were dissolved. In other words there should be a leachate capacity of 2.18 g/s, i.e. roughly 70 tons/year for a flow of 1 l/s.

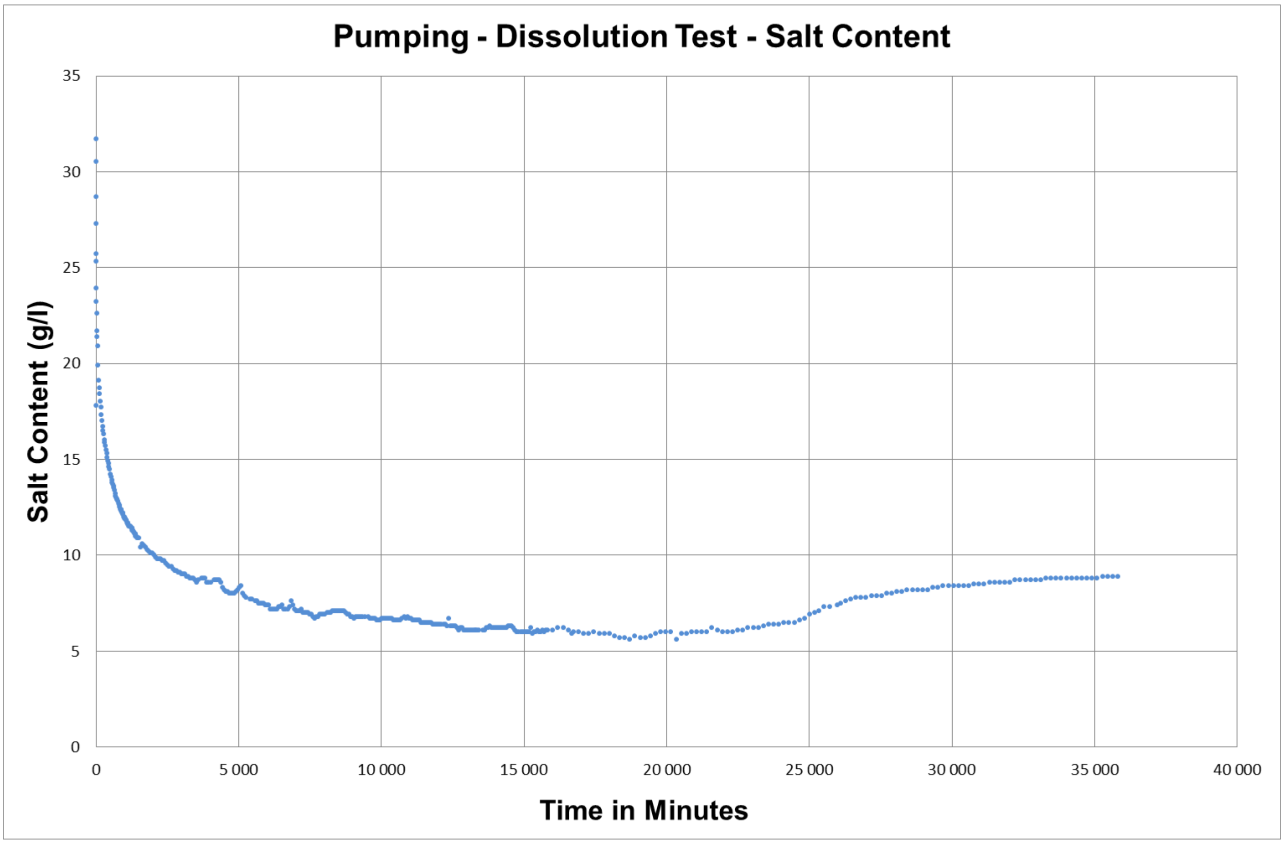


Figure 6.9 : Variation of minerals content (in g/l) of pumped water with time (in days)

6.5 Analysis of the previous hydrogeological / dissolution conditions and 2012 current conditions

The Ionakhsh Fault cap aquifer is a specific feature inside the main aquifers and acts as a draining body. Since the Ionakhsh Fault hemming formations to the south are clayey, the Ionakhsh cap aquifer drains principally the northern formations. The estimated hydraulic groundwater gradient along the fault is 1.6/1000, as per 1978 Design Report (Ref.[2]), and is presented in Figure 6.10.

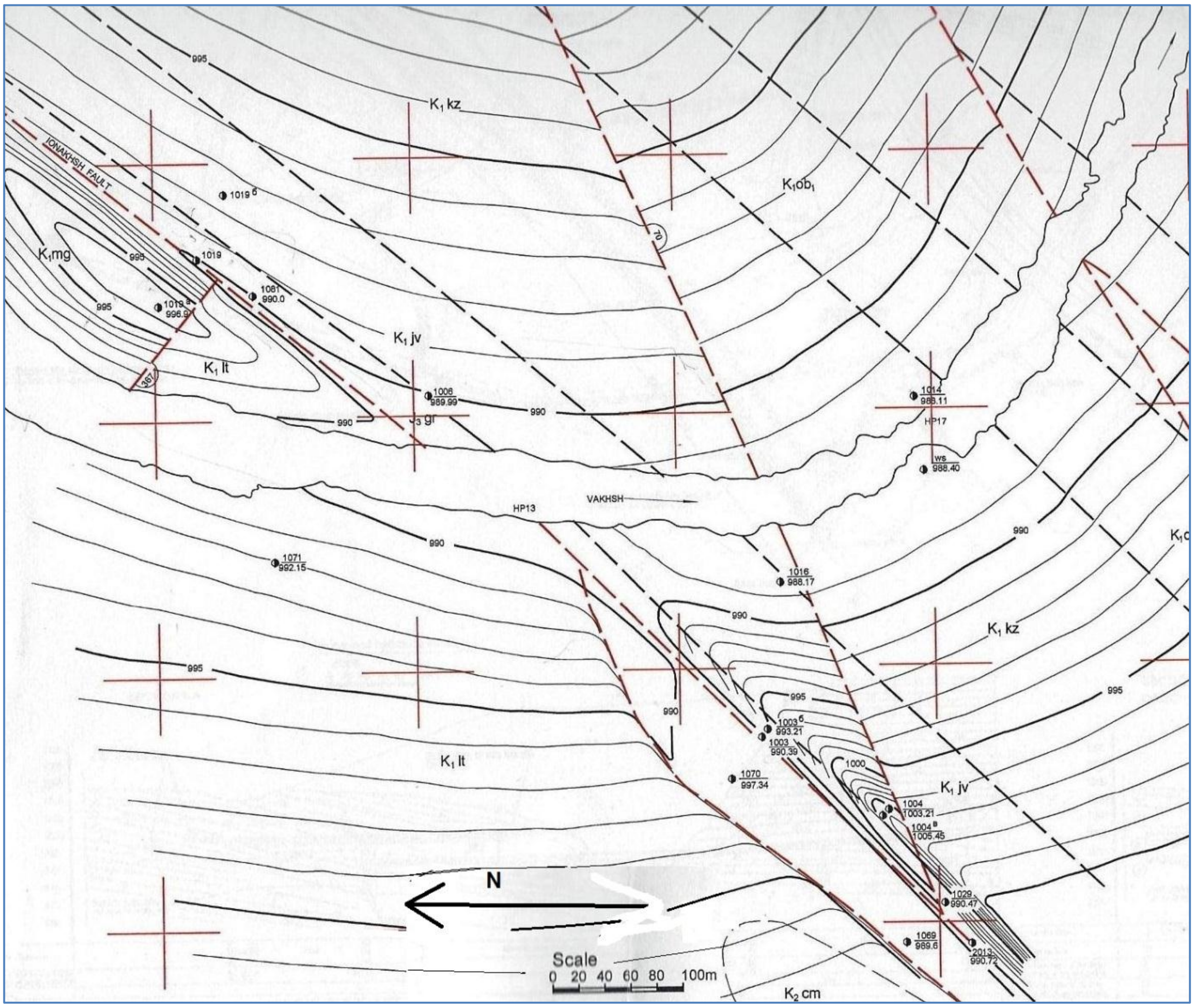


Figure 6.10 Groundwater level lines at Ionakhsh Fault (after Ref.[3])

The flow from the right bank to the Vakhsh River is estimated using Darcy law : Q= T x i x w_i with, according to the results of the pumping-dissolution test :

T: transmissivity = 3.10^{-4} m²/s; i: gradient =0.0016 and an assumed width w_i: aquifer width=7 m, leading to a flow of Q=$3.4.10^{-3}$ litre/sec.

Perpendicular to the fault one observes a groundwater gradient with respect to the upward less permeable argillite. For 100 m fault length one has: Q= 3 10^{-2} litre/sec.

In natural condition the dome is rising at an assumed rate 2.5 cm/year, according to HPI assumptions. The mass corresponding to this rising process is leached. With a volumetric mass of 2.3t/m³ for the salt rock, the leached mass for 100 m length of fault is 40 ton/year. Therefore, one can notice that, considering the different approaches made up to now, by Prof. Lekhov and HPI, as well as by mean of the pumping / dissolution test performed in 2012 in HG1, the salt leaching rate derived is in the same order of magnitude, showing good consistency of the different results.

6.6 Analysis of the transport processes, current and stage 1 conditions

For different conditions, assuming hydraulic conductivity of the grouted rock material to 10^{-7} m/s, and considering the hydraulic conductivity of the salt as measured in the pumping test, the Péclet number as defined in paragraph 6.1 is determined and given in Table 6.2..

	Conditions	K (m/s)	Gradient i	d (m^2/s)	ω_c	l (m)	Péclet number	Dominant phenomenon
	Cap aquifer in natural conditions	1,2E-04	0,001	6,5E-10	0,13	1,0E-03	1,4	Advection / diffusion
STAGE 1	"Do nothing" option	1,2E-04	0,01	6,5E-10	0,13	1,0E-03	14,2	Advection
	Grouting of top of salt wedge	1,0E-07	0,01	6,5E-10	0,01	1,0E-04	0,0	Diffusion
	Transport to hemming rock	1,0E-08	0,01	6,5E-10	0,001	1,0E-05	0,0	Diffusion
	Hydraulic barrier only	1,2E-04	0,0001	6,5E-10	0,13	1,0E-04	0,0	Diffusion
	Grouting and hydraulic barrier	1,0E-07	0,0001	6,5E-10	0,01	1,0E-04	0,0	Diffusion

Table 6.2: Orders of magnitude of Péclet numbers for the different conditions; the three last lines considers the Stage 1 with grouting only, without hydraulic barrier

According to the Péclet number for the different considered conditions, the transport process is slow and diffusion contributes moderately to the process in the actual conditions.

The fact that diffusion is an intervening transport process is corroborated by the observation of a significant salt content inside the hemming formations as well up- as downstream (Ref [3]). 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.

6.7 Conclusions

The Ionakhsh fault geometrical and chemical characteristics have been derived from existing results of investigations and recently performed tests as recommended by TEAS Consultant. The dynamics of fault creeping analyzed in the view of field observations in order to understand the potential dynamics of salt dissolution at present stage and derive the most appropriate assumptions for the numerical models. Dissolution processes where described theoretically, in particular transport processes dominant in the different scenarios to be studied. This was allowed by the use of the results of the pumping dissolution test carried out in 2012.

This extensive analysis of the key parameters intervening in this complex dissolution phenomenon is the basis of the critical analysis of existing models and the implementation of three sub-models by the Consultant as described in the following section.

7 MATHEMATICAL MODELLING OF THE DISSOLUTION PROCESS; ANALYSIS

7.1 Assessment of current HPI model

7.1.1 General comments

Prof. Lekhov, recently and Prof. Orekhov earlier, have modeled the whole dissolution transport process (Ref.[1] and [4]).

The models are based on the same principles but the model of Professor Lekhov is adapted to the actual current Rogun concept dimensions (2009-2010) and its different stages of construction.

There are two parts of the model, which are coupled.

The first is modeling the dissolution process, taking into consideration the dome salt composition, the dissolution products and dissolution kinetics of each component. The anhydrite hydration with the corresponding volume increase and the favorable residual cap left covering the top of the salt wedge is also included in the model. The analytical formulas are correct and the fundamentals right.

The second includes the three transport processes; the advection/convection and the diffusion are considered together, while the gravity convection is separated. The software being used is SEEP, which integrates the three transport processes.

The model is a bi-dimensional model, perpendicular to the Ionakhsh Fault. As seen above, the flow along the Ionakhsh Fault is negligible; therefore a three-dimensional model is not required for the current conditions. The fact that the aquifer above the salt wedge cap is unconfined leads to the same conclusion under conditions of dam operation. The model boundary conditions are taken sufficiently far away from the Ionakhsh Fault, according to groundwater model standards. There is no infiltration and no anisotropy considered.

7.1.2 Selection of input parameters

7.1.2.1 Recall of the most important input parameters

The crucial parameters are the hydraulic conductivity, groundwater gradient, anisotropy, effective porosity, dissolution kinetics, clay coating covering the wedge cap and salt rock composition (and of course the assumed salt wedge rising rate).

7.1.2.2 Hydraulic conductivity, anisotropy

From several water tests performed for the initial design, the hydraulic conductivity of the hemming rock is assumed decreasing with depth. The hydraulic conductivity of the aquifer inside the residual soil above the wedge cap (assumed 0.85 10^{-5} m/s), however, does not fit with values obtained from the December 2012 pumping test (1.2 10^{-4} m/s). This underestimation of the hydraulic conductivity by one order of magnitude is not conservative.

No anisotropy is considered within the hemming rocks, which is a conservative assumption since the bedding is dipping 60° towards downstream, sub-parallel to the fault, and the model is bi-dimensional. Moreover anisotropy would have limited consequences with respect to the rather low hydraulic conductivity in the hemming rocks. Decrease of hydraulic conductivity together with increased salt concentration has not been considered. It is conservative and the influence on the results would have been negligible in comparison to the accuracy of the various input parameters.

7.1.2.3 Groundwater gradient

The groundwater gradient for current conditions can be estimated from the groundwater level measured in piezometers. For impoundment stages, it is calculated from the SEEP code. This is adequate in particular as the wedge cap aquifer is unconfined, and thus in direct relation with the reservoir.

On the other hand silting up of the reservoir bottom is not considered. Since the silting up generally generates a less permeable blanket at the bottom, It certainly will have influence on the deeper groundwater gradient. But not considering the silting up is a conservative approach for the considered dissolution process.

7.1.2.4 Effective porosity

This parameter is ruling the transport process, as well as the chemical dissolution processes. It is difficult to infer from the report which value has been used but it seems that a 0.2 value inside the dome cap aquifer has been selected. It is a large value, higher than the 0.13 value determined from the pumping test.

In advective/convective or gravity/convective transport, it is the kinematic porosity which is the predominant parameter. The kinematic porosity is smaller than the effective one, but considering the present lithological conditions, the kinematic porosity must be close to the effective porosity. In our model we will adopt this assumption. For the transport process, an overestimated porosity is not conservative, because the real solute particles velocity, which controls the dynamics of transport, is reversed proportional to the porosity. On the other hand for the chemical dissolution processes, an overestimated porosity is conservative because a high porosity infers a higher exchange (dissolution) surface.

In the HPI model, the advection/convection and diffusion transport processes are considered together using the same porosity. For diffusion, total porosity has to be considered because the Brownian movement also affects the adsorbed water within the ground, while in advection/convection the solute particles are not moving through the adsorbed water, which remains fixed to the ground particles. Total porosity is always larger than the effective porosity, and in case of clay formation might be much larger (up to one order of magnitude) due to the higher proportion of voids filled by adsorbed, fixed water. This is why some groundwater transport models calculate the Péclet number for each model cell, and subsequently allocate to each cell the adequate porosity value according to the prevailing transport process.

Finally the porosity value is not constant, since according to the results of the pumping/dissolution test, it increases with the dissolution process when it becomes significant.

It is thus suspected that the porosity value considered in the model is not properly assessed. An overestimation of this porosity is not conservative for the dissolution processes, but conservative for the transport process.

7.1.2.5 Dissolution kinetics and salt rock composition.

The related parameters are coming from laboratory test and hydrochemical databases. They seem to be adequate, although somewhat different from the first estimations of 1978 (see paragraph 6.1).

7.1.2.6 Infiltration

No infiltration has been considered in the model, because it has been considered negligible.

7.1.3 Assessment

The model is calibrated on the previous conditions, it means 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 a 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 process leaching the salt at the same rate. The model results give a similarity at an acceptable level between the observed salt concentration distribution inside the Ionakhsh Fault hemming rock and the calculated one.

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. Also not conservative is the overestimation of the kinematic porosity, since it slows down the transport process. The adopted value results 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. It is worth to recall in this respect that the only successful water test reportedly made inside the cap aquifer gave absorption of 10 litre/min (borehole 1029, Ref [2]), a result which is quite close to the 10^{-4} m/sec deduced from the pumping test carried out in 2012.

The good fit of the model with the estimated rising rate of the salt wedge and the salt concentration inside the hemming rock results from the calibration through the value of the percentage of the top of the salt wedge covered by clay (clay coating).

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 leaching that could be ten times higher as assessed by the HPI model, requiring a 25 cm salt dome yearly rise for equilibrium in the actual conditions. There are until now no field evidences of such a high rising rate of the salt wedge within the Ionakhsh Fault.

7.2 Mitigation measures

It is worth to note as it will be confirmed later that the worst conditions with regard to leaching of the salt wedge will prevail during impounding and operation of Stage 1 dam, located just above the Ionakhsh Fault, since the hydraulic gradients above the wedge are the highest. This period is forecasted to last more than 10 years. However, once the final dam constructed, gradients will be much more reduced, and leaching risk lower.

In existing studies, as the salt dome dissolution as always been a focus of studies, some techniques to mitigate the effect of a leaching of the salt wedge on the dam integrity have been extensively detailed.

These techniques are:

- (1) Grouting of the rock immediately above the top of the salt wedge, over 10 m height, as well as a large part of the whole rock column located above, in order to significantly reduce the hydraulic conductivity,
- (2) Injection of water under pressure of the reservoir (elevation 1055 or more) downstream of Ionakhsh Fault to reduce the groundwater gradient above the salt wedge, or "hydraulic curtain" made of a line of boreholes fed with the water of the reservoir,
- (3) Injection of brine, with the aim of eliminating the leaching potential (already implemented over 200 m length between December 1987 and October 1992, according to Ref.[3])
- Combination of (1), (2) and (3)
- Combination of (1) and (2)
- Combination of (2) and (3)

The main outcome of the saline curtain operation was the requirement of huge quantities of brine to inject. Moreover clogging of the injection wells with the brine was faced during the in situ tests implemented (Ref [1], [3], [4], and [8]). This has led to expressing doubts about the feasibility of such technique.

7.3 Analysis and comparison of the different mitigation techniques according to HPI model

All the scenarios were analyzed 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 results of the different scenarios combined with the parameter variation are summarized in Table 7.1. From this table is the following is inferred:

1. If the salt dome rise is confirmed to be 2.5 cm/y, the model is calibrated with the cap of salt wedge coated with clay over 50% of its surface. The model results fit also well with 75% clay coating and pessimistic range of parameters,
2. With grouting alone, even with maximum efficiency, this would correspond to a leaching phenomenon ranging between 8.5 and 15 cm/year,
3. Minimum leaching, less than 1 cm/year, requires in all cases a brine curtain; grouting seems as per the model not very efficient, and even worse than the "no remedial measures" option; this is not possible and shows a model weakness, probably related to the selection of inadequate input parameters (hydraulic conductivity distribution)

4. With grouting and hydraulic barrier, the leaching rate is of the order of 5 cm/year, hence close to the estimated wedge rising rate 2.5 cm/year. Results are sensitive to the achieved hydraulic conductivity of the grouted rocks,

5. Results are very sensitive to the percentage of the wedge cap coated with clay.

The whole model liability 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.

It is to be noted that a higher rate of rising of the salt wedge unfavorable, since it would mean, to achieve the present conditions of equilibrium, a much higher leaching rate.

The HPI model outcomes have been verified with the Consortium model (detailed description in the next chapter). The Consortium model is a simplified model. When using the parameters introduced by HPI in their model, there is no significant difference between the HPI model and the Consultant model for the conditions before any work (range of 20 to 30%). The dissolution rate foreseen by Prof. Lekhov model is about 2.17 cm/year against 1.8 cm/year for the Consultant model using the HPI parameters. The difference is small if we consider the uncertainty of the input parameters. It is related to the fact that gravity convection has not been considered in our model and maybe to a lesser extent, because of differences in the computing process.

Subsequently the HPI model seems likely to be reliable, but the choice of the input parameters has to be enhanced following the results of tests and observation data.

					Results : diapir leaching: cm/year (m/100 years)			
	K grouting (m/s)	Kind of groutin g (No, cap or column	Waterhead at brine injection (elevation)	Waterhead at hydraulic barrier (elevation)	50% surface of wedge cap coated with clay Best estimate parameters	50% surface of wedge cap coated with clay Most unfavourable parameters	75% surface of wedge cap coated with clay	75% surfac of wedge cap coatec with clay Most unfavourak e parameter
Initial conditions.		N			2.17	3.32	1.12	1.72
Do nothing		N			9.46	17.71	4.90	9.18
Grouting	10-7	Col			16.25	28.94	8.42	14.99
Grouting	10-6	Col			19.61	36.08	10.16	18.69
Grouting + Hydraulic barrier	10-6	Col		1054	10.42	19.20	5.40	9.94
Grouting + Hydraulic barrier	10-7	Col		1054	4.18	7.35	2.17	3.81
Grouting + Hydraulic barrier + Saline curtain	10-6	Col		1054	5.37	9.84	2.78	5.10
Grouting	5 10-7	Cap			14.10	27.54	7.31	14.27
Grouting + Hydraulic barrier + Saline curtain	5 10-7	Cap	1041	1055	0.22	0.22	0.11	0.11
Grouting + Hydraulic barrier + Saline curtain	5 10-7	Cap	1042	1055	0.25	0.25	0.13	0.13
Grouting + Hydraulic barrier + Saline curtain	5 10-7	Cap	1045	1054	0.26	0.26	0.13	0.03
Hydraulic barrier + Saline curtain	5 10-7	N	1040	1054	0.17	0.22	0.09	0.11
Hydraulic barrier		N		1054	4.20	6.90	2.17	3.57

Green	Yellow	Pink	Red	
<0,5cm/y	0,5 to 6cm/y	6 to 14cm/y	>14cm/y	
G	H	S	Col	Cap
grouting	hydraulic barrier	brine curtain	Grouting column abov	grouting cap

Table 7.1: Synthetic Analysis of HPI model simulation for different scenarios and crucial parameters (colours refer to range of leaching rate as per the legend)

7.4 TEAS Models

The Consultant has built its own model in order to assess independently the model prepared by HPI, but also to use parameters to assess scenarios and extreme conditions which were not considered by the existing models. This will provide a wider range of sensitivity analysis to be included in the overall risk assessment of the dissolution phenomenon.

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

7.4.1 Model description

The whole leaching process is simulated by three separated sub-models which are used sequentially. The sub-models are not coupled as they are for the HPI model.

Sub-model 1: Groundwater flow model

The results of this flow model are presented in Annexure 4. It simulates the groundwater flow around the salt wedge for various natural conditions, different project stages, mitigation works and different levels of mitigation efficiencies.

Filtration conditions were first studied for the Stage 1 dam. Figure 7.1 shows the geometry of the model, with different hydraulic conductivities assigned to the different geotechnical zones of each geological formation of the foundation.

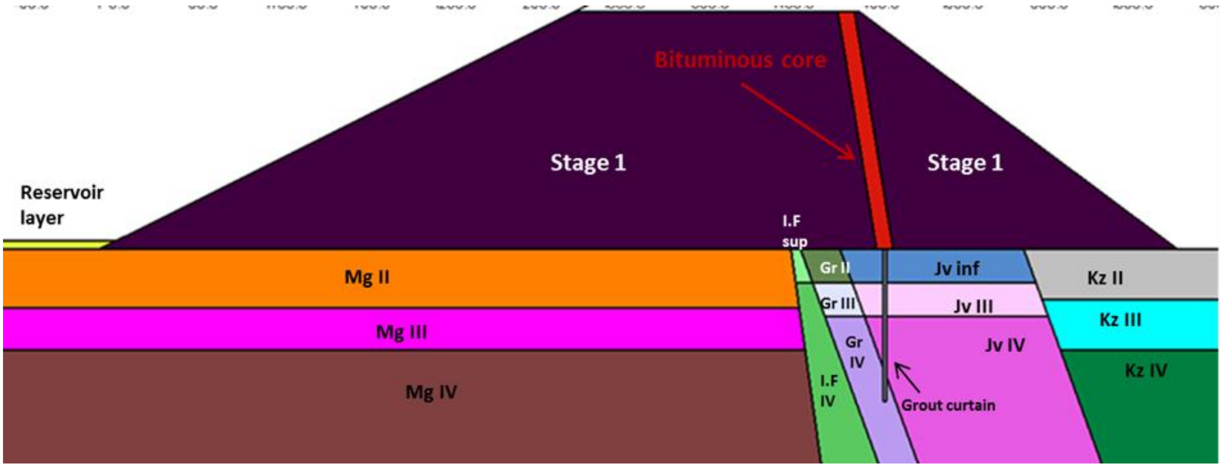


Figure 7.1: Geometry of the model used for the stage 1 dma and foundation; the salt rock within Ionakhsh Fault is referred as "I.F. IV" in light green colour

Filtration conditions (gradient, Darcy's velocities and real velocities taking into account the kinematic porosity) have been examined for the two stages and for the different configurations of mitigation measures contemplated in the report (grouting of the top of the salt wedge, hydraulic barrier).

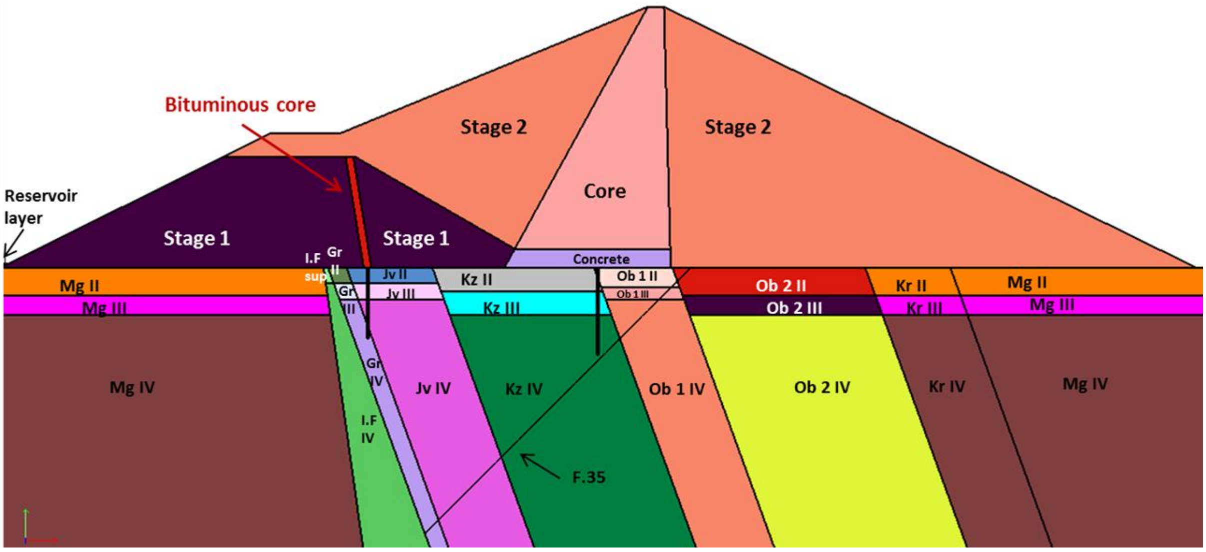


Figure 7.2: Geometry of the model for the final dam; salt wedge of Ionakhsh fault referred to as "I.F. IV" in light green colour, "F.35 being the Fault 35

The gradient around the salt wedge calculated by the model in case of presence of the hydraulic barrier has to be considered cautiously. When the hydraulic barrier is made out of vertical wells, the value obtained by the model (negative gradient) is too optimistic. It corresponds in the model to a vertical draining trench, thereby overestimating the barrier efficiency.

On the other hand, when the barrier is made out two or three horizontal wells, the obtained gradient is close to the one obtained without any hydraulic barrier. In this case, the modeled hydraulic barrier corresponds to two or three draining wells, underestimating dramatically the barrier efficiency. In both cases the over or underestimation is related to a two dimensional effect. We therefore considered for further analyses a residual gradient of 10^{-5}. When combined with a grouting of the top of the salt wedge, we considered a residual gradient of 10^{-4}.

Sub-model 2: Leaching process.

It models the maximum leaching 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, considering its components. The results are the dissolution rates of the rock salt for different scenarios, as far as the dissolved elements - chlorides and sulphates - can be evacuated. It is a maximum rate in term of quantity of leached material. A salt wedge thickness submitted to leaching has to be introduced, the introduced gradient at the salt wedge results from submodel1.

Sub-model 3: Transport model.

It represents the transport processes: diffusion and advection/convection. The gravity convection is not modelled. The corresponding flow has been considered equal to the flow at the salt wedge. A summary calculation comparison shows that for current conditions the whole leaching process is underestimated by 20%, in case of grouting our model is conservative and in case of very low groundwater gradient (stage 2 conditions or efficient hydraulic barrier conditions) , the own made model could underestimate the leaching process of one order of magnitude.

In this model the exact analytical formula (advection, diffusion) are used (see Figure 6.1). The results of the pumping test: hydraulic conductivity and kinematic porosity are introduced. The introduced groundwater gradients are the results of sub-model 1. The model is calibrated on the observation that the leaching is equal to the salt wedge rise.

7.4.2 Parameter analysis of the three sub-models

The different parameters which are used in the three sub-models and the way they were estimated are presented hereafter in Table 7.2

		sensible within reasonable range	in situ test	laboratory test	data room	calculated	best estimate	visual inspection
basic flow model (1)	K							
	Layers geometry							
	Dam geometry							
	Waterhead							
hydrochemical model (2)	NaCl content							
	CaSO4 content							
	Clay content							
	NaCl mol weight							
	CaSO4 mol weight							
	NaCl solubility, saturation							
	CaSO4 solubility, saturation							
	Diapir volumic weight							
	K							
	K mitigation							
	i					1		
	i mitigation					1		
	wk							
	wk grouting							
	Contact surface							
	Dome rise							
	Diapir thickness affected					calibr.		
final dissolution model (3)	NaCl, CaSO4 concentration					2		
	K							
	K mitigation							
	Aquifer geometry							
	i					1		
	i mitigation					1		
	wk							
	wk grouting							
	Diffusion coef							
	Dispersion coef							
	Clay coating					calibr.		
	Dome rise							

Table 7.2: Sub-model parameters: source, sensitivity estimation (where K is the hydraulic conductivity, i the hydraulic gradient, wk the kinematic porosity)

- Sensitivity analyses indicate that the most sensible 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 could be significant for the clay coating and the rate of rising of the wedge.

- The basic assumption, fitting with the observation that the leaching rate is equal (or close) to the dome rise makes that (in permanent regime), if changing one of these above mentioned parameters, the others have to be modified accordingly. Roughly simplified : K / cov x rise = Cte, where K is the hydraulic conductivity, “cov” the part of the slat wedge surface coated with clay, and “rise” the rate of rising rate of the salt wedge.

Thus, considering that the hydraulic conductivity is properly assessed from the pumping test, and the fact that a clay cover is very commonly present above salt rock, we will further limit the global sensitivity analysis (including the three sub-models) to the only variation of the salt wedge rising rate : (~0, 2.5,5,12,30 cm/y) .

7.4.3 Scenarios simulations

Different scenarios for various wedge rising rates are considered for stage 1 and 2, taking into consideration the period of exposure of each situation. The wedge rising rate is subtracted from the leaching rate, so that the final result corresponds to the forecasted vertical height of cavity or salt wedge intrusion. Results of the global model, which is the combination of the three sub-models, are given hereafter in Table 7.3.

As per the conclusions of Annexure 1, the maximal size of cavity to be generated without damage to the dam, considering quite conservative assumptions which have a low probability of occurrence is estimated to 25 m. This value is highly conservative considering the rock condition. Indeed, as described in Annexure 1, this value is basically derived from geometrical consideration estimating from what minimum size of cavity the integrity of the dam body would be endangered (rupture of continuity of filters or dam core). When the salt wedge parametric analysis indicates the generation of a cavity larger than 8 m, the results are shown in red color. The 8 m threshold corresponds to the 25 m cavity divided by 3 (safety factor). It shows that the 8 m cavity is only exceeded for the “do nothing scenario” and in the worst, multi-parametric case. The safety factor of 3 relates to standard engineering practice. Moreover, immediate analysis of the data collected from the planned monitoring will enable timely rectification measures if needed.

Global decrease (meter) of salt dome level, rise in case of negative value								
Salt dome rise (cm/y)	Conditions before any work. Parameters from pumping test,	No remedial measures	Grouted	Poor grout or harmed grout	Hydraulic barrier	Hydraulic barrier, grouting	Hydraulic barrier, harmed grouting	Rreduced hydraulic barrier efficiency, harmed grouting, coating lost
Stage 1 after 10 year								
2,5cm	0,0	2,5	-0,2	0,2	-0,2	-0,2	-0,2	1,8
5cm	0,0	5,0	-0,3	0,0	-0,4	-0,5	-0,5	1,6
12cm	0,0	10,8	-0,8	-0,7	-1,1	-1,2	-1,2	0,9
30cm	0,0	27,0	-1,9	-2,5	-2,7	-3,0	-3,0	-0,9
dissolution>salt rise	1,5	17,7	0,4	0,2	-0,1	-0,2	-0,2	1,8
no or negligible rise	0,1	0,5	0,0	0,5	0,0	0,0	0,0	2,1
Stage 2 after 140 year								
2,5cm		-0,8	-3,7	-2,9	-3,7	-3,7	-3,7	-1,3
5cm		1,9	-4,8	-3,2	-3,9	-4,0	-4,0	-1,6
12cm		-5,0	-17,5	-17,2	-17,7	-18,0	-18,0	-15,6
30cm		-15,0	-43,8	-44,2	-44,3	-45,0	-45,0	-42,6
dissolution>salt rise		15,7	-3,0	-2,9	-3,3	-3,7	-3,7	-1,3
no or negligible rise		8,2	0,0	0,5	0,1	0,0	0,0	2,4

Global decrease (meter) of salt dome level, rise in case of negative value								
Salt dome rise (cm/y)	Conditions before any work. Parameters from pumping test,	No remedial measures	Grouted	Poor grout or harmed grout	Hydraulic barrier	Hydraulic barrier, grouting	Hydraulic barrier, harmed grouting	Rreduced hydraulic barrier efficiency, harmed grouting, coating lost
Stage 1 after 40 year								
2,5cm	0,0	10,0	-1,0	0,8	-0,9	-1,0	-1,0	7,4
5cm	0,0	19,9	-1,2	-0,2	-1,8	-2,0	-2,0	6,4
12cm	0,0	43,0	-3,0	-3,0	-4,3	-4,8	-4,8	3,6
30cm	0,0	108,0	-7,5	-10,2	-10,8	-12,0	-12,0	-3,6
dissolution>salt rise	6,2	70,9	1,7	0,8	-0,3	-1,0	-1,0	7,4
no or negligible rise	0,2	2,2	0,0	1,8	0,0	0,0	0,0	8,4
Stage 2 after 110 year								
2,5cm		7,4	-3,7	-1,6	-3,6	-3,7	-3,7	4,9
5cm		17,5	-4,0	-2,6	-4,5	-3,2	-3,2	3,9
12cm		30,6	-16,2	-15,9	-17,4	-18,0	-18,0	-9,3
30cm		77,0	-40,5	-42,9	-43,5	-45,0	-45,0	-36,3
dissolution>salt rise		68,2	-1,0	-1,6	-2,8	-3,7	-3,7	4,9
no or negligible rise		8,2	0,0	2,1	0,0	0,0	0,0	8,7

Table 7.3: Height of cavity (or wedge intrusion) at stage 1 and at stage 2 after 150 year for various conditions and mitigations efficiencies (figures are the balance of salt leaching and salt wedge rising for 150 year duration of the Project: they mean the vertical height of the cavity generated by salt dissolution (or height of penetration of the salt wedge upwards if negative); left part of the Table considers the basic sequence of construction, with a Stage 1 dam lasting 10 years before Stage 2 is impounded; the right part of the table considers a delay in the construction of the Stage 2, with a Stage 1 dam lasting for 40 years

The assumed rising rate of the salt wedge within the fault is one of the important input data. Therefore, additionally to the most realistic 2.5 cm/year rising rate, other rising rates were considered: 5 cm/year, 12 cm/year, - reportedly the highest observed on (Ref [1]) and even 30 cm/year. Negligible wedge rise and even hypothesis of a leaching rate exceeding the rising rate were taken into consideration.

There are two main series of scenarios for total project duration of 150 years.

The first series of tests corresponds to the basic assumption: stage 1 is followed after ten years by stage 2, which means no interruption of construction.

The second series corresponds to the situation where stage 1 is followed by stage 2 after 40 year only, considering a delay in construction of the whole project. This assumption is highly pessimistic as it was considered several times in the current Phase II report that no interruption of works can happen during the project implementation. This is only given as a worst case scenario sensitivity analysis;

For each of this two series, the following scenarios were considered:

- Conditions before any work, corresponding to the model calibration and natural equilibrium between salt leaching and salt wedge rising. The difference between salt leaching rate and the rate of salt wedge rising is zero, as currently observed on site.

- The “No remedial measures” option after construction of Stage 1 dam: none of the forecasted mitigation measures is implemented, i.e. no grouting of the top of the salt wedge, nor brine barrier, nor hydraulic barrier. Since currently the salt wedge along the Ionakhsh Fault is grouted on both river banks, this is only possible only below the Vakhsh River. The calculations show that:

    - 10 year duration for the stage 1 dam: decametric cavity generation for large wedge rising rates, or in case of a leaching rate larger than the wedge rise, as early as Stage 1

    - Stage 1 dam lasting 40 years: in almost all cases, decametric cavity generation in stage 1 and stage 2

- The mitigation scenarios: with only grouting, with only harmed grouting, with only hydraulic barrier, with hydraulic barrier and grouting, with hydraulic barrier and harmed grouting ,: the height of the generated cavity is always lower than 3 m, or the salt wedge penetrates the dam body. l

- One specific “worst case” scenario considering a reduced hydraulic barrier efficiency, harmed grouting and loss of clay coating of the salt wedge, for a 40 year stage 1 duration: the cavity generation might exceed 5 m.

  Additionally, the different dam heights alternatives for stage 2 have been considered. There is no significant groundwater gradient difference at the salt wedge for these alternatives, such as the results remain in the range of the one of the two series considered above. Regarding Stage 1 dam, which has different crest elevation depending on the alternative considered for stage 2 (respectively 1110 m a.s.l, 1090 m a.s.l and 1075 m a.s.l), only the highest alternative has been simulated which is the most critical.

Other comments

When efficient grouting of the cap aquifer has been achieved all along the Ionakhsh Fault, the hydraulic conductivity within the grouted zone is assumed not being more than 1 LU, which has been confirmed by water tests in control holes. In that case the leaching rate is limited to an acceptable range of values. The Consultant considers that the grouting has a significant mitigation effect. This conclusion differs from what was presented by HPI model and derived from the results.

The efficiency of the hydraulic barrier was limited to obtaining a groundwater gradient of 10^{-5}.

All results are closely dependent upon the area of the salt wedge actually covered with clay. The clay-coating is very favorable, since it stops the dissolution process. There is no doubt that the top of the salt wedge is coated with clay, since evaporites have a significant clay content and this clay-coating has been generally observed worldwide on extruding diapirs.

Scenarios with a brine curtain give extremely low leaching rates. Results are given hereafter in Table 7.4.

Global decrease (meter) of salt dome level, rise in case of negative value								
salt dome rise (cm/y)	Conditions before any work. Parameters from pumping test,	No remedial measures	grouted	poor grout or harmed grout	hydraulic barrier	hydraulic barrier, grouting	hydraulic barrier, harmed grouting	reduced hydr barrier efficiency, harmed grouting, coating lost
Stage 1 after 10 year								
2,5cm	0,0	0,4	-0,2	-0,1	-0,2	-0,2	-0,2	0,3
5cm	0,0	0,9	-0,5	-0,4	-0,5	-0,5	-0,5	0,0
12cm	0,0	1,8	-1,1	-1,1	-1,2	-1,2	-1,2	-0,7
30cm	0,0	4,5	-2,7	-2,9	-2,9	-3,0	-3,0	-2,5
dissolution>salt rise	1,5	4,2	-0,1	-0,1	-0,2	-0,2	-0,2	0,3
no or negligible rise	0,1	0,5	0,0	0,1	0,0	0,0	0,0	0,5
Stage 2 after 140 year								
2,5cm		-0,8	-3,7	-2,9	-3,7	-3,7	-3,7	-1,3
5cm		1,9	-4,8	-3,2	-3,9	-4,0	-4,0	-1,6
12cm		-5,0	-17,5	-17,2	-17,7	-18,0	-18,0	-15,6
30cm		-15,0	-43,8	-44,2	-44,3	-45,0	-45,0	-42,6
dissolution>salt rise		15,7	-3,0	-2,9	-3,3	-3,7	-3,7	-1,3
no or negligible rise		8,2	s	0,5	0,1	0,0	0,0	2,4

Global decrease (meter) of salt dome level, rise in case of negative value								
salt dome rise (cm/y)	Conditions before any work. Parameters from pumping test,	No remedial measures	grouted	poor grout or harmed grout	hydraulic barrier	hydraulic barrier, grouting	hydraulic barrier, harmed grouting	reduced hydr barrier efficiency, harmed grouting, coating lost
Stage 1 after 40 year								
2,5cm	0,0	1,7	-1,0	-0,5	-1,0	-1,0	-1,0	1,1
5cm	0,0	3,5	-1,8	-1,5	-1,9	-2,0	-2,0	0,1
12cm	0,0	7,2	-4,4	-4,3	-4,7	-4,8	-4,8	-2,7
30cm	0,0	18,0	-10,9	-11,5	-11,7	-12,0	-12,0	-9,9
dissolution>salt rise	6,2	17,0	-0,3	-0,5	-0,8	-1,0	-1,0	1,1
no or negligible rise	0,2	2,2	0,0	0,5	0,0	0,0	0,0	2,1
Stage 2 after 110 year								
2,5cm		7,4	-3,7	-1,6	-3,6	-3,7	-3,7	4,9
5cm		17,5	-4,0	-2,6	-4,5	-3,2	-3,2	3,9
12cm		30,6	-16,2	-15,9	-17,4	-18,0	-18,0	-9,3
30cm		77,0	-40,5	-42,9	-43,5	-45,0	-45,0	-36,3
dissolution>salt rise		68,2	-1,0	-1,6	-2,8	-3,7	-3,7	4,9
no or negligible rise		8,2	0,0	2,1	0,0	0,0	0,0	8,7

Table 7.4: Results of different scenarios, with salt barrier (brine curtain) for 150 year duration of the Project: figures mean the vertical height of the cavity generated by salt dissolution (or height of rising up of the salt wedge if negative); left part of the Table considers the basic sequence of construction, with a Stage 1 dam lasting 10 years before Stage 2 is impounded; the right part of the table considers a delay in the construction of the Stage 2 with a Stage 1 dam lasting for 40 years

8 OVERALL ANALYSIS,

8.1 Main conclusions about the leaching process

- "No remedial measures" option at Ionakhsh Fault, i.e. dam constructed without any mitigation measure against salt dissolution, is not acceptable for scenarios with high wedge rising rate, or in case of extended duration before the completion of stage 2, since with time, leaching could lead to large cavities, more than 25 m high, which could affect the core and maybe the dam integrity (as shown in annexure 1),

- The most effective combination of mitigating actions is grouting together with hydraulic barrier. In that case, and even considering the most pessimistic values of porosity and hydraulic conductivity, no significant leaching or cavity formation is observed. In most cases the salt wedge will penetrate the dam body with time. It means that the salt intrusion may damage the grouting. It belongs to the analyzed scenarios and to the most realistic scenarios. The consequences of the intrusion of the evaporitic wedge inside the dam are negligible. The dam body above Ionakhsh. Fault has a porosity of about 10%, and in the worst case the salt intrusion is metric after ten years. It will fill the voids and gradually be leached according to the existing groundwater flow inside the dam body until a new equilibrium is reached. Conditions of this new equilibrium will be, in the worst case, returning back to the initial conditions, which would not be a risk if the mitigation measures are maintained as per conclusions.

- The brine curtain would still reduce the leaching process. Unfortunately, previous trial proved the brine curtain technique to be not reliable, because of clogging of wells and considering the enormous quantities of salt required for its operation. The model shows in any case that the brine curtain appears to be superfluous in comparison to the reduction of dissolution phenomenon attained.

- All results are closely depending upon the part of the wedge cap surface covered with clay. The clay-coating is very favorable, since it stops the dissolution process. There is no doubt that the top of the salt wedge is coated with clay, since evaporites have a significant clay content and this clay-coating is generally observed worldwide on extruding diapirs,

- The combination of hydraulic barrier and grouting should lead to an acceptable leaching rate always lower than the salt dome rise. The grout curtain, actually almost completed, and even if reaching a hydraulic conductivity less than 10 LU (hydraulic conductivity of 10^{-6} m/s) should be sufficient to reduce the dissolution rate to an acceptable level,

- 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 not safe. The same conclusion is drawn in case of only cap rock grouting. It is therefore required to implement these two mitigation methods: grouting of the cap rock and hydraulic barrier.

8.2 Recommended mitigation methods to implement

When it comes to evaporites, and especially salt, leaching is a phenomenon that may be very rapid, and generates dramatic consequences.

Active karst phenomena in evaporite are observed worldwide. They are the consequence of an important change in the groundwater conditions. The best known with catastrophic consequences are the several hundred sinkholes appearing each year at the Dead Sea, and the large sinkhole generation in Algeria close to Hassi Messaoud. The sinkhole diameter is more or less the thickness of the evaporite layer, and is appearing with a decametric cavity depth. In our case, if the sinkhole happens to reach the upper surface of the current natural ground, under the dam foundation, huge quantities of fresh reservoir water would enter the sinkhole and accelerate the leaching process and cavity growth by gravitational convection, out of control.

Geotechnical 3D modeling carried out by HPI shows no significant risk for the dam integrity as long as the extent of the cavities created by salt leaching does not reach a threshold value of 30 to 40 m depth.

A serious uncertainty (one or two orders of magnitude) of the leaching, even hard to explain cannot be fully excluded. The possibility that some particular conditions could not be recognized by investigations, as numerous they are, always exists. In the case of “no remedial measures” option, such an underestimation would lead to unacceptable dissolution rates.

On the other hand, with the same grade of underestimation, once mitigated with hydraulic barrier and even, combined with grouting, the risk of deep decametric cavities remains very low.

Therefore, and as deduced from the above analysis, the proposed mitigation technique is the combination of hydraulic curtain and grouting of the wedge cap. Grouting needs to be optimal, and thus checked with Lugeon tests and if needed (everywhere values higher than 1 LU are observed) re-implemented until the control water test shows everywhere values lower than 1 LU.

In the following paragraphs, a review of the different situations susceptible to affect the efficiency, either of cap grouting or hydraulic curtain, is presented and remedial measures suggested.

8.3 On the requirements for the hydraulic barrier

In order to reach the objective of equilibrium of water pressure on both sides of the cap aquifer, a detailed study of the characteristics of this hydraulic barrier will be necessary at the stage of detailed design.

The extent of the hydraulic barrier is to be discussed, since considering the different hydraulic conductivities on both sides of the fault, a gradient will be established between the two walls of the fault during impounding, and everywhere the cap aquifer is present. This gradient will persist probably quite a long time before pressures equilibrates on both sides.

Conditions within the parts of the river banks to be submerged will depend upon the presence or absence of cap aquifer above the salt wedge. It could be observed from the grouting galleries that in the right bank, the Ionakhsh Fault, above the cap aquifer is infilled with a strongly compressed, stiff breccia made of aleurolites with inclusions of gypsum and residues. But below this breccia, the exact extent of this cap aquifer is actually not known.

It was however found all along the investigated part of the Ionakhsh Fault, and grouting of the cap wedge is consequently actually being performed over this whole section, from the portals of the derivation tunnels until some 400 m inside the right bank.

Therefore, the hydraulic barrier shall be implemented on the downstream side of the fault at least over the whole length of the fault where presence of a cap aquifer is evidenced. An extent to the left bank, in order to protect the intake structures and avoid the activation of potentially unstable masses hanging in the slopes in this area shall also be taken into account.

Depth and intervals between holes, vertical or horizontal, as well as adequate measures to prevent clogging of the wells constituting the barrier have also to be determined. Since the hydraulic conductivity of the Gaurdak argillites constituting the downstream limb of the fault, is rather low, an interspace between water injection wells would be about three meter, or even less.

The distance to the fault is also an important parameter, which has to be selected at best.

Another aspect, which shall not be forgotten, is to avoid the generation by way of the hydraulic barrier of a reverse gradient, which would leach the salt towards upstream, in “no remedial measures” conditions. The gradient in such a case is however expected to be lower than in the opposite direction. The need for an upstream barrier in order to guarantee the best possible equilibrium shall however checked during next phases of the studies.

Additional technical and economical comparison is to be made for making the best choice between a barrier made of vertical wells or horizontal wells (directional drilling may be used, refer to Annexure 2).

However, long-term efficiency of the hydraulic barrier, whatever the solution, will require previous treatment of the water to feed the injection wells of the hydraulic barrier, which pressure shall also be maintained same as that of the reservoir.

Despite the low hydraulic conductivity of the host rock, the hydraulic barrier implies water injection. In order to avoid the clogging of the hydraulic barrier some actions have to be taken as :

- Before injection the water will be de-aerated in order to avoid air bells formation along the pipes, which act as a sealing blanket.
- Before injection the dissolved oxygen within the water will be removed in order to avoid the formation by oxidation of iron hydrates which have a strong clogging potential.
- A hydrochemical study with previous determination of the Ph, redox potential and major elements of the host rock and injected water in order to know the exact oxido-redox conditions and other possible chemical interactions with insoluble precipitations inferring clogging risk. If required the redox potential is modified with Ph lowering of the injected water.

The feasibility of the hydraulic barrier is further detailed in Annexure 2, where the Consultant specifies the alternative for sub-horizontal curtain, in addition to describing the vertical curtain as proposed by HPI.

8.4 Leaching assessment considering the most unfavorable conditions

There are some conditions under which the situation may reach the worst case (last scenario of Table 7.3), as for example:

- if clay-coating of the salt wedge has already been damaged during the performed grouting operations, and consequently replaced by a more permeable material (no more clay-coating)
- if grouting at long term turns so damaged (by fault movement or by salt rising, no more compensated by leaching) that the hydraulic conductivity of the grouted body falls back to values only slightly lower than the one of the cap aquifer before grouting; we assume here 10^{-6} m/s,
- if the hydraulic barrier is to lose its efficiency at long-term, due to progressive clogging or other phenomena.

In those cases, the dissolution rate could only overpass significantly the acceptable rate and generate large cavities in the specific case of a 40 year delay before completion of stage 2, and a significant degradation of the hydraulic barrier efficiency and the grouting, without any reimplementation or maintenance. Table 7.3 evidences that for other scenarios the cavity generation remains within an acceptable range and in any case less than 25 m.

Given the experience of the Tajik competent authorities in the monitoring of the downstream located Nurek dam during 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.

In any case it is necessary to establish an adapted monitoring system, so that in case of observation of large discrepancies between measurements and model predictions, interventions can be made in time.

The reservoir fluctuations amplitude during the dam operation is expected to reach 100 m per six month interval. This would infer inside the Ionakhsh Fault a groundwater gradient from the reservoir to the banks, and six months later, from the banks to the reservoir. This process, similar to the current phenomenon of interaction between Ionakhsh Fault and Vakhsh River, could enhance the dissolution. But the excess salt has to be evacuated:

- by the same way as above considered, mainly close to the Vakhsh River bed, whereby mitigation techniques would be identical or very close to the above considered conditions,
- via the hemming rock, which hydraulic conductivity is very low, and therefore without any important consequences,
- via the cap aquifer and further to the reservoir; unfortunately there are no data about the lithological structure above the wedge cap far enough within the banks. However, field observations and refraction seismic survey show that

this body out of the Vakhsh River influence should be as good as impermeable.

We thus consider the risk of large cavities as a result of the seasonal reservoir level fluctuation as low.

9 TENTATIVE RISK ANALYSIS

9.1 Selected approach

For this tentative risk analysis, we will review risks that may infer from the assumptions of the dissolution model, and those linked with the implementation on site of the necessary mitigation measures, and their long-term behavior.

Before this, it is worth to refer to what could be the damages to the dam if salt leaching occurs.

Leaching of the salt will generate cavities, and the nature and behavior of the embedding rock massif is essential to assess the consequences for the dam. It shall first be emphasized that the rock massif downstream of the Ionakhsh Fault is cut by a set of persistent, clay-in filled faults dipping towards upstream, such as Fault 70 located just downstream.

If we assume that cavities of width equivalent to the thickness of the dissolved part of the salt wedge are generated, a movement of the corresponding amplitude of the foundation block located just downstream may occur along those joints (which dip is roughly 30 to 45 degrees towards upstream).

However, given that within the right bank, presence of the stiff, highly compressed breccia above the cap rock (see paragraph 8.3) will impede this movement to take place, as far as the dimensions of the cavity remains reasonable.

The potential movements of the foundation block downstream of the Fault would therefore be limited to the river bed and the left bank of the river, i.e. everywhere the rock above the cap rock cannot be considered as providing sufficient buttressing, and could result in a vertical settlement of some meters of the corresponding block. The upstream shell of the dam would therefore deform accordingly.

By considering the different attitudes of the dam, Ionakhsh Fault and upstream-dipping discontinuities, it is estimated that, in order to prevent unacceptable deformation of the dam, the vertical leaching should not exceed a depth of the order of 25 m (see Annexure 1)..

Considering that the worst conditions for salt dissolution are to prevail from impoundment of stage 1 dam until impoundment of the final dam, we will assume this value of 25 m, to correspond to a maximum admissible leaching rate of 25 cm/year of the salt, hence 25 m in 100 years.

Justification for the selection of this value is given in Annexure 1 of this report, where the potential impact of void generation by salt dissolution on the dam is analyzed.

9.2 Input parameters – sensitivity analysis

- Rate of rising:

The key assumption for the input parameters of the model is, as already emphasized, the achieved equilibrium in natural conditions between salt leaching rate and salt rising rate within the Ionakhsh Fault.

Therefore, calibration of all existing dissolution models, HPI's one like the Consortium's one, are using best estimate input parameters to reach this condition of equilibrium, and the assumed rising rate of the salt wedge is the key parameter.

As already emphasized in paragraph 7.3, and illustrated by the results presented in Table 7.4, an increased rise of salt leaching with respect to assumed values means that the potential for leaching is higher than forecasted, and therefore the dissolution more intense.

This is why the 12 cm/year rising rate for the wedge was considered, and even an extreme and improbable value of 30 cm/year, as it can be seen from Table 7.4 that with these rates, results remain acceptable even with the only hydraulic barrier.

If the rising rate reveals to be lower, conditions are still better than assumed.

As a consequence, considering a calibration of the model with those different values of rising rate supersedes most of the possible variations of other parameters.

Hence, the main conclusion to be drawn is that, being a very important input data for the salt issue, especially for model calibration, we strongly recommend an immediate implementation of adequate monitoring to assess the actual rate of rising of the salt wedge within the Ionakhsh Fault. This question is dealt in paragraph 10.1.1.

Measuring the actual rising rate of the salt wedge within Ionakhsh Fault should thus allow correct calibration of dissolution model. This is also fully endorsed by HPI while building their most updated model (Ref [1], paragraph 6.5.).

- Clay coating:

The assumption of the absence of clay-coating, which may have been removed or partially removed by the grouting operations of the wedge cap already performed, can formally not be excluded and this assumption is made in the worst scenario (last case of Table 7.4 with both grouting and hydraulic barrier degradation) . Even in such conditions, less plausible, the dissolution height does not exceed the admissible value of 25 m, as defined in Annexure 1. However, in this case, grouting and hydraulic barrier are necessary to cope with the risk, in accordance with our conclusions.

- Other parameters:

Additional investigations such as pumping tests to further verify the hydraulic parameters, or boreholes for a better estimation of the clay-coated part of the salt surface, are not required because:

- there is no place left for an additional pumping test, since grouting of the top of the salt wedge has been already achieved in the other parts of the Ionakhsh Fault,

- the part of the salt wedge surface coated with clay is not constant, but this coating is known to be everywhere present.

  - Extent of hydraulic curtain :

On the other hand, the definition of the required extension of the grouting and hydraulic barrier would require the existing galleries to be extended for visual inspection of the length of influence of the leaching process.

9.3 Implementation and long-term behavior

9.3.1 Loss of efficiency of the hydraulic barrier

As designed now at the feasibility stage, the hydraulic barrier is made of boreholes fitted with slotted pipes and placed within porous material. The holes are to be connected to the reservoir, so as to apply in the foundation the corresponding water head.

Holes are to be located within argillites or siltstones, and then a loss of efficiency of the hydraulic barrier by progressive clogging of the holes shall be analyzed.

To delay or avoid such phenomena, it is in any case mandatory that injected water is adequately treated before injection in the hydraulic barrier, as described in paragraph 8.3 here above.

From the results of Table 7.3, it can be seen that, in case of loss of efficiency – or insufficient efficiency of the hydraulic barrier -, grouting of the cap aquifer, even if reduced to 10 LU is necessary to remain in acceptable conditions.

9.3.2 Reversed leaching in presence of the hydraulic barrier

As already emphasized in paragraph 8.3, putting into operation the hydraulic barrier alone may trigger some leaching by means of a reversed gradient, salt being leached towards upstream, even if at lower rates than without hydraulic barrier.

This possibility has to be studied in the detailed design of the hydraulic barrier, but grouting having an obvious beneficial effect, this demonstrates again the necessity to have both mitigation measures operational and not only the hydraulic barrier.

In case grouting is destroyed rapidly by fault movement or wedge rising and if no remedial measures of re-grouting are put in place, it could be envisaged to consider if two hydraulic barriers, one downstream, and one upstream of the Fault could be implemented. The main reason of the upstream hydraulic barrier is to avoid, in case of decrease of the reservoir water level which in transient flow conditions, leaching processes from downstream to upstream. This leaching process is hypothetic because the flowing water will be saturated according to the “normal conditions leaching”. This upstream barrier might be excessively conservative and could be easily avoided by ensuring that the cap grouting integrity is maintained.

9.3.3 Poor grouting or loss of efficiency of the grouting of the cap aquifer

Grouting is actually performed by means of injection of cement with high bentonite content, apparently complemented where necessary by injection of chemical solution, in order to reach the target value of 1 LU for the hydraulic conductivity of the grouted cap aquifer.

However, the risk of occurrence of poor grouting, or less of efficiency of the grout with time is to be considered here in case of difficulties to implement the measures on site or long term loss of efficiency of the grouting put in place.

Moreover, the movement of the Ionakhsh Fault evidenced by measurements is reportedly a creeping movement of 2 mm/year or slightly more for tectonic lenses within the fault. Therefore, cracks will slowly develop within the grouted zone, decreasing its efficiency.

Therefore, loss of efficiency of the grouting is a risk which appears quite real.

The conclusion is that an efficient hydraulic barrier is necessary to cope with this risk, which probability of occurrence is not inconsiderable.

10 RECOMMENDATIONS

10.1 Monitoring

10.1.1 Monitoring of salt rising rate

Accurate monitoring of the salt dome rise has to start immediately. This value is crucial for the dissolution rate prediction and models reliability.

A possible monitoring could be the association of the two following types of device:

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

For this purpose, we would recommend five profiles made each one of three boreholes of at least 100 m depth, penetrating into the salt rock. Each profile would at least include the following devices.

- ➢ Two boreholes, to be fitted with a special type of extensometer (Distofor type), working with inductive captors fixed to a special casing moving with the ground, posted at five different depths, which allows to get detailed measurements of the longitudinal deformations of the holes. It shall however be checked that salt creeping under the high tectonic stress might not harm the device.
- ➢ The third borehole to be fitted with clinometers at different depths, in order to follow the deformations within the salt body and the overlying rock.

The five profiles would be distributed along the whole of the grouted Ionakhsh Fault.

10.1.2 Monitoring with respect to salt leaching

Three monitoring systems are proposed:

- groundwater head monitoring, in order to check the hydraulic barrier efficiency,
- water conductivity monitoring to check the model reliability and the on-going leaching process if any,
- microgravity in order to check rate at Ionakhsh Fault and cavity generation.

Recommendations are given hereafter for the monitoring system to be further detailed at detailed design stage:

- for groundwater head : 10 boreholes of 70 m depth with 4 pressure cells at 15, 30, 45 and 60m depth, with their bottom end between 10 and 30 m distance downstream of Ionakhsh Fault, to be further refined after detailed design of the hydraulic barrier, with same number of holes symmetrically on the upstream side of the fault.
- for conductivity another 12 inclined boreholes: 6 profiles of two boreholes, one inclined at 60°, 60 m long, and the other at 45° and 70 m long. Both with 4 conductivity cells at equal distance. Permanent monitoring is required.
- for microgravity, only time relative data are required. Concrete blocks are placed at fixed places on the dam crest of stage 1. 30 blocks are proposed. Microgravity campaign from these blocks every six months during the operation time of stage 1 (at least 8 years). Later for stage 2 only extended if significant negative anomalies would have been detected by other means.
- regular sonar inspection of the dam face once impounded, to detect any abnormal deformation of the upstream face.

A tentative drawing showing the monitoring principles is presented in Annexure 3.

10.2 Recommendations regarding the follow-up and maintenance

10.2.1 HPI numerical model

The dissolution numerical model made by HPI is to be enhanced and recalibrated with more accurate values of hydraulic conductivity and kinematic porosity of the cap aquifer. Further investigations may still improve our knowledge on the input parameters. Especially the rate of salt rising within the fault is required to be thoroughly assessed and measurements shall resume at the earliest.

This model must be permanently adapted while being fed with new monitoring measurements. It is a useful predictive tool which is to be permanently fed back by data from the work site, and be maintained operational during the whole life of the scheme.

10.2.2 Maintenance of mitigation measures

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

The design of the hydraulic barrier is crucial and has to be thoroughly defined before implementation, as already detailed in paragraph 8.3.

If the two mitigation measures would happen to fail or lose their efficiency, the grouting and hydraulic barrier would have to be re-implemented. Some measures shall be foreseen to intervene and restore these two processes. At this stage, the proposed system is the same for the 3 dam FSL alternatives. The mitigation measures can be repeated over time so to ensure the sustainability of the dissolution prevention process (except, much likely, the grouting of the top of salt wedge after completion of stage 2, but the situation is far less critical at this stage).

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 then be to operate from the banks, above the reservoir water level. This could be implemented only using the now fully operational and effective technology of angle and directional boring (see Annexure 2 for details). This goes in favor of implementing a sub-horizontal hydraulic barrier through directional drilling.

Of course, this implies that adequate equipment to perform directional boring is made available in time.

Should this not be the case, the best option would be to lower the reservoir level, at least down to the Stage 1 elevation, to allow more precise observations, and drilling and grouting operations to take place from elevation 1100.

11 CONCLUSIONS

From the here above different assumptions, and because the risk of failure of one of these two mitigation measures exists – especially in the case of grouting, it is clear that both efficient grouting and efficient hydraulic barrier are by far necessary to prevent salt leaching, or to reduce it to the acceptable rate of 25 cm/year.

Moreover, the results evidence the fact that even if efficient hydraulic barrier only, as well as efficient grouting only is also acceptable, it is clear that at least one of these two mitigation measures shall be maintained operational throughout the lifetime of the scheme.

We would recommend that intervention for restoring efficiency of both mitigation measures to be allowed. In order to follow the efficiency of the design mitigation measures, an adequate monitoring is required, so that in-time reaction and repair works can be carried out as soon as possible. Suggestions for this monitoring are given here below.

With the implementation of the hydraulic and grouting barriers, the related monitoring system, and the design of remediation works in case of the barriers failure, the thorough analysis of the scenarios shows that the leaching issue at the Ionakhsh Fault does not affect the project feasibility.