COYNE ET BELLIER
Ingénieurs Conseils

ELECTROCONSULT

IPA
Energy + Water Economics

TECHNO-ECONOMIC ASSESSMENT STUDY
FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

OSHPC BARKI TOJIK

Geological and geotechnical investigation of the salt dome in the dam foundation and reservoir (Summary)

Phase 0 report

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OBJECTIVE OF STUDY – TERMS OF REFERENCE

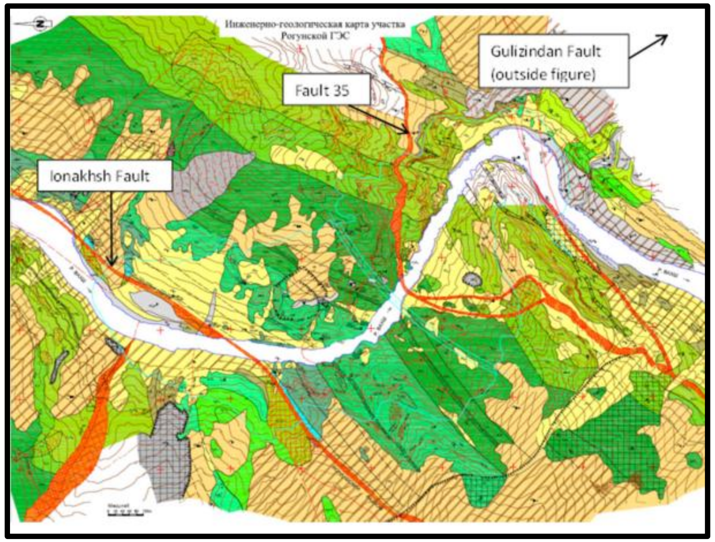
- The Consultant shall perform under this Phase 0 a **risk assessment** pertaining to the salt dome influence on **dam safety**. The assessment shall be based on **existing documentation and visual surveys**. The Consultant may recommend **additional investigations** as appropriate. The assessment shall **recommend** possible **treatment options**, residual risks during Rogun operation and how to manage them, and based on it, the Consultant shall recommend the **most appropriate course of action to the Client**.

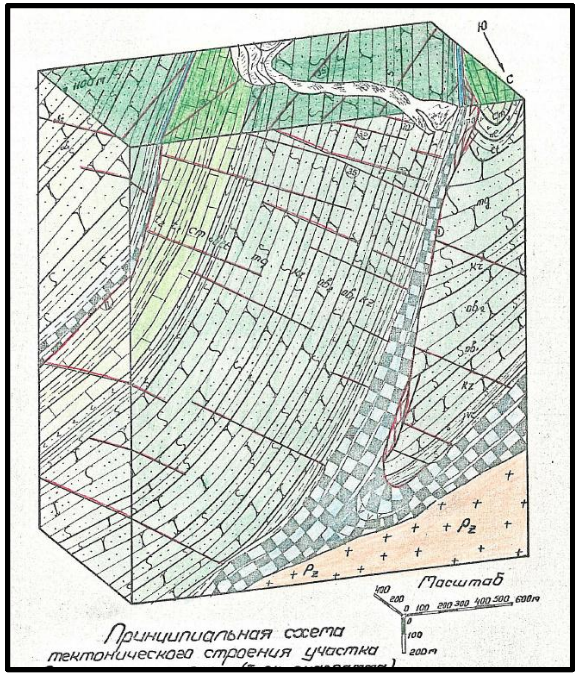
OBJECTIVES OF THE REPORT

- This report presents the potential salt dissolution scenarios analyzed by the Consultants and proposed mitigation, monitoring and remedial measures.
- This report addresses one of the first output under ToRs (Phase 0 report). It encloses cost estimate of remedial measures to be implemented as a main input to Phase II Cost estimate.

SALT WEDGE – DEFINITION

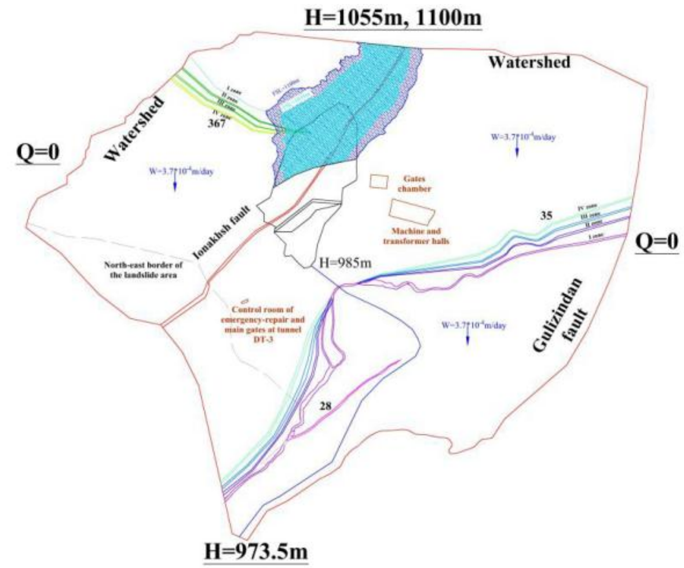
- Salt within the Ionakhsh Fault
  - Ionakhsh Fault is cutting Rogun dam site in a NE-SW direction
  - Presence of salt has been evidenced within the Ionakhsh Fault
  - The salt body (salt dome) has been extensively investigated and has been found to have a wedge shape along this 1 km stretch of fault centered on the River (thickness increasing by about 15 m every 100 m depth)
  - Due to this specific geometry, this structure will be referred to as salt wedge of Ionakhsh Fault
- This is a specific feature with very few similar cases in the world
- This issue shall be addressed as impounding of the reservoir could increase hydraulic gradients that if not mitigated, could lead to dissolution of the salt body and creation of a cavity that could endanger the integrity of the dam body



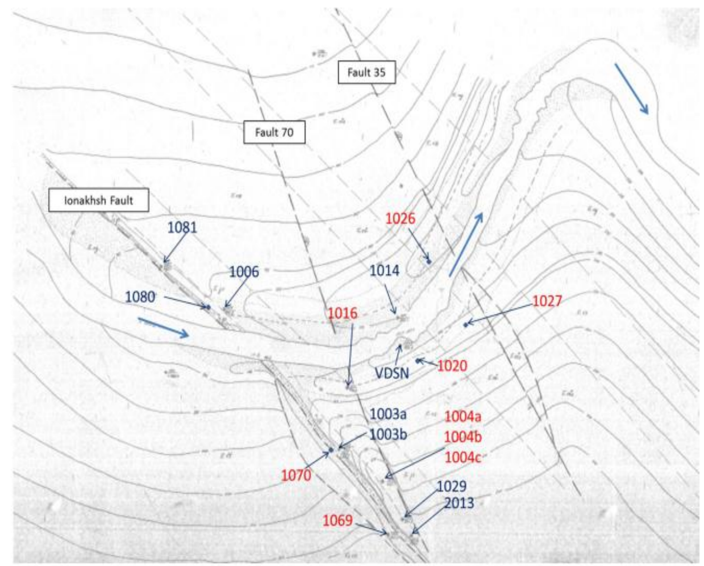


APPROACH – DATA REVIEW

- Review of previous assessments and available data
  - Existing models and literature since **1978 design**
  - Thorough analysis of **HPI model** that needs to be enhanced and recalibrated (hydraulic conductivity)
  - Analysis of the **mitigation measures** foreseen in initial design: hydraulic curtain, brine curtain, grouting cap.



- **Identifying the key parameters** impacting the results
- Analysis of **model sensitivity** to these parameters
- **Reliability of data** defining these key parameters and recommend additional investigations



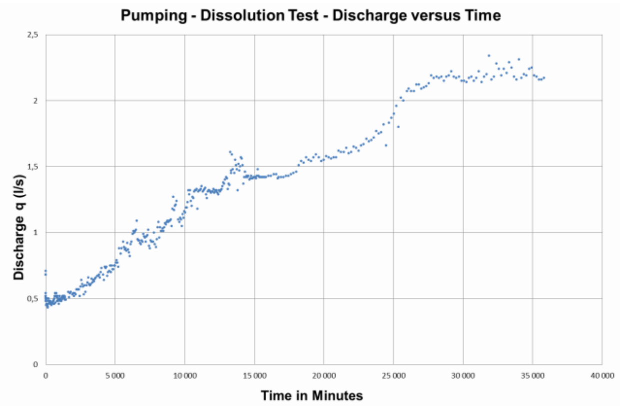
APPROACH – SITE DATA COLLECTION

- Site data collection
  - Use of data available from existing campaigns (piezometer readings…)
  - Site visit with data collection (discharge measurements, chemical content analysis of springs)
  - 18 boreholes equipped with observation wells and monitored
  - Large scale pumping dissolution test carried out in December 2012 in one of the boreholes

➢ Understand the overall hydrogeological context

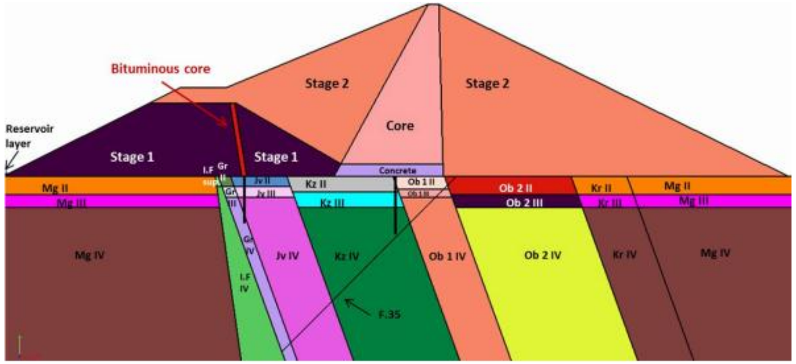
➢ Obtain more readings to calibrate the models

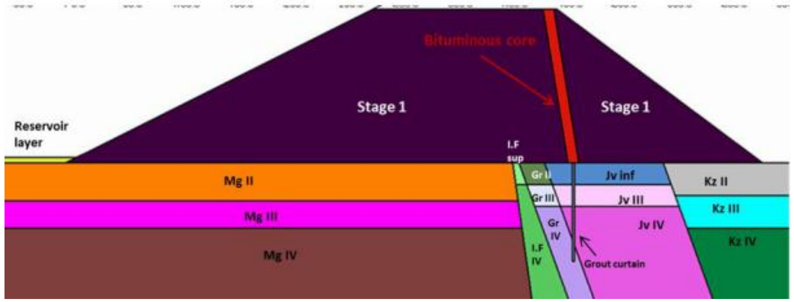
➢ Determine more accurately key parameters



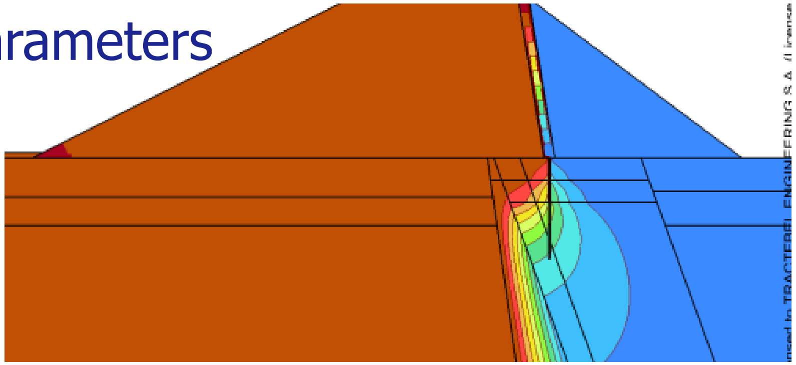
APPROACH - MODELING

- Modeling
  - Three interconnected sub-models have been set up by TEAS consultant
  - Groundwater flow model
  - Dissolution process model
  - Transport model



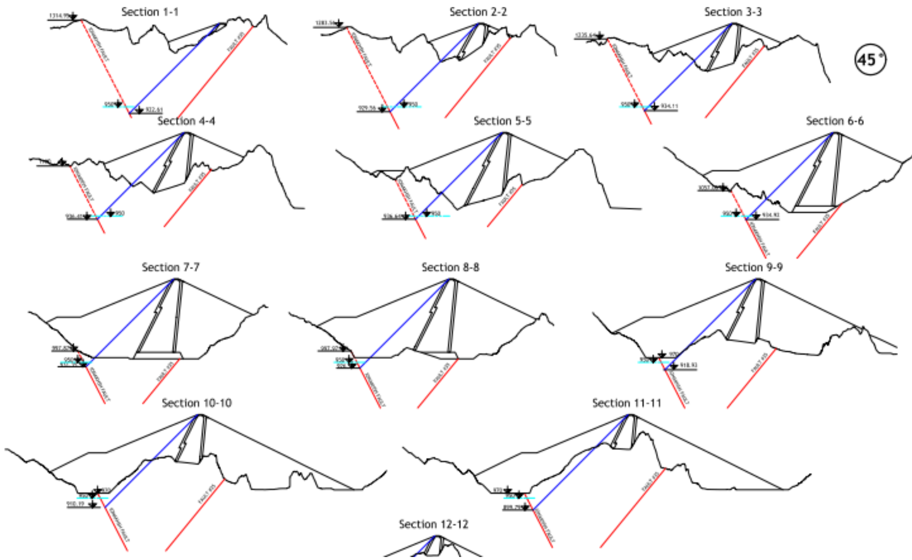


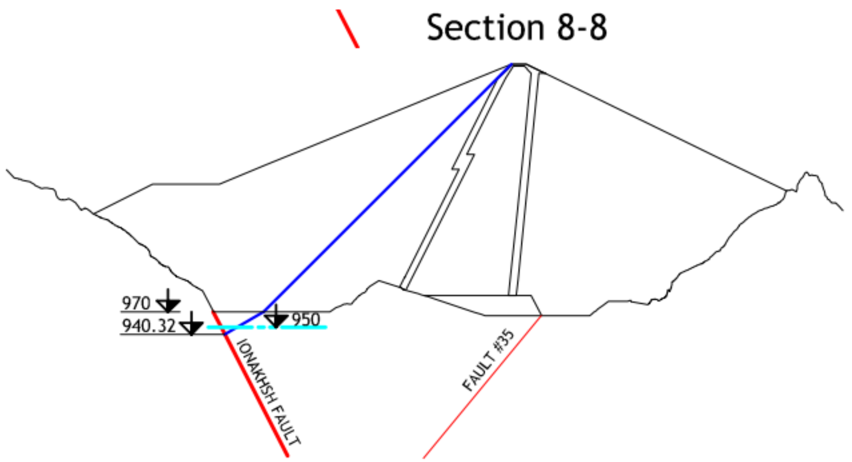
- ➢ Assess independently existing models
- ➢ Assess scenarios not considered previously
- ➢ Carry out sensitivity analysis on the most sensitive parameters
- ➢ Assess mitigation measures efficiency
- ➢ Carry out Risk assessment



APPROACH – RISK ANALYSIS

- Risk Analysis based on various scenarios
  - Study was carried out to determine the maximum cavity size that would not damage the core and filters of the dam : Cavity generation is critical only if larger than 25 m (threshold taken at 8 m in the analysis of results).
  - Most sensitive parameters are hydraulic conductivity, groundwater gradient, wedge uplift rate, clay coating %.
  - Different mitigations measures and combinations (including existing conditions and no remedial measures scenario).
  - Sensitivity analysis on input parameters
  - Impact of delayed implementation of Stage 2 dam (Main dam construction)





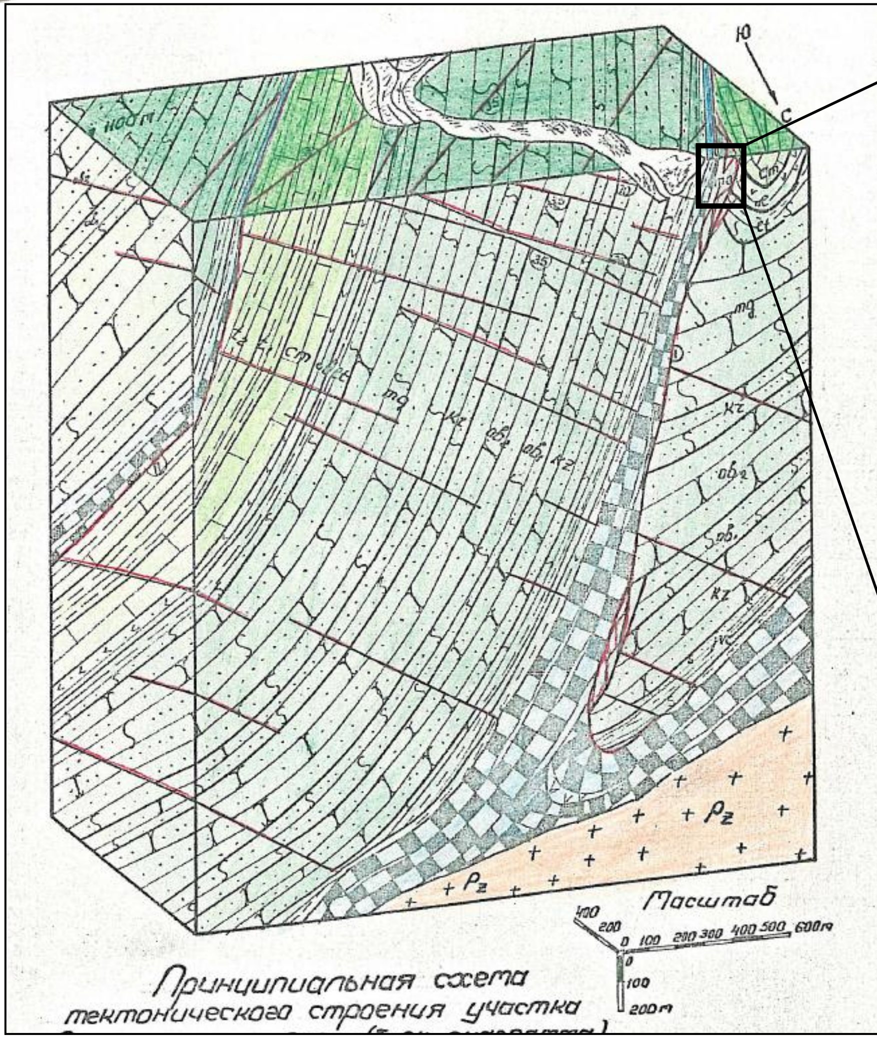
APPROACH - RECOMMENDATIONS

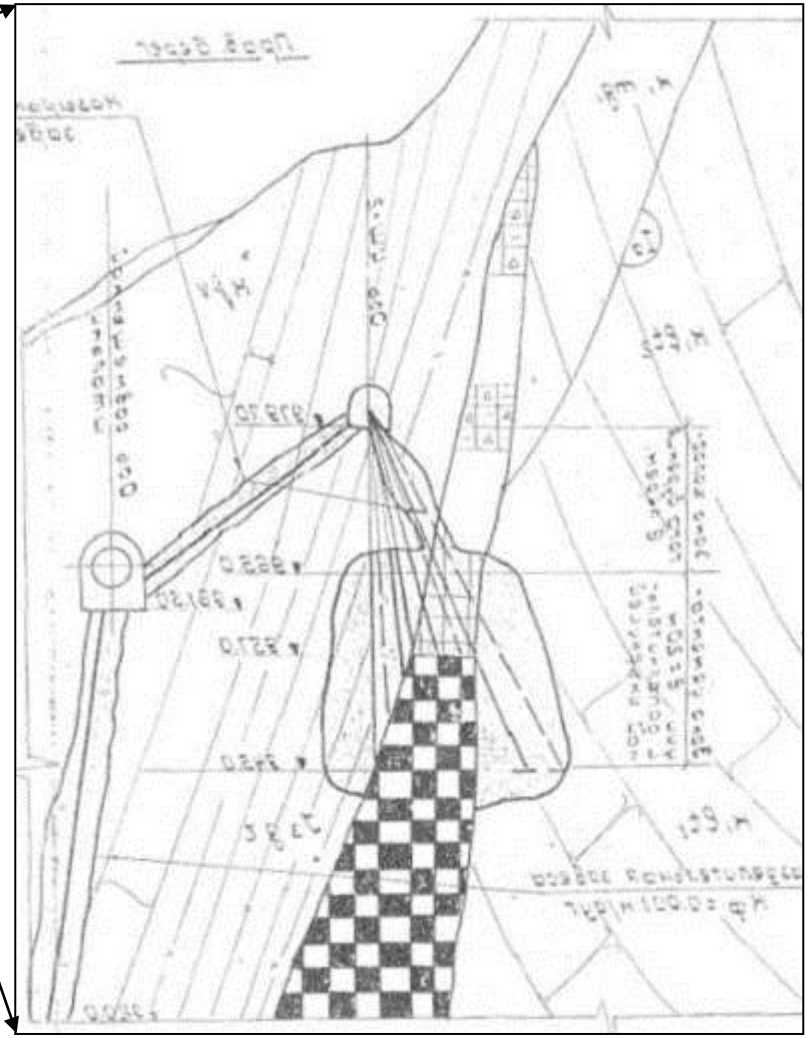
- Results of modeling led to recommend the most appropriate combination of mitigation measures to ensure dam safety
- Recommendations for monitoring and maintenance of mitigation measures
- Cost of mitigation measures and monitoring system included in the overall cost of the project (Phase II cost)

ASSESSMENT – SALT WEDGE

- The Geometry of the salt body has been extensively investigated since the first studies
- Salt body has a wedge shape with a thickness increasing with depth (15 m width increase every 100 m depth).
- Under the effect of orogenic forces the salt is being extruded at an estimated rate of 2.5 cm per year.
- It is being dissolved by the River flow at the same rate, resulting at present stage, in a state of equilibrium between rising rate and dissolution.
- The impoundment of the Rogun reservoir would result in an increase in the hydraulic gradient and this increase, if not mitigated, would result in an increase in the dissolution rate and a possible formation of a cavity.

ASSESSMENT – SALT WEDGE





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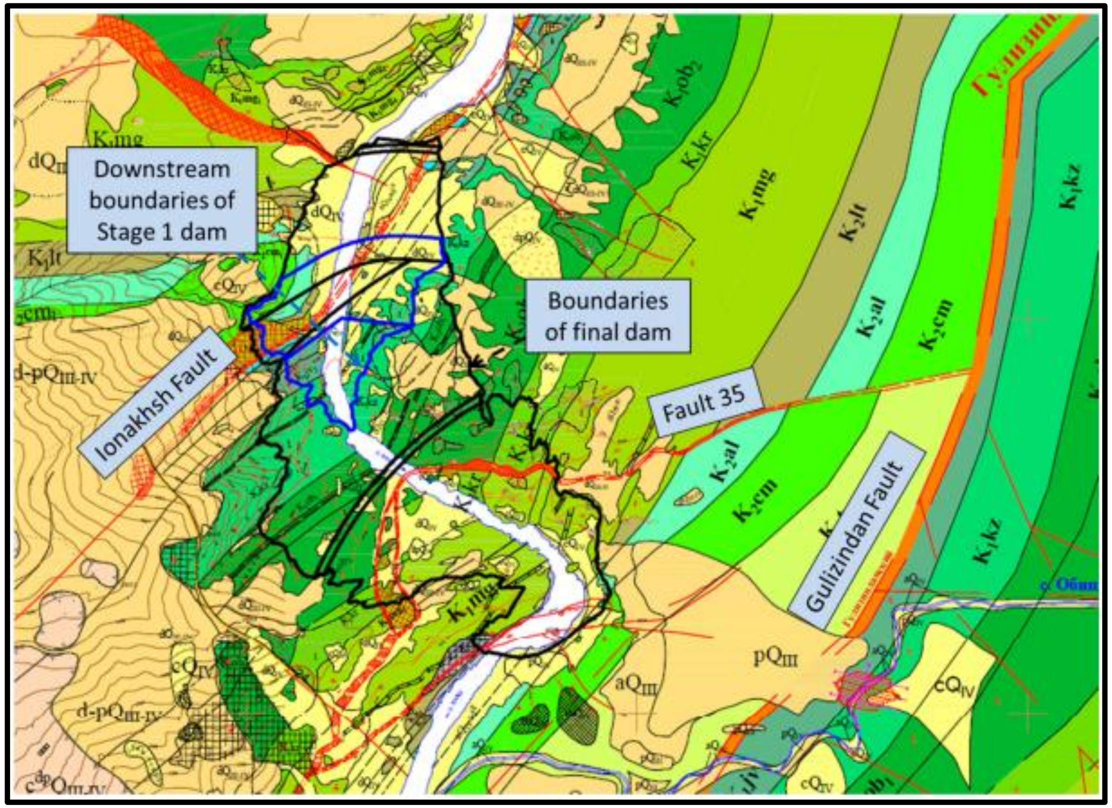
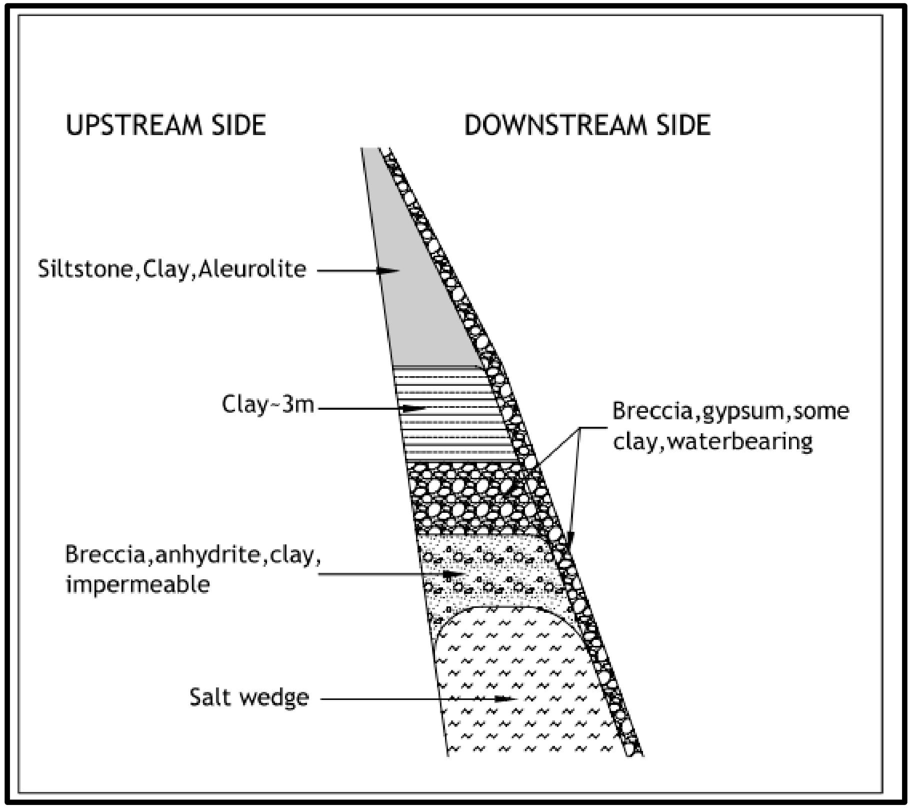
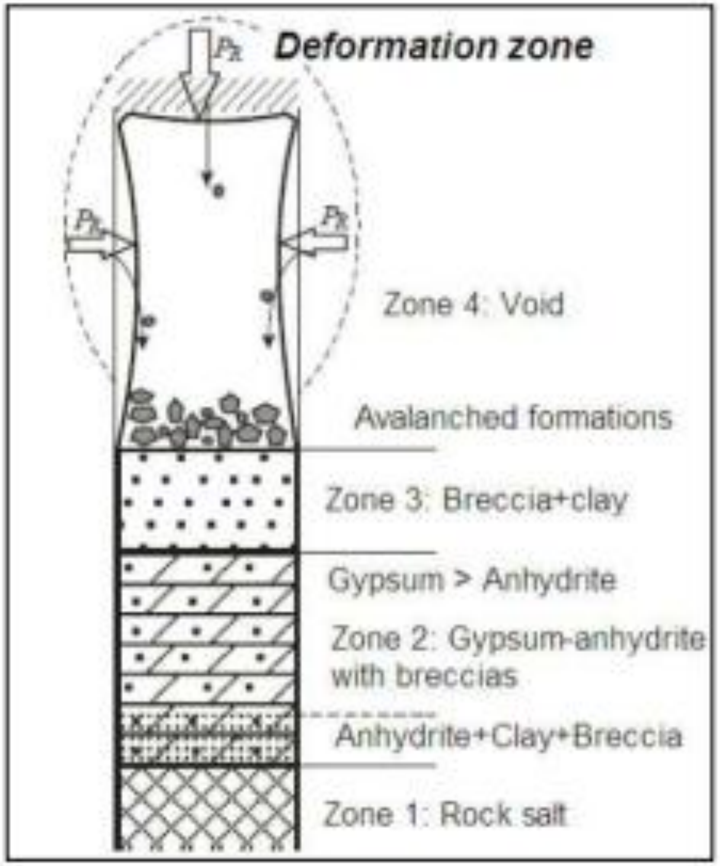




ASSESSMENT – SALT WEDGE

- Specific aquifer over the top of the salt wedge of Ionakhsh Fault
  - Zone of higher hydraulic conductivity detected above the top of the salt wedge
  - With the dissolution of the salt, clay and anhydrite particles remain
    - Anhydrite is hydrated into gypsum
    - Boreholes data show that over the salt exist a breccia of clay and anhydrite, then gypsum/ anhydrite/clay zone and a distressed zone remaining after salt leaching ("caprock")
    - After further gypsum dissolution have occurred, a clay coating is left (commonly observed for evaporites)
  - Higher above the caprock, the high compression stresses force closure of this space into a compact clay/gypsum breccia
    - As can be observed in grouting galleries of the right bank
  - Aquifer slopes very low (less than 10%)
  - Drainage effect of underground works



ASSESSMENT – MODELING

- Summary of key parameters
  - Rate of salt wedge rising
  - Hydraulic conductivity of embedding rocks
  - Hydraulic conductivity within the dissolution zone "caprock"
  - Effective porosity
  - Clay-coating over the salt wedge
  - Dissolution kinetics
  - Groundwater gradients deduced from modelling of flow under the dam (Sub model 1)

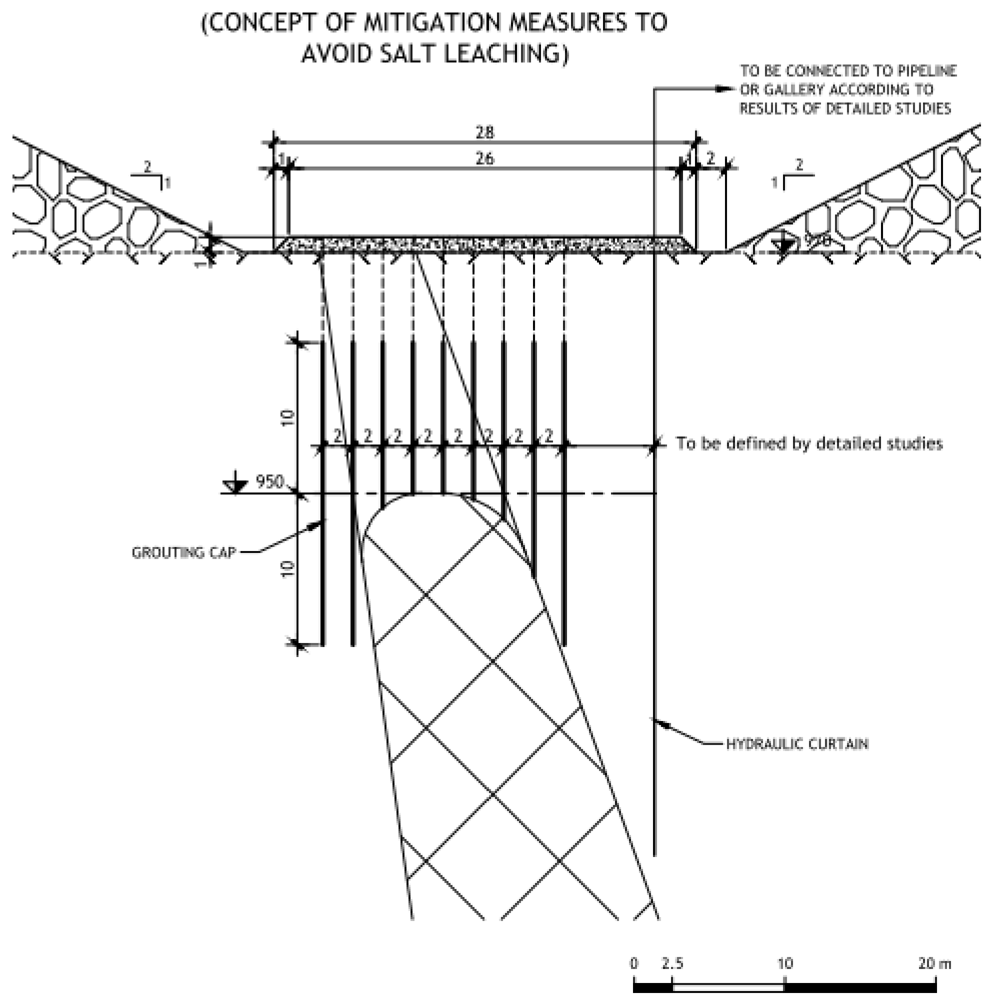
**hydraulic conductivity: the ease with which a fluid (usually water) can move through pore spaces or fractures of a rock/soil.*

ASSESSMENT – MODELING

- Sub-model 1 Groundwater flow model
  - 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. **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**.

ASSESSMENT – REMEDIAL MEASURES

- Assessment of remedial measures:
  - Grouting of the rock all around the top of the salt wedge
  - Hydraulic barrier: series of boreholes on the downstream side of the salt wedge to maintain reservoir pressure so as to minimize water gradient between the two sides of the salt wedge
  - Alternative proposed for hydraulic barrier: horizontal directional drilling



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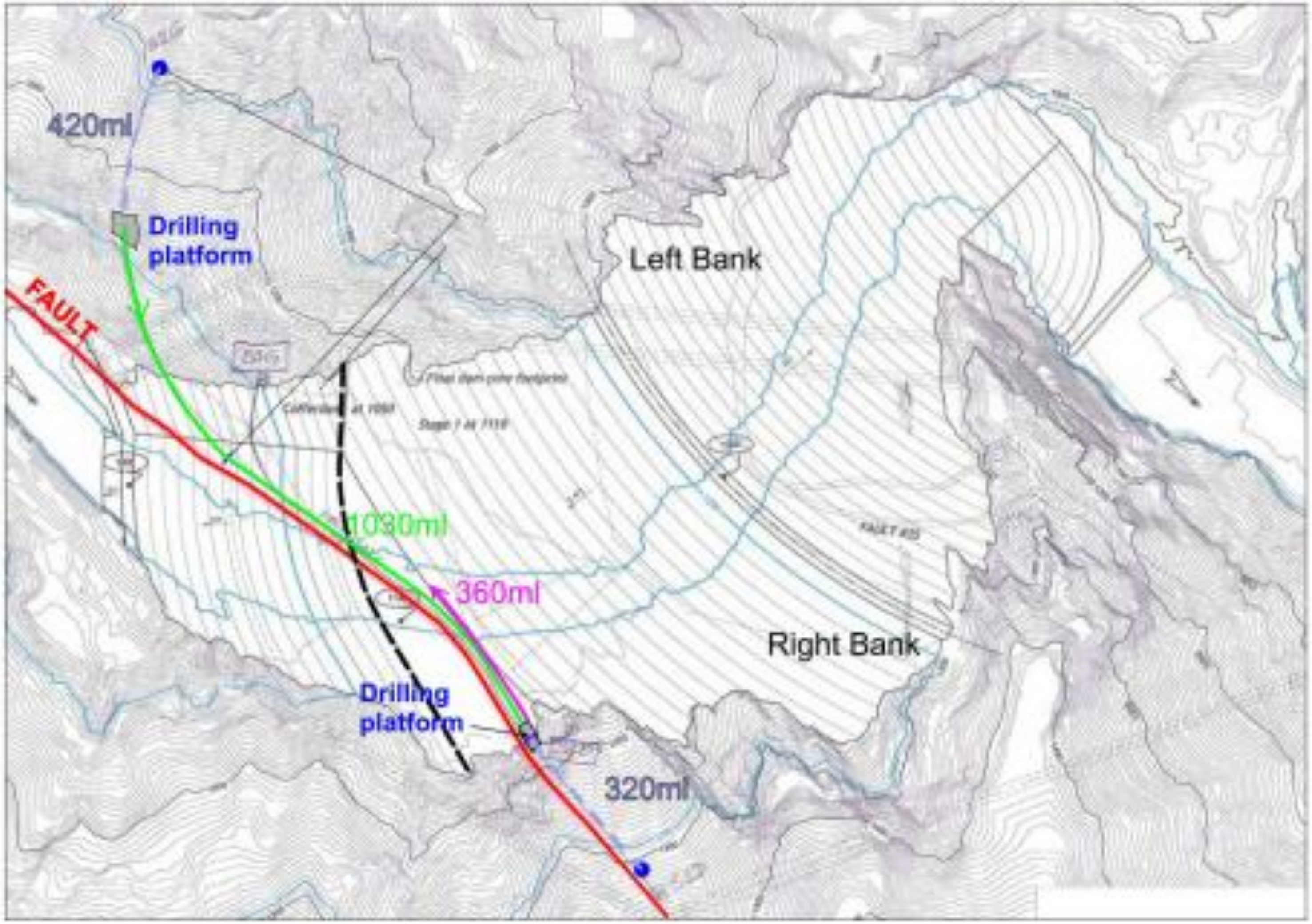

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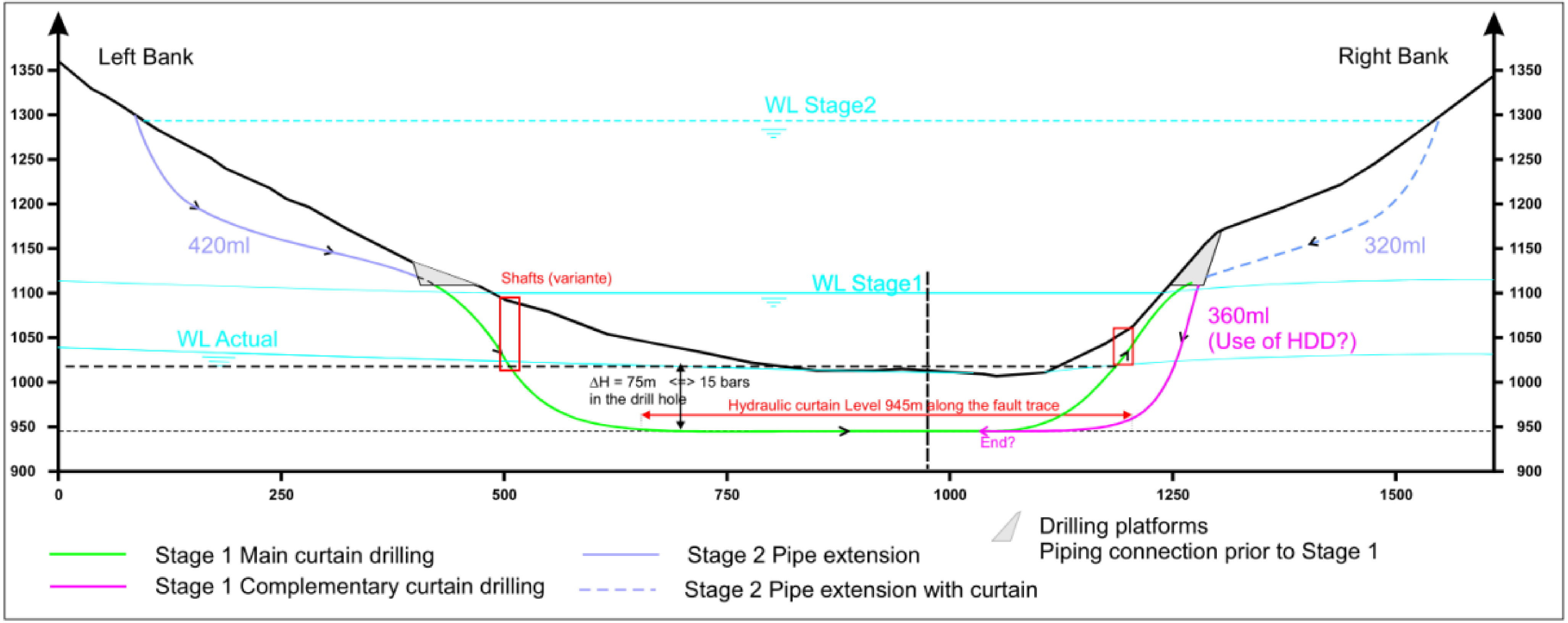


ASSESSMENT – RISK ANALYSIS

- Multiple scenarios studied:
  - 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.

➢ 10 year duration for the Stage 1 dam (first step of construction sequence): 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 (Main dam construction phase),

➢ No remedial measures option is not acceptable

ASSESSMENT – RISK ANALYSIS

- The following mitigation measures were modelled 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.

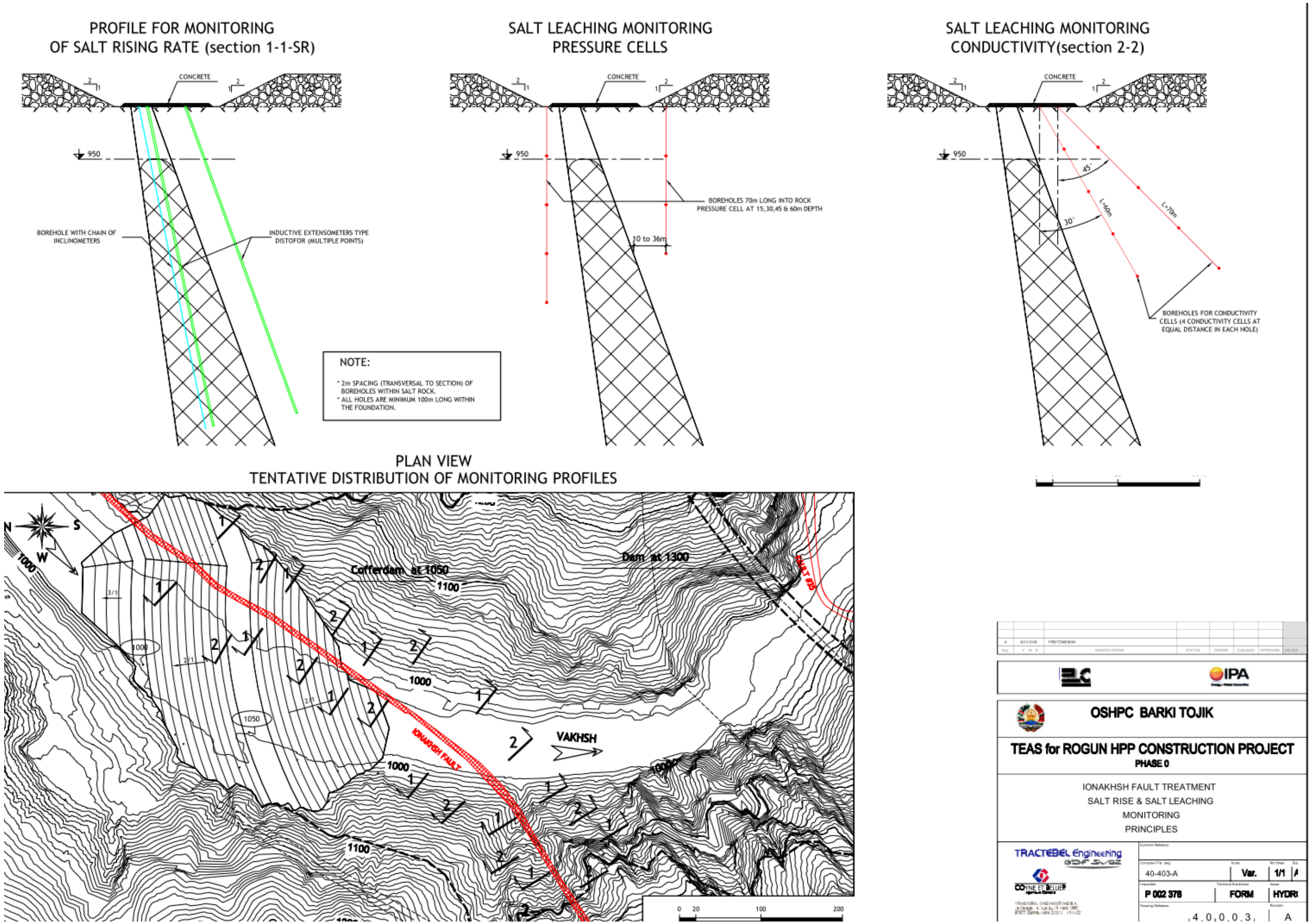
➢ In all cases, the height of the generated cavity is always lower than 3 m (fixed as a threshold of acceptability by the Consultant), or the salt wedge penetrates the dam body.

➢ It is recommended however to implement both grouting cap of the cap rock and hydraulic barrier.

RECOMMENDATIONS - MONITORING

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

RECOMMENDATIONS - MONITORING



RECOMMENDATIONS – MAINTENANCE

- Dissolution model of HPI to be recalibrated and enhanced and to be used as a predictive tool (need for a thorough assessment of the rising rate of salt wedge)
- 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.
  - Stage 1: the re-grouting and reinstallation of the hydraulic barrier can be performed from the crest of the stage 1 dam.
  - Stage 2, the only option for re-grouting and hydraulic barrier restoration would then be to operate from the banks, above the reservoir water level. This could be implemented only using directional boring.

CONCLUSIONS

- Remedial measures are needed to manage the potential dam safety and sustainability risks of the salt wedge
- Measures should include both grouting of the cap rock and hydraulic barrier.
- Adequate monitoring to detect any loss of efficiency and ensure timely maintenance
- These two measures are sufficient to ensure that the salt wedge dissolution does not endanger the integrity and function of the dam
- The costs of these measures have been estimated and appropriately included in the economic analysis of the proposed project