TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

PHASE II: PROJECT DEFINITION OPTIONS

Volume 2: Basic Data

Chapter 2: Geology

Part A - Assessment of geological conditions

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1. Background

List of main references relevant for the geological conditions of Rogun HPP

[1] Rogunskaya hydropower station on the Vaksh River, Technical project. Gidroproyekt Tashkent 1978.

[2] Engineering-geologic conditions of constructing the Rogun dam, A.V.Kolichko and V.N.Fil, 1981.

[3] Feasibility study for phase I of the stage 1 construction of Rogunskaya hydropower station dam. HPI Moscow, 2000.

[4] Instrumental monitoring of the newest tectonic in the region of Rogunskaya HPS construction. Lenmetrogiprotrans ("LMGT"OJSC), Saint-Petersburg 2005

[5] Specification of prestack seismicity of the area of Rogunskaya HPS and definition of design earthquake effect parameters. LLC "Center of geodynamical researches" "CGR", Moscow (for Gidrospetsproyekt) 2005

[6] Specification of initial seismicity of Rogun HPP area and characterization of the designed seismic load HPI Moscow 2005

[7] Geophysical and geological engineering survey for diagnostic study of the existing constructions of the underground part of Rogunskaya HPP Geodynamic Research Center (CGI), Moscow 2005

[8] Instrumental monitoring of the newest tectonics in the region of Rogunskaya HPS construction, A.V.Kolichko, 2005.

[9] Contemporary status of Rogun HEP underground turbine house, Kolichko A.V., 2006

[10]Rogun Hydroelectric Plant in the Republic of Tajikistan, Bankable Feasibility for Stage 1 Construction Completion. Geology, Geotechnics and Seismic Characteristics. LI, 2006.

[11]Comparative analysis of rockslide hazard in the area of the Rogun reservoir for FSL 1240 and 1290m options, CSGNO, Moscow, 2006

[12]Report on compilation and analysis of the results of engineering geology, ground water infiltration, geomechanical, geophysical and other types of research in the area of the main structures for the development of the Rogun project. HPI, 2009.

[13]Rogun HPP, Conception of project completion, HPI, 2009. In particular ‘Concept of extension of the 1st stage plant, explanatory note’ and ‘Geotechnical conditions’.

[14]TEAS for Rogun HPP, Inception Report, 2011

[15]TEAS for Rogun HPP, Geological investigations in the Right Bank, 2012

Former investigations and brief history of Rogun HPP

The field investigations and surveys started in 1967. The great majority of geological and geotechnical investigations were carried out within the frame of the Technical Project, issued in 1978. The results of this comprehensive work are the principal reference for all later studies. The main location of boreholes and exploratory galleries is presented in Illustration no. 1. The amount of work for the main types of investigation carried out for the Technical Project is summarized in Table 1 below:

Table 1. Summary of geological investigations carried out at Technical Project stage

Type of investigation	Amount
Geological mapping and surveys at 1:25 000 scale	390 km^2
Geological mapping and surveys at 1:5 000 scale	19.6 km^2
Geological mapping and surveys at 1:2 000 scale	2.5 km^2
Geological mapping and surveys at 1:1 000 scale	0.6 km^2
Drilling with core recovery	8960 m
Permeability tests in boreholes	557
Exploratory galleries	4080 m
Geophysical surveys	
- Vertical Electrical Sounding	117
- Seismic profiling in galleries	3400 m
- Seismic profiling in boreholes	480 m
Monitoring of tectonic movements by levelling, inclinometers, measurements of deformation across faults	

Subsequent to the Technical Project, additional geological and geotechnical data was obtained during construction works, which were carried out between 1976 and 1993. Over such long period most valuable data was obtained from monitoring convergence and behavior of rock mass and support in the underground workings, comprising half of the Power House cavern, the transformers cavern and not less than 27 km of tunnels excavated for various purposes.

Other studies were later carried out after the 1993 flood. Recent studies for updating the design according to modern international standards have been carried out since the year 2000, for which most relevant references from the list above are [4], [7], [12] and [13].

On the whole, after the initial studies for the Technical Project, relevant geological data could be retrieved from studies which addressed specific issues:

- Monitoring of deformation in existing underground workings
- Monitoring of neotectonic movements
- Dilatometer testing and geophysical investigations for the Power House and Transformers Hall caverns
- Seismic and electric surveys for the atypical area located in the right bank downstream of the dam site, interpreted as an ancient landslide
- Treatment and test panels for the treatment of the “salt dome” in the foundation of the dam.

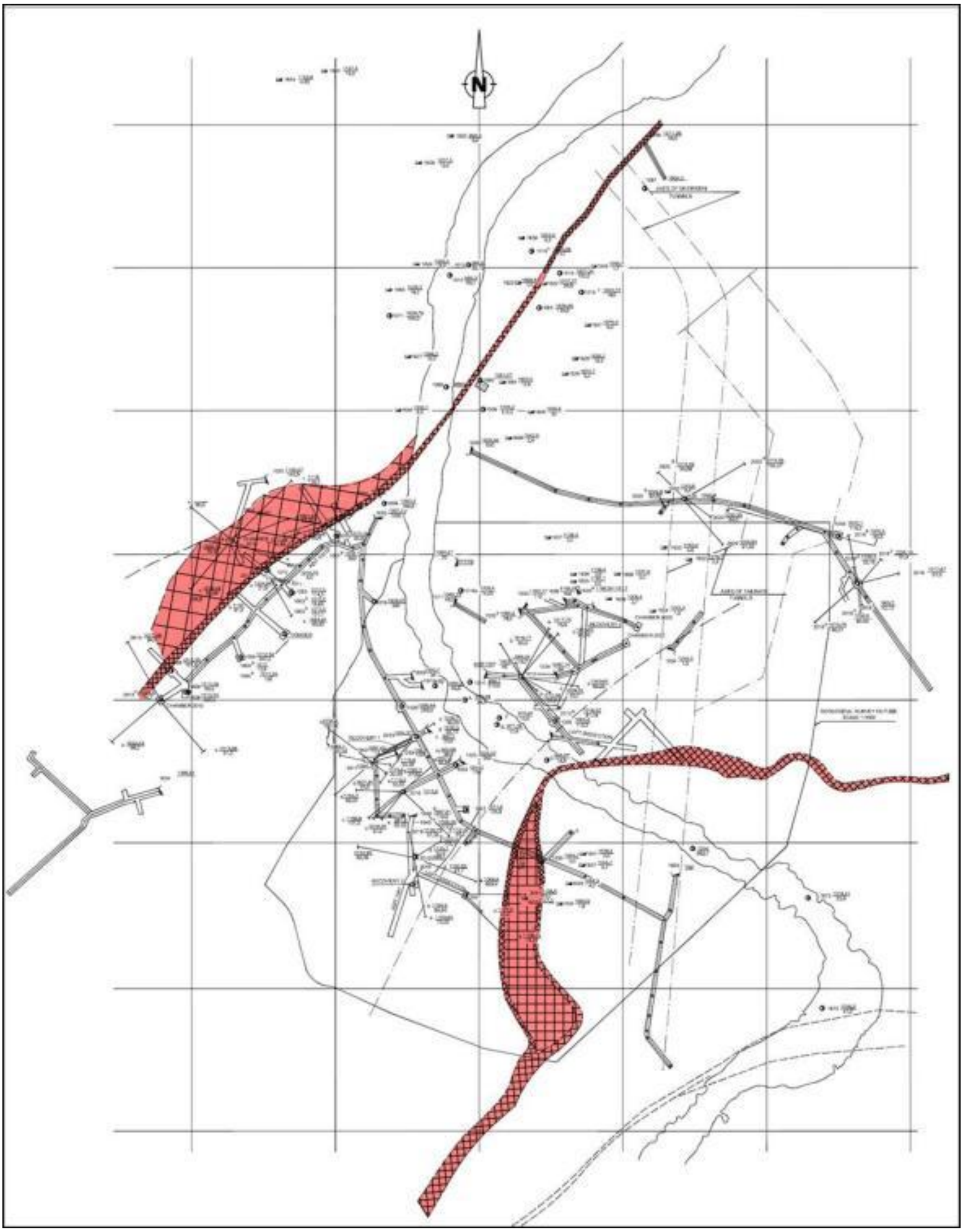

Illustration no. 1. Location of exploratory galleries and boreholes at the dam site (from [10], after drawing 1079-03-183 of the FS).

Additional investigations 2012

Taking into account the significant amount of geological and geotechnical data provided by previous investigations, only limited additional investigations was required to be carried out within the frame of the TEAS. As discussed in the Inception report of 2011, additional investigations have been designed for the following major objectives:

- Better understanding of the geological setting in the Right Bank
- Update of the hydrogeological data and model
- Update of some geotechnical characteristics

The content of this additional program is recalled below:

- Surface geological mapping at 1:5 000 scale
- Drilling with core recovery and permeability testing, as summarized below

Borehole	Length (m)	Lugeon test
IF1	115	15
WRB1	110	10
WRB2/DZ2	217	10
DZ2	166	

- Refraction seismic profiles: 3 lines, with cumulative length of 2380 m
- Microgravimetry measurements: 684 stations on 25 profiles
- Installation of 30 stations for monitoring of potential slope movements
- Inspection of existing galleries, purposely rehabilitated
- Springs: discharges measurements, chemical analyses
- Piezometer drilling and measurements (19 piezometers installed and followed-up)
- Pumping-dissolution test of Ionaksh fault zone.

As mentioned above, one of the main scopes of the additional investigations was to refine the interpretation of the geological setting in the Right Bank, with particular regard to ancient massive landslides described at the Technical Design stage. A separate report has been issued for this important topic ([15]), wherein most of the results of additional investigations have been analyzed. The relevant finding and results will be recalled at the appropriate places in this report.

2. Regional geology

The geological setting and processes which govern the conditions at the HPP site can be fully understood only if regional geological context is apprehended. More than usual, the design of Rogun HPP structures is directly influenced by large scale tectonics and structural geology. For this reason, the regional geology has been thoroughly integrated since the early studies and is incorporated in the present assessment with necessary details.

2.1. Location and regional morphology

The HPP site lies within the area of junction of the southern Tien-Shan with the uplifted northern ridges of the Afghan-Tajik Depression (the short name 'Tajik Depression' will be used in the present report).

The Vakhsh River valley is generally 1 or more km wide. The elevation of the river channel in the project area is roughly around 1000 m. Upstream from the dam site, the river cuts through Quaternary alluvium which can reach a thickness of 150 m.

The southern slopes of Tien-Shan form much of the right bank of the Vakhsh River and of the future reservoir, roughly starting from upstream of the Obi-Djushon tributary near the Rogun city. Within the project area, the hill slopes rise up to 2500-3000 m, with variable slope angles. Highly eroded and incised deeply by several major right hand tributaries of the Vakhsh River, this flank shows a rather irregular slope pattern (Illustration no. 2).

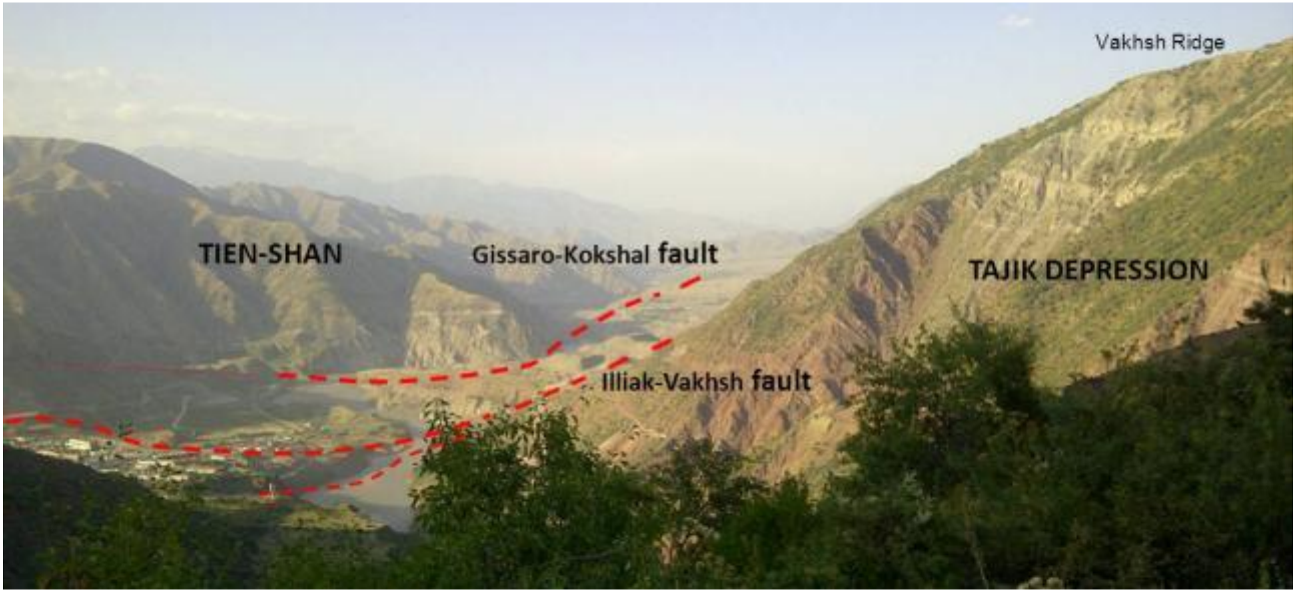

Illustration no. 2. View upstream from the Right Bank of the dam site.

The main structural elements are also highlighted on the illustration. They will be described in the following paragraphs.

In the project area, the left bank of the Vakhsh River, called in the dam site area the Vakhsh Ridge, shows rather regular slopes in the order of 1.5/1 to 1/1, rising up to 3200 m (Illustration no. 3). The homogenous slopes are likely related with the ongoing activity of the Vakhsh regional thrust fault, which carries in its hanging wall the Vakhsh Ridge.

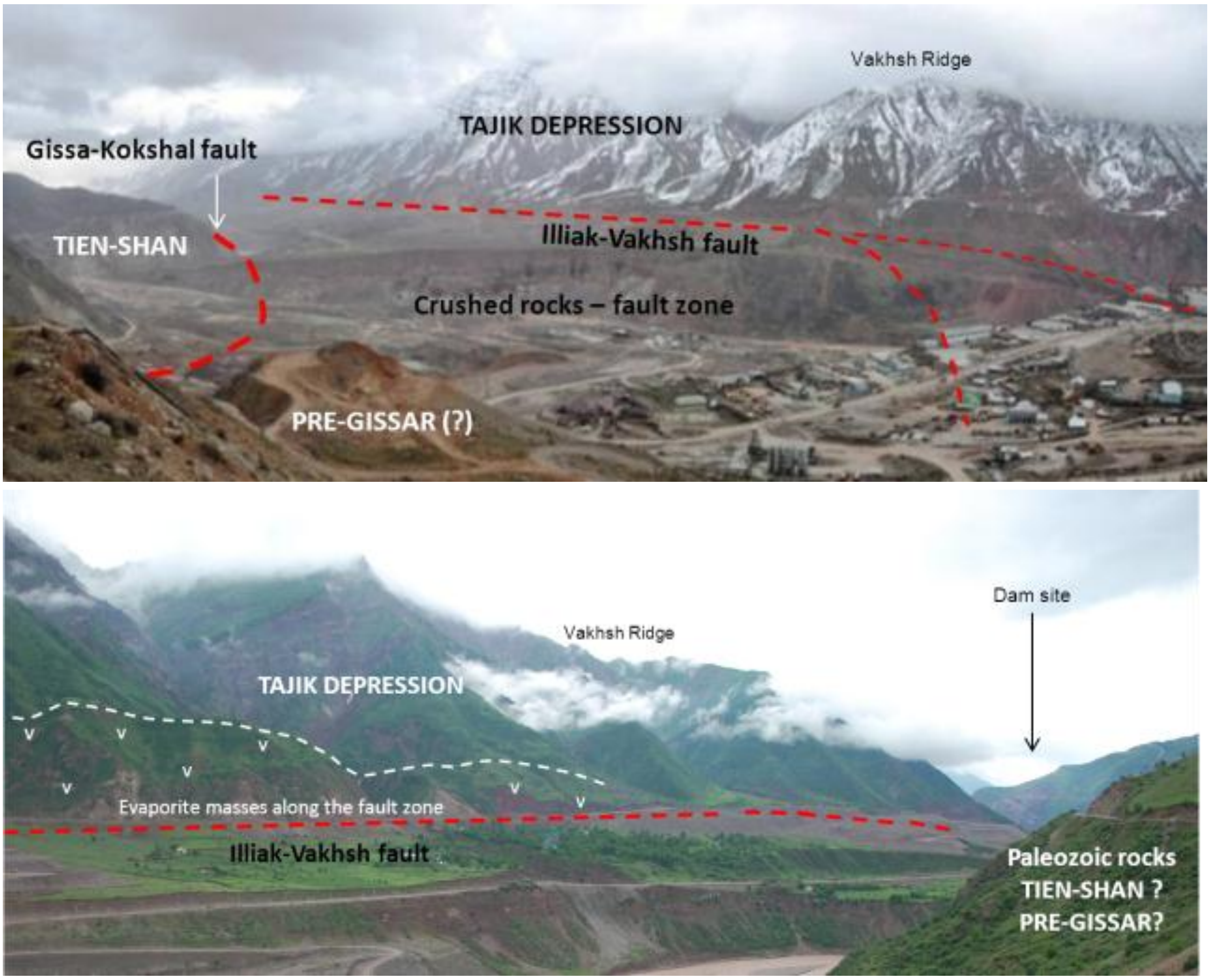

Illustration no. 3 Left bank of Vakhsh River near the dam site, from downstream (above) and from upstream (below).

As showed in the illustration, evaporite rock masses form peculiar morphological features at the toe of the Vakhsh Ridge. Aligned on the fault zone, they are detached from the main slope owing to high rate of extrusion and to the differential erosion. The outcropping part comprises principally gypsum. The presence of salt at deeper levels along the fault or below the alluvial and colluvial cover can not be discarded. A closer look shows numerous sinkholes, resulting from dissolution (Illustration no. 4 Detail of gypsum tectonic lenses and sinkholes at the toe of the Vakhsh Ridge.).

Illustration no. 4 Detail of gypsum tectonic lenses and sinkholes at the toe of the Vakhsh Ridge.

The presence of thick evaporitic layers is an important element in regional tectonics but also at the HPP site. The most conspicuous of these is the salt layer of Upper Jurassic Gaurdak Formation, credited with a thickness of around 400 m. At regional scale, it constitutes the base décollement level for internal deformation within the Tajik Depression. At the dam site, it is found as a thin wedge along the Ionaksh Fault and made the object of detailed studies.

2.2. Regional tectonic units

Illustration no. 5 shows the location of the Rogun HPP within the regional structural geology setting.

According to relevant literature, the tectonic blocs in the project area are:

- The Tien-Shan
- The Tajik Depression
- Pre-Gissaro 'downfold'

The dam site lies within the structural domain of the Tajik Depression, more precisely very near the northern boundary of this unit (enhanced on the illustration).

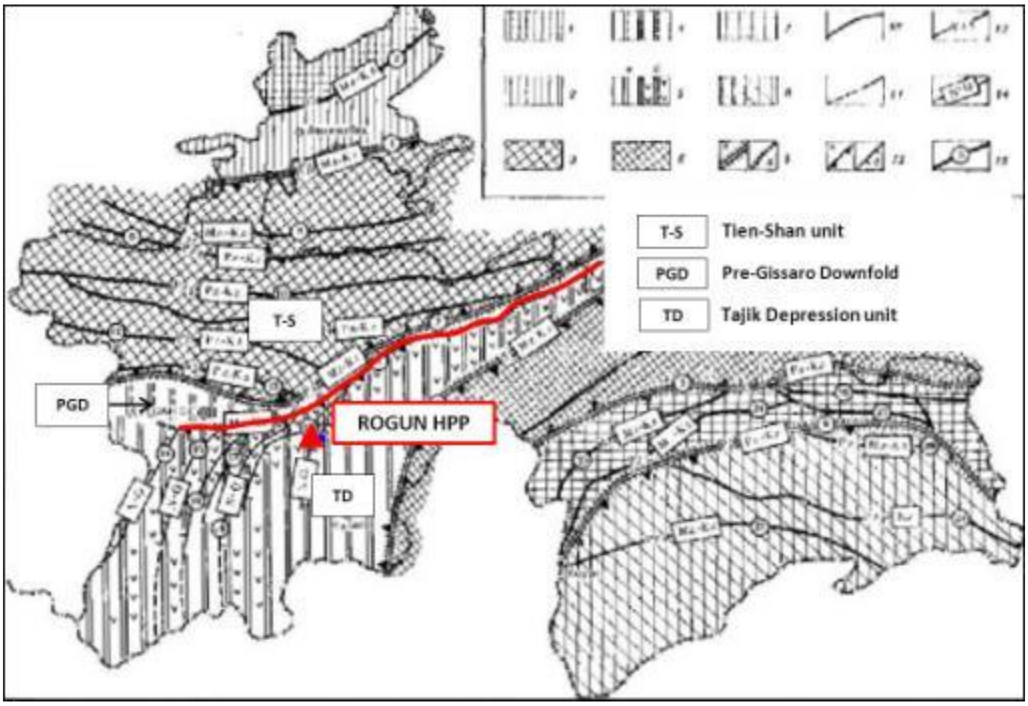

Illustration no. 5 Location of Rogun HPP on the map of tectonic zoning of Tajikistan with major seismogenic faults.

The **Tajik Depression** unit consists of Mesozoic-Tertiary continental and marine sedimentary cover overlying the Paleozoic basement. Its northern limit is the regional Illiak-Vakhsh fault system (Vakhsh Fault in the project area). As a consequence of high compressive stresses and regional uplift, the Mesozoic-Tertiary sedimentary sequence, formerly deposited above the Paleozoic basement in the Afghan-Tajik basin, is now exposed in young mountain ranges. Based on the absence of Mesozoic rock fragments from upper Neogene to low-Quaternary deposits, the rising from the peneplain of the Vakhsh Ridge would have started as recently as the low- to mid-Quaternary [1]. Accordingly, for the approximate 2000 m by which the ridge dominates the river valley, the balance rise vs. erosion is in the order of 2 mm/y, which is well in the range characteristic for such geodynamic settings.

To the north, the **Tien-Shan** unit, represented by the Karateginsk bloc, is formed by Paleozoic deposits with granitic intrusions. The southern limit of the Tien-Shan bloc is formed by the Gissaro-Kokshal crustal fault system.

According to existing documents, the Tajik Depression and Tien-Shan are separated by a narrow tectonic unit known as the **Pre-Gissaro** (or Fore-Gissaro) "Downfold". This is a down-thrown bloc composed of Paleozoic sediments and Neogene molasses. However, in the reaches of the dam site, the distance between the Tajik Depression and the Tien-Shan unit is reduced to about 1 km. At this location, at surface, the zones of influence with mylonites and crushed rocks of Gissaro-Kokshal and Illiak-Vakhsh fault zones could be practically in touch with one another, which results in forming a wide fault zone. Illustration no. 2 and Illustration no. 3 above show the narrow space between the two structural domain Illustration no. 6 shows a very wide zone of crushed and weathered rock in the interval between Gissaro-Kokshal and Illiak-Vakhsh faults, just upstream from the canyon. It is in this same zone that the Vakhsh fault is assumed to form a sharp bend to the N, then to the W and to cross the Vakhsh River.

Illustration no. 6 Wide zone of crushed rock between two major faults: Gissar-Kokshal (left) and Illiak-Vakhsh (right).

2.3. Main regional structures

As a result of high tectonic stresses in the project area, tectonic deformation occurs as seismic displacement along faults, as creeping, aseismic movements especially related with salt tectonics and as folding. Illustration no. 7 and Illustration no. 8 show the main faults in the project area. Illustration no. 9 shows schematically the geological setting involving the boundary crustal faults and the faults internal to the Tajik Depression.

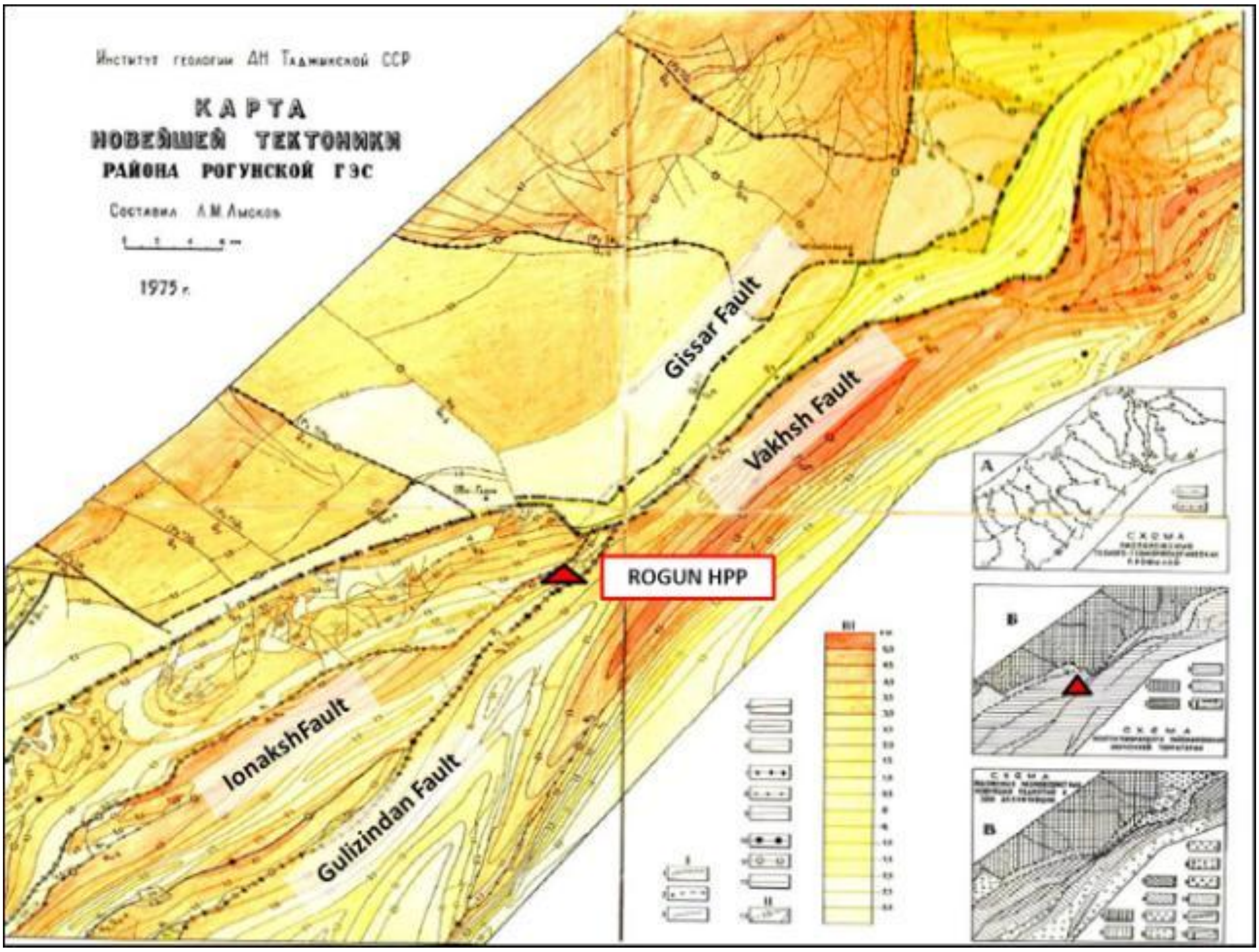

Illustration no. 7. Map of Neogene tectonic movements in the Rogun HPP area, 1975 (modified from [10], Vol.3C)

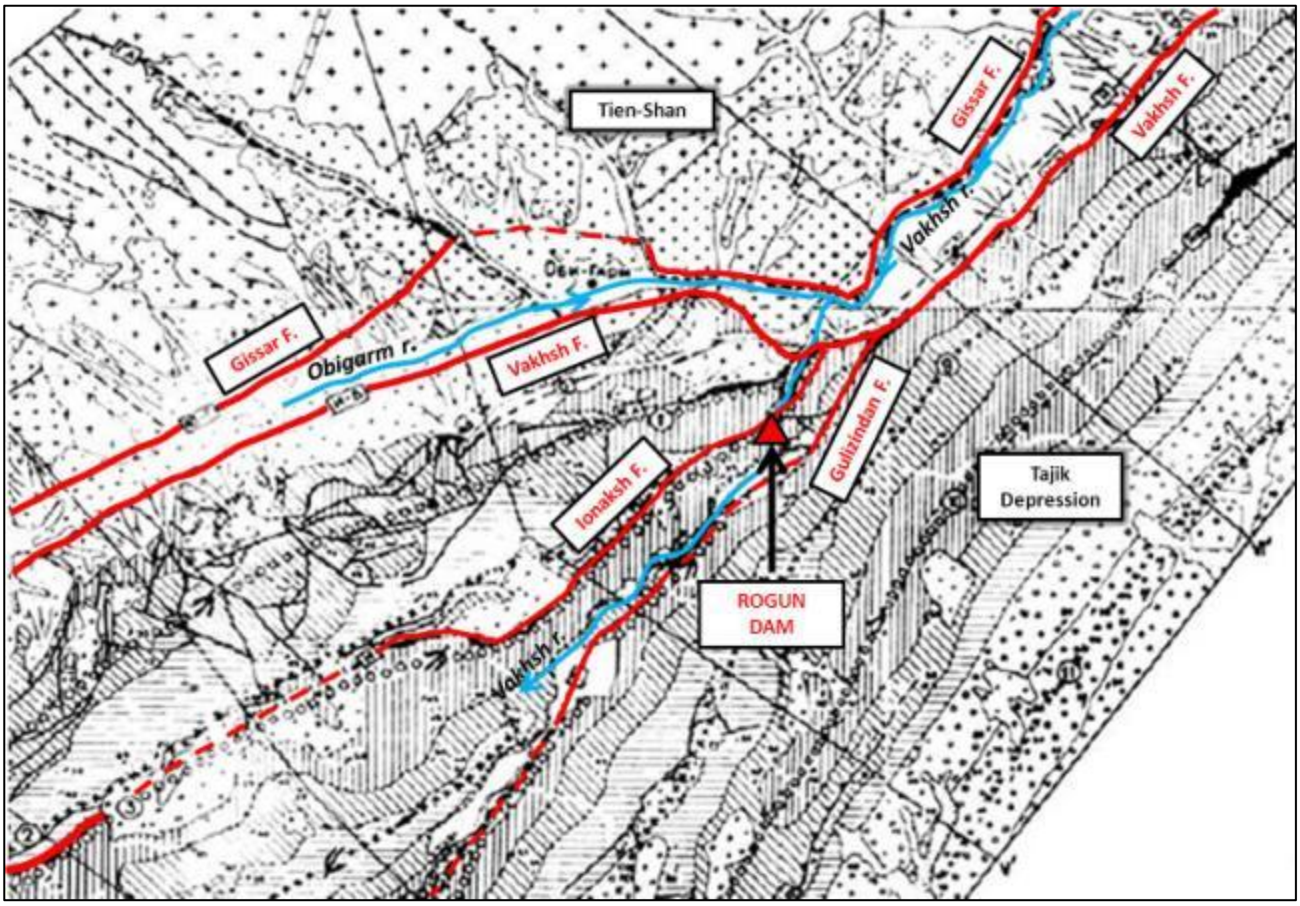

Illustration no. 8. Main faults near the project area. Background: extract of structural geology map of Rogun HPP, 1975.

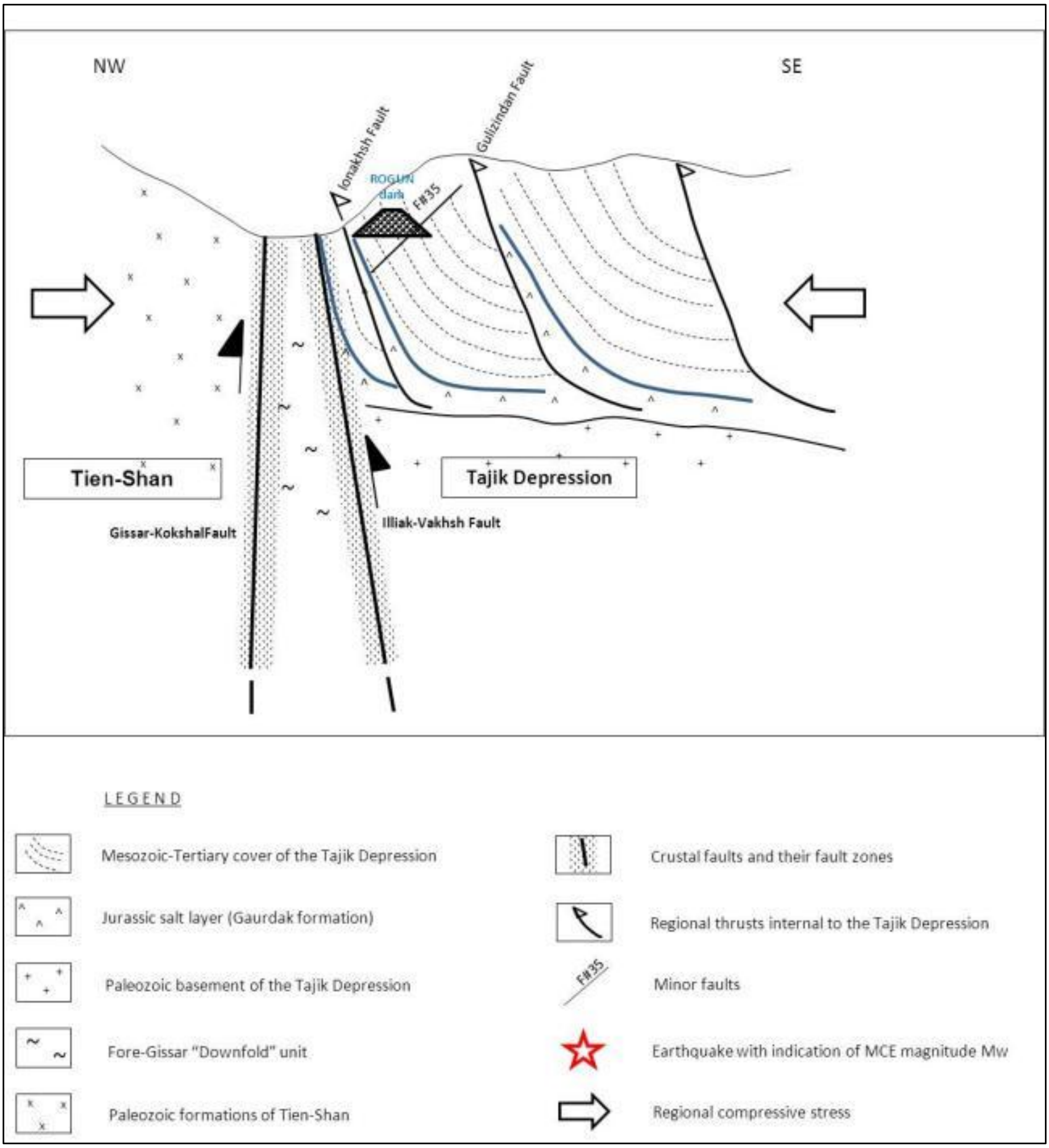

Illustration no. 9. Schematic regional geological setting

2.3.1. Crustal deep faults: Gissar-Kokshal and Illiak-Vakhsh

In the project area, the present-day tectonic stresses related with global geodynamics are largely accommodated by intense shortening along the major fault systems of Gissar-Kokchal and Illiak-

Vakhsh. Both these crustal-scale faults are several hundreds km long, 800 km for the former and 500 km for the latter. Gissaro-Kokshal fault dips toward NNW, Illiak-Vakhsh fault to the SSE, so that they diverge at depth. These two fault zones are credited with the highest seismogenic capability in the area of the project.

As discussed above, the lineaments of the faults are difficult to distinguish in the zone of the river bend near the dam site. Illustration no. 7 and Illustration no. 8 above show sharp changes of strike of these major faults and the narrow gap between.

2.3.2. Upper crustal levels

- Regional thrust faults within the Tajik Depression: Ionaksh and Gulizindan

As a consequence of the intense shortening, the Mesozoic sedimentary sequence located in the hanging wall of the Illiak-Vakhsh fault has been uplifted and is now exposed at surface. The considerable shortening of the sedimentary cover in response to compressive stresses is mainly accommodated by a series of steep folds and thrusts with NW vergence. The main base décollement level where the thrusts root is the thick Jurassic salt layer few kilometres deep identified as the Gaurdak Formation. Taking into account the wavelength of the associated folds and the thickness of the sedimentary sequence above the Gaurdak salt layer, these thrust faults would be rooted not deeper than 5 to 7 km.

The Rogun HPP scheme lies between two of these regional thrust faults: Ionaksh Fault, at the upstream side, and Gulizindan Fault, downstream (Illustration no. 7, Illustration no. 8 and Illustration no. 9 above). They dip toward SE and their length is of several tens of km. To the NE, few kilometers upstream from the dam site, they are cut by the Illiak-Vakhsh fault. The width of the fault zones with crushed rocks reaches generally 10 to 20 m. The zone of influence can reach 80 – 100 m, as has been observed in particular along Ionaksh fault in the right bank at the dam site.

According to [1], based on monitoring of recent deformation, slip rates along these faults are 0.5 - 1.8 mm/year for Ionaksh Fault and 1.0 mm/year for the Gulizindan Fault. The rate would increase to 2-3 mm/year during periods of higher seismic activity.

- Local faults: F#35, F#70, F#28,…

Numerous minor faults participate to the general stress relaxation. Among these, Fault#35 and Fault#70 are directly involved in the dam foundation. Dipping NW, they seem to branch out from Ionaksh Fault, which dips SE, within a few tens to hundreds of meters from surface. Fault#35 was identified at surface between Ionaksh and Gulizindan faults. It exhibits an outstanding crushed zone in the left bank at the dam site. However, its morphological print is more discrete in the right bank and it even becomes untraceable just downstream the dam site.

- Second order décollement levels

Above the Gaurdak salt layer, other thick gypsum layers of Upper Cretaceous and Tertiary age form décollement levels for spectacular bubble wrap folding, likely concurring in this way to the general release of tectonic stresses.

2.4. Particularities of the regional setting

Several particular features of morphological and structural geology nature characterize the area of the HPP site. These features are summarized below.

- Regional faults splay from this location, like from a knot, towards SW
- Illiak-Vakhsh fault forms sharp bends and its trace in westward direction is shifted to the north, instead of following the natural extension along strike, which is the Passimurakho valley. To note that large evaporite masses or assumed landslides could hide this feature.
- Gissaro-Kokshal and Illiak-Vakhsh faults zones come very near one to another.
- Vakhsh River course diverges from the Vakhsh fault alignment to cut across the Vakhsh Ridge, forming at the same time the canyon topographically favorable for the dam location.
- Peculiar in situ stress regime revealed by measurements at the dam site

As reported in [13], based on measurements in boreholes driven from adits near the Power House cavern:

- σx, subhorizontal along bedding strike = 11 to 19.5 MPa (average 18.2 MPa)
- σy, horizontal, perpendicular to the bedding = 7.5 to 14 MPa (average 12.9 MPa)
- σz vertical = 7 to 13 MPa (average 10.6 MPa), which is between equal and double the load of the cover

Based on measurements following the pressure compensation method and ultrasonic logging:

- σx = 11 to 33 MPa
- σy = 7.5 to 9 MPa

The stress regime as determined from measurements in underground workings is surprising. The main compressive stress at regional scale is expected to be oriented NW-SE, perpendicular to the bedding planes. This would be consistent with the vergence of the thrusts and of the regional folds. The anomalous results of tests at the dam site are not yet explained. It is recalled that initial data in Technical Design report [1] indicated maximum stress perpendicular to the bedding averaging 26 MPa. As highlighted in this chapter, the area of the site shows several singularities. Maybe a blockage to the W of the site, related with structural rising, could explain the results?

As for the turn of the river course, according to [1] and later reports (for instance [8]) the ancient Vakhsh valley (or pre-Vakhsh) ran along the present day alignment of rivers Sourhob – Vakhsh – Obigarm (Illustration no. 10). The shifting would have occurred between mid- and late-Quaternary periods, but the reasons of the shifting are not clarified.

Figure 1. Scheme of Rogunskaya HPS construction: 1 – The Southern Tien-Shan; 2 The Afghani-Tajik Drawdown; 3 – the Ancient Vakhsh Valley; 4 – The Vakhsh Thrust; 5 – tectonic breaks at the construction site and their numbers; 6 – border of the territory of geodesic monitoring of modern tectonic movements; 7 – the area of basic HPS structures; 8 – the line of geological break.

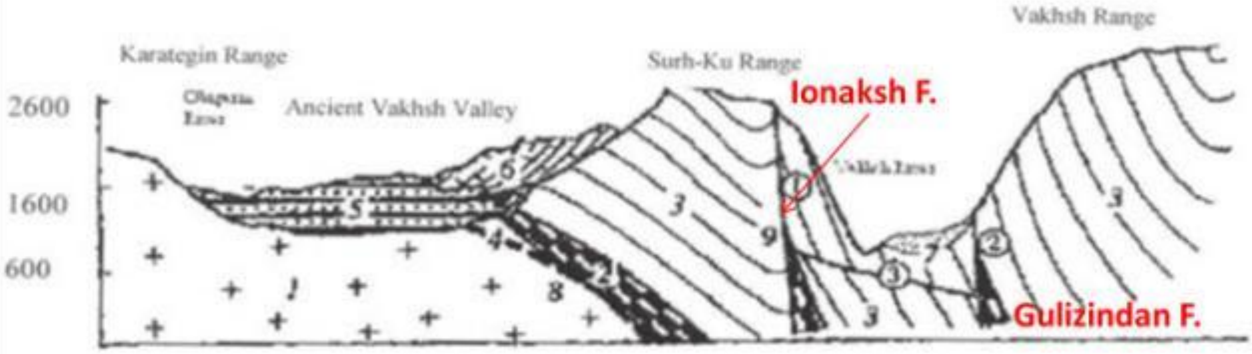

Figure 2. Schematic geologic profile along the line I-I, 1 – Paleozoic formations and sediments; 2 – Upper Jurassic sediments; 3 – Cretaceous Paleogene sediments, 4 – Neogenic sediments, 5 – alluvial Low Quaternary sediments, 6 – landslide Middle-Low Quarternary sediments, 7 – modern alluvial sediments, tectonic breaks; 8 – Vakhsh Thrust, 9 – upcasts at the construction site territory and their numbers.

Illustration no. 10. Interpretive reconstruction of pre-Vakhsh valley (from [8]).

The mentioned references report that massive landslides developed as creeping of slopes in adjustment to the progressive dissolution of salt at the toe. In the area between Passimurakho and Obigarm rivers, the rock outcrops are scarce and highly disturbed, while the morphology is dominated by lower slopes with deeply incised short streams: Passimurakho and Obi-Djushon. The field observations are indeed more consistent with slow deformation than with sudden landslides. The relationship between shifting of the river valley and those landslides is not obvious. The same setting with salt masses at the toe of the slope is very common, but nowhere else the river bended to cut across the ridge. In addition, since several noticeable changes of regional geological structures converge at this location, driving forces related with regional tectonics or diapiric rising could be taken into consideration as alternative explanations.

Irrespective of the cause, the zone Pasimurako and Obigarm rivers, including the city of Rogun (Illustration no. 11), comprises disturbed rock masses and thick, completely weathered and soft materials. These materials are at present subject to superficial slow gravitational movements, as discussed in the chapter dealing with slope stability.

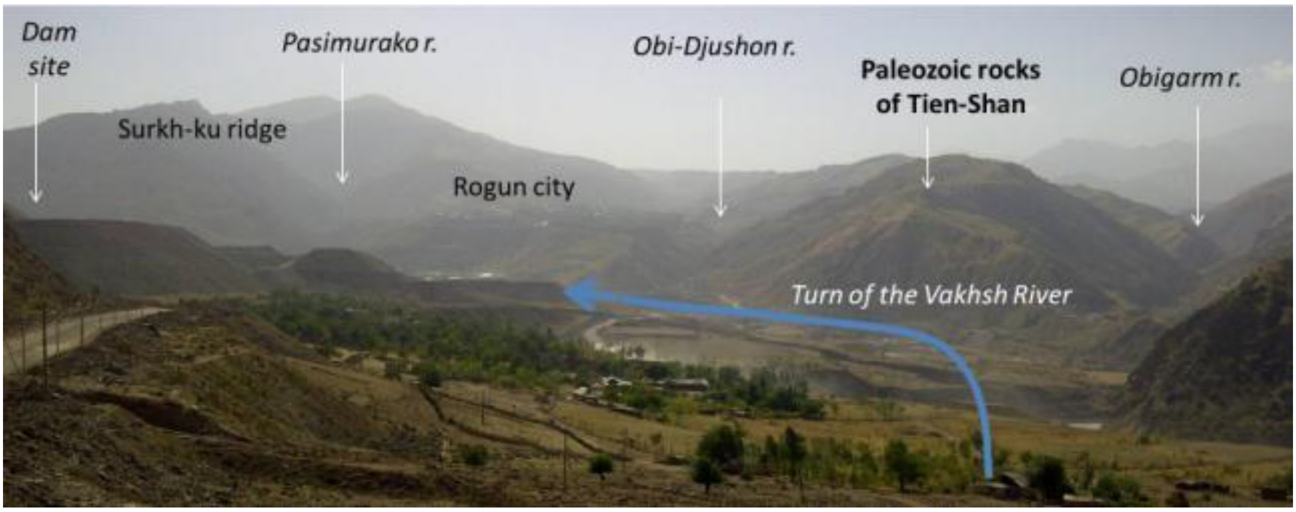

Illustration no. 11. Upstream view of the area of bending of the Vakhsh River.

3. Site geology

The site geological map is presented in the Annex, together with the geological map of the Right Bank completed in 2012.

3.1. Morphology

The elevation of the river at the construction site varies around 970 - 980 m. The river channel is narrow and the valley profile has a relatively tight 'V' shape (Illustration no. 12).

The favorable morphology for the retention structure is a result of the river cutting across the general structural trend and of the bedding. The majority of the discontinuities, including faults, are also cut under favorable angles, allowing for relatively high steep slopes. Over 350 to 450 m above the river level, the overall slope angle in both sides of the river is in the order of 45-50°, with local very steep sections of 70-80°. The 'V' shape valley profile has a double slope, widening above approximate elevation 1300-1350.

Illustration no. 12. Dam site view from upstream (above) and downstream (below).

3.2. Lithology

Table no.2 presents the result of compilation from available sources of information on composition and thickness of the Mesozoic formations. As opposed to former reports, which indicate very accurate thickness for each formation (10^{-1} m precision), adequate for a small areas, Table no.2 shows ranges of variation.

The approach initiated in the 1978 FS, which consisted in distinguishing groups of formations, is followed in this report. Those groups are:

(i) Upper Jurassic salt formation (Gaurdak Formation)

(ii) Lower Cretaceous continental sequence

(iii) marine sequence, principally Upper Cretaceous.

Jurassic Gaurdak formation

This Upper Jurassic formation is the oldest of the Mesozoic sedimentary cover. It is principally composed of salt, subordinate gypsum, with a thin reddish mudstone layer at the top. The maximum thickness at regional scale is assumed to be 400 m. In the project area, it forms a wedge which is truncated by the Ionaksh Fault. Based on data from drilling and adits, the thickness of the wedge would increase by 15 m every 100 m depth. In this way, from a few meters near surface the thickness would reach about 100 – 150 m at a depth of 800 – 1000 m below the dam axis. The thickness would further increase down to the flat-lying zone where Ionaksh Fault and the other regional thrusts are rooted, around 2000 m below the river level (Illustration no. 13).

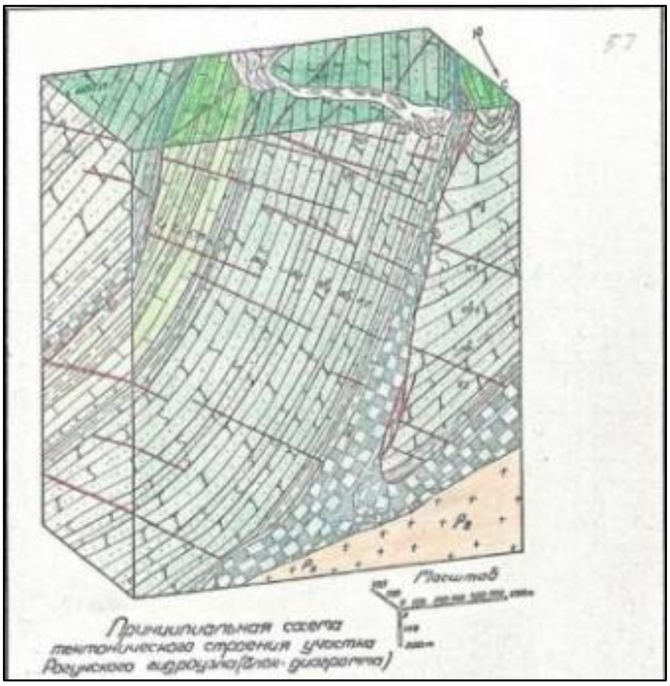

Illustration no. 13. Interpretive bloc-diagram of deep dam foundation (from FS 1978).

The thickness of the salt formation at great depth can only be assumed. In any case, under the strong compressive regime, the thickness of such deposits is extremely variable: it can be 'zero' where the salt was squeezed and extruded, or exceed by many times its original thickness when accumulated in decompressed areas or in diapiric structures.

Salt wedge in the dam foundation

The presence of the salt wedge (or dome) in the upstream part of the dam footprint being an engineering challenge, this feature has been extensively studied along with the Ionaksh Fault. The main characteristics are summarized below:

- The salt extrusion rate is in the order of 2 cm/year, that is about ten times higher than the vertical slip rate of the fault walls.
- The top of the salt wedge was found between elevations 952 and 970, with thickness in the range 2 to 12 m. It pinches out above these elevations, presumably owing to dissolution (for instance drawing 1174-03-41 in [1]).
- Above the salt wedge, the residuum left behind after the dissolution of the salt forms a cap of heterogeneous material, 10 to 12 m wide and thinning upwards. For 7-8 m above the salt, the residual cap comprises soft, insufficiently confined materials. Permeability tests showed that this particular facies could be locally highly permeable and particular treatment has been designed (HPI Moscow). (This major design topic is discussed separately.)

Illustration no. 14 presents a typical section of the salt wedge and its residual cap.

Lower Cretaceous continental sequence

This group, recognizable upon the dominant reddish color, includes formations dated form Valanginian to Lower Albian: Javan, Kyzyltash, Obigarm, Karakuz, Mingbatman and Lyatovan.

They consist principally of sandstone, siltstone and mudstone layers, with only rare, generally thin, evaporitic layers. The thickness of this sequence at the dam site is in the order of 1100 m (1082 m indicated in the FS report).

Marine sequence

At the dam site, it includes formations from Upper Albian, Cenomanian and Turonian. The thickness of this group reaches about 550 m (544.7 in the FS report). Further in the RB, in particular in the LB of the Ararak stream, the Upper Cretaceous sequence was identified during mapping in 2012 up to the Maastrichtian, adding about 250 - 300 m to the thickness of the Upper Cretaceous marine sediments.

Comprising sandstone, siltstone and shales, this sequence is especially characterized by the presence of limestone, marls and gypsum layers. Grey to dark-grey and greenish-grey colors are common. Fossils are also frequent.

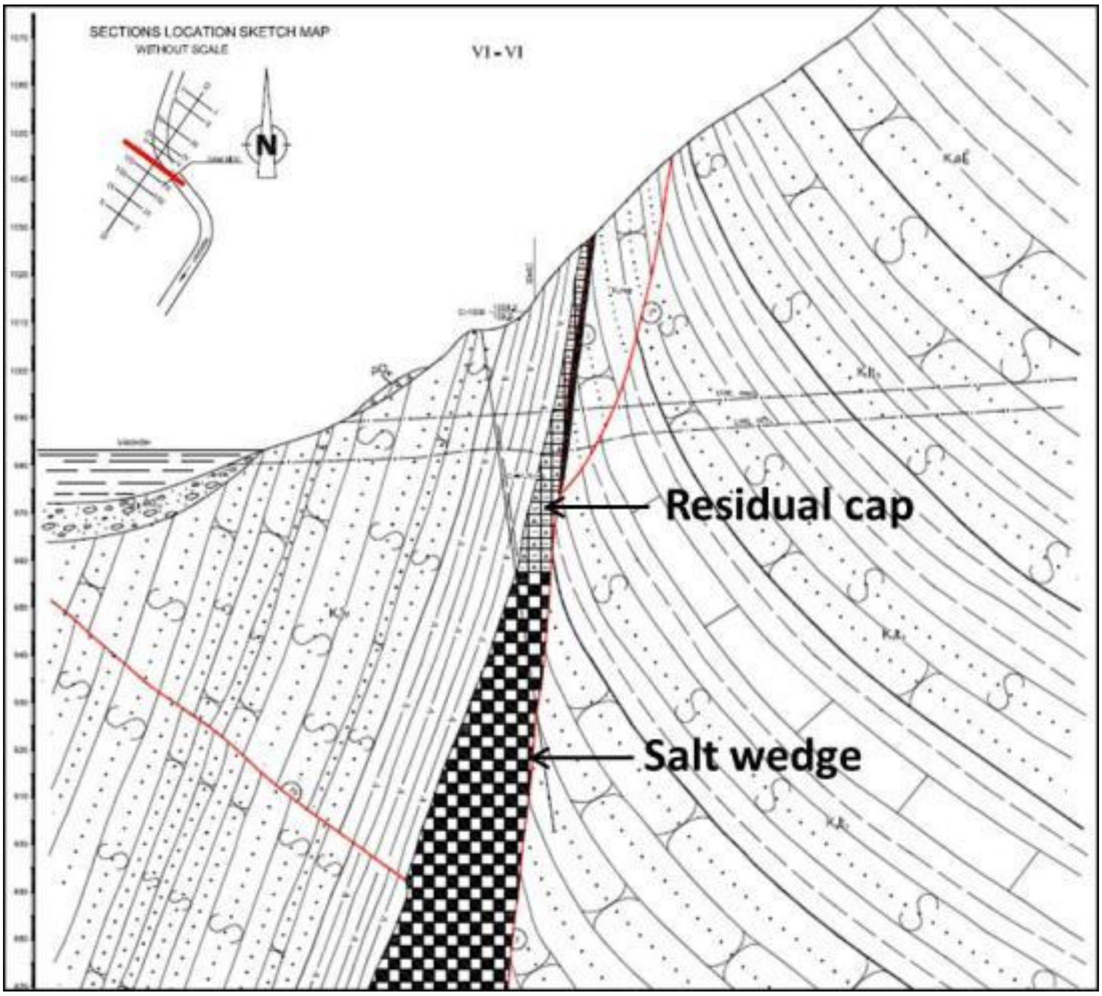

Illustration no. 14. Salt wedge on Ionaksh Fault in the Right Bank.

Table no.2. Stratigraphic sequence

Geological age		Formation	Symbol	Thickness	Lithology
Cretaceous	Maastrichtian		K_2m	80 - 110m	Grey, pink-grey, massive LIMESTONE with rare interlayers (0,5-10 m) of SANDSTONE. Limestone in the basis are slightly argillaceous, grayish-green and fossiliferous.
	Campanian		K_2cp	50 - 55m	Green, grayish-green mudstone, slightly sandy, with interlayers (0,5 m) of marls; grayish-green, weakly sandy limestone with fossil debris; grey sandstone.
	Santonian		K_2st	53	Bedded, greenish-grey and pink, bedded gypsum; grey, yellowish-grey, brown, reddish, greenish-grey, purple mudstone, siltstone and sandstone.
	Coniacian		K_2cn	65 - 80m	Greenish-yellow micaceous sandstone with interlayers of grey, sandy limestone and yellowish argillaceous limestone.
	Turonian	Upper Turonian	K_2t_2	150-160m	Upper suite: thin alternant grey, and dark grey shales and yellowish-grey, clayey limestone and marls. At the base of this suite, up to 20 m thick fossiliferous limestone layer. Lower suite: grey fossiliferous limestone, greenish-grey, marly shales with interlayers of fossiliferous marls. Gypsum mentioned in source (2)
		Lower Turonian	K_2mt_1	90m	Dark-grey and greenish-grey shales with rare interlayers of grey fossiliferous marls.
	Cenomanian	Upper Cenomanian	K_2cm_2	33 - 60m	Alternant grey, fossiliferous clayey limestone with dark grey and grey shales, micaceous sandstone, siltstone and shales with gypsum lenses.
		Lower Cenomanian	$K2cm_1$	45 - 50m	(1): Mudstone, sandstone, limestone, gypsum; (2):Grey, pinkish-grey cryptocrystalline compact limestone, greyish-green, locally brownish, medium-grained sandstone. (3): alternant dark grey and gray shales, with gypsum lenses, grey argillaceous limestone.
	Albian	Upper Albian	K_1al	50-65m	Mostly alternant brownish-reddish mudstone and gypsum, with grey sandstone.
		Upper Lyatovan	K_1lt_2	30 - 130m	Frequent interlayers of white and pink saccharoidal gypsum with greenish-grey and brownish mudstone, siltstone and sandstone. Rare interlayers of light-grey limestone.
		Lower Lyatovan	K_1lt_1	35 - 115m	Thin, dark-grey, greenish-grey shales with thin layers (0,3-0,5 m) of light-grey cryptocrystalline limestone, dolomite, marls (0,6 m) and white saccharoidal gypsum. In the medium part of the layer - dark-brown, fine-medium grained, micaceous sandstone with interlayers of greenish-grey sandstone (0,1-0,2 m).
		Mingbatman	K_1mg	130 - 375m	Brown and reddish-brown, fine-medium grained sandstone; light-grey sandstone, up to 10 m-thick, in the upper-middle section.
		Karakuz	K_1kr	85 - 175m	Reddish-brown sandstone with interlayers of grey and brownish mudstone.
	Barremian - Aptian	Upper Obigarm	K_1ob_2	110 - 240m	Sandstones, mainly brownish-reddish and purple with brownish-grey and light-grey interlayers; subordinate thin mudstone interlayers.
		Lower Obigarm	K_1ob_1	80 - 115m	Brown, dark-grey, green mudstones, siltstones; white gypsum interlayers, up to 30 cm thick in the middle part; upper part includes light-grey sandstone interlayer.
	Valanginain - Hauterivian	Kyzyltash	K_1kz	165 - 205m	Brownish-red, fine-medium grained, micaceous sandstone, subordinate interlayers of siltstone and mudstone.
		Upper Javan	K_1jv_2	40 - 100m	Reddish-brown and brown, foliated mudstone, siltstone. Source (2) mentions malachite (Cu) in two interlayers of greenish-grey, bluish-grey mudstone.
		Lower Javan	K_1jv_1	30 - 285m	In the upper part, reddish-brown, brown and purple fine-grained sandstone, siltstone and mudstone. Lower part: dark-brown and reddish-brown shales and siltstone, some gypsum lenses 0.1 - 0.3 m thick.
Jurassic		Gaurdak	J_3gr	400 m	Reddish-brown mudstone, salt and gypsum.

Sources mentioned if the description is different: (1) FS 1978; (2) Stratigraphic column 1962-63; (3) Geological report (draft) 2012, Barki Tojik

3.3. Geological structures

3.3.1. General trends and bedding

The main structural trend at regional and at local scale is ENE-WSW. This is the orientation of the bedding, of the major thrusts and that of the axis of the only noticeable fold at the dam site, namely Kirbitch syncline. The vergence of thrusts is NNW. Accordingly, the thrusts, but also the bedding planes away from fold axis, dip mostly to the SSE. At the dam site, the dip angle of the thrusts and of the bedding is generally high, exceeding 75° for the Ionaksh Fault and 60° for the bedding of the monoclinal sequence downstream of the fault.

Folds

The main large scale fold identified during the Technical Project studies is the Kirbitch Syncline. It is well visible in the Right Bank, where it abuts against the Ionaksh Fault from the upstream. Illustration no. 15 shows the Right Bank, the Ionaksh fault (in red), fault no.70 and the assumed axis of the Kirbitch syncline (in white).

Illustration no. 15. Right Bank at the dam site

This fold is tight, owing to the strong compressive stress. Except for the hinge zone, the bedding dip is steep in both limbs of the syncline.

During the present TEAS, it could be observed in the field that the structure is more complex than just an asymmetric syncline in the foot wall of a thrust. While this is the case in the lower part of the abutment, part of the sequence, involving also the upper reaches of the Ionaksh Fault and the axis of the syncline, bend and become overturned in the upper part of the abutment, as showed in the Illustration no.15 above. Based on interpretation of field data as detailed in [15], the overturn could have been caused by squeezing and injection of Albian gypsum in the upper part of the Right Bank. At the dam, the bending seems to initiate at approximate elevation 1450 - 1500 m, i.e. considerably above the maximum foreseen operating level.

3.3.2. Faults

The main faults at the project site have been described in the chapter dealing with regional geology. Some details relevant for the project are recalled below.

Results of monitoring of recent movements are summarized in Illustration no. 16 and Table 3.

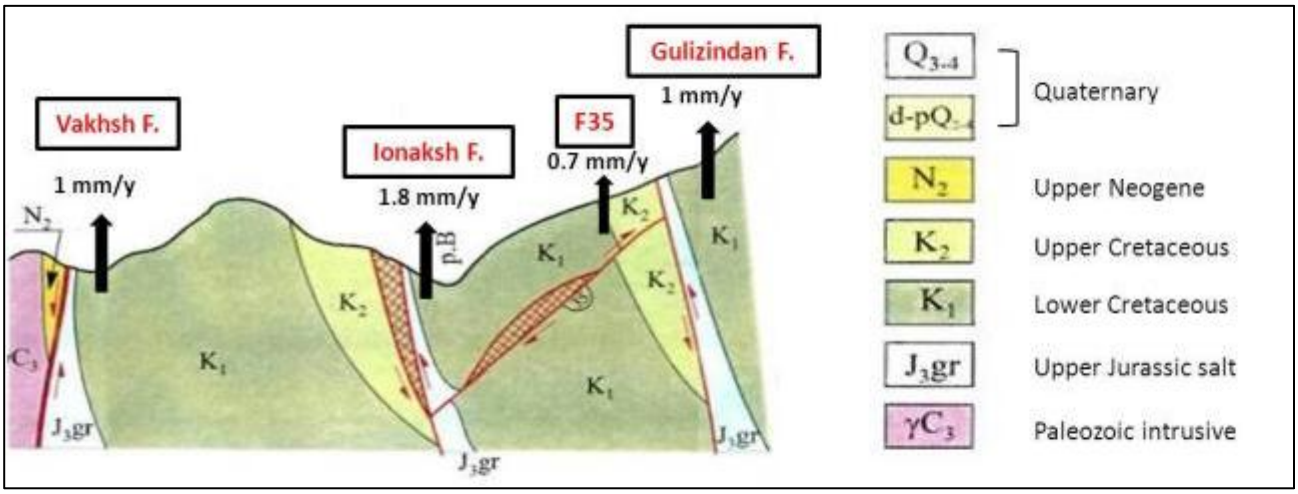

Illustration no. 16. Schematic cross section showing thrust rates for the main faults (modified from [3])

Table 3. Summary of monitoring of displacements along the main faults in the Rogun HPP area

Fault no.	Name and nature of faulting		Average rate of recent vertical movements (mm/year)
1	Vakhsh fault (SE wall)		1.0
2	Yonaksh fault	Walls offset	1.8
		Tectonic lens	2.8*
3	Gulizindan thrust		1.0
4	Fault no.35	Walls offset	0.7
		Tectonic lens	2.3*

(*)Monitoring results suggest that the rates of uplift of the plastic infill material of the fault zones or tectonic lenses squeezed between two fault branches are systematically higher than the vertical displacement of the walls. In addition, it is recalled that in the last salt dissolution models, the estimated rate of extrusion of the salt dome on Ionaksh fault is 2 cm.

It should be noticed that in detail, the records of displacement rate were much contrasted between different stations. The results from all stations are summarized on drawing 1074-03-F12.

The analysis of monitoring results concluded that the tectonic bloc delimited by Ionaksh fault and fault no.35 is uplifted by approximately 2 mm/year in average. However, the differential uplift recorded between different stations could indicate that the movement of the bloc as a whole is not pure uplift but could involve tilting. Such complex deformation could be accommodated by differential movements (rotation, tilting?) of smaller blocs delimited by minor faults. The definition of the actual kinematic model could call for increased number of monitoring stations.

Ionaksh Fault

Illustration no. 17 shows the thrust fault in the Right Bank at the dam site. It is clearly outlined by the reddish strip of Upper Jurassic mudstone. In the foot wall, the SE limb of Kirbitch syncline abuts against the fault.

Illustration no. 17. Ionaksh Fault in the Right Bank.

The presence of the salt wedge along this fault was identified as a potential challenge for the project since the early studies. As a consequence, substantial amount of investigations have been carried out, including drifting of longitudinal and cross-cut galleries, drilling, permeability testing, geophysical surveys, laboratory testing and monitoring of displacement. At upper elevations, the fault zone has been crossed by the right branch of the gallery #1034.

Recent investigations have been carried out during the present TEAS to complete the assessment of the fault at upper elevations. They comprised 2 boreholes with core recovery and permeability tests. The main characteristics and findings are summarized below:

- Borehole IF1

Location and length: upper part of the right bank at the dam site; drilled inclined in direction near perpendicular to Ionaksh fault, 115 m long.

Objective: to investigate the Ionaksh fault in the upper part of the abutment, to verify the lack of salt at this elevation, to carry out permeability tests at high pressure.

Main results: Ionaksh fault zone has been crossed approximately between 103 and 113 m. The fault zone is characterized by strongly sheared mudstones and gypsum in the hanging wall (Jurassic formation) and by breccia in the foot wall (Upper Cretaceous). The ground water level recorded in October was 74 m depth along the hole. This GWL is high with respect to the one assumed in the Technical Design in these reaches. Table no.4 summarizes the results of permeability tests.

Table no.4. Results of permeability test in borehole IF1

Stage	Effective Pressure (in bars)	Permeability (in LU)
42-47	5	19
47-52	5	41
52-57	21	16
57-62	10	24
62-67	22	15
67-72	7	1
72-77	7	30
77-82	12	3
82-87	31	8
87-92	18	2
92-97	19	2
97-102	19	1
102-107	20	1
107-112	20	1
112-115	20	2

The fault zone lies within the interval 102 – 112, where the permeability is very low. On the contrary, several stages in the upper part of the borehole yielded high values.

- Borehole WRB2/DZ1

Location and length: within the atypical zone, but near the boundary with the undisturbed setting of the dam foundation, 217.2 m long, vertical.

Objectives: to investigate the geological structures, to characterize the rock mass in the atypical zone, to cross and characterize the reversed Ionaksh fault in the atypical zone, to carry out permeability tests.

Main results: The borehole crossed about 30 m of overburden, than Upper Cretaceous Turonian rocks (grey to dark grey limestone, commonly argillaceous, marls and shales) before crossing the IF zone between approximately 160 and 170 m depth. The fault zone is characterized by sheared red mudstone and gypsum, but no salt mass. The entire sequence, including the IF fault zone, dip moderately to the NW. The Turonian rocks above the fault zone exhibit several intervals of crushed cores. The RQD values mostly vary between 0 and 50.

The ground water level recorded during tests was varying between 65.3 and 70 m depth, that is around elevation 1450. Table no. 5 summarizes the results of permeability tests (to note that reported results by subcontractor have been modified to integrate the actual ground water level).

Table no. 5. Results of permeability test in borehole WRB2

Stage	Effective Pressure (in bars)	Permeability (LU)
40-45	22	10
130-135	20	18
152.5-157.5	10	22
157-162	10	19
167-172	11	6
177-182	11	10
187-192	11	3
192-197	12	2
197-202	11	3
202-207	12	3

Accordingly, the fault zone shows variable permeability values in the range 6 to 19 LU. The Upper Cretaceous series above the fault yielded almost systematically moderate to high permeability values, which seems consistent with the aspect of the cores, whereas the Lower Cretaceous rocks below the fault have low permeability.

At this stage, the grouting treatment of the upper zone of the wedge has been almost completed. These workings provided additional data on the behavior of this particular feature.

Based on available data, the main characteristics of this fault at the dam site are summarized below:

- The recent observations generally confirmed the descriptions done at the FS stage.
- The facies of the fault zone are variable. Above the salt wedge and its residual cap, the fault zone includes sheared reddish mudstone mixed with strongly disturbed gypsum and fault breccia.
- The thickness of gypsum in the fault zone is variable, from less than 1 m to more than 5 m. It is rarely visible at surface. Illustration no. 18Illustration no. 18. Ionakhsh Fault zone in borehole WRB2 shows thick gypsum in borehole WRB2. Very likely, the same thick, disturbed gypsum lens is also visible at outcrop in the road cut near the borehole (Illustration no. 19 for photograph and Illustration no. 20 for the geophysical profile across this lens). The presence of this thick lens coincides with the area of bending of the structures from normal to overturned position, which suggests that such thickness is local but can occur in special settings.

Illustration no. 18. Ionakhsh Fault zone in borehole WRB2

Illustration no. 19. Thick and deformed gypsum lens within Ionaksh Fault zone,

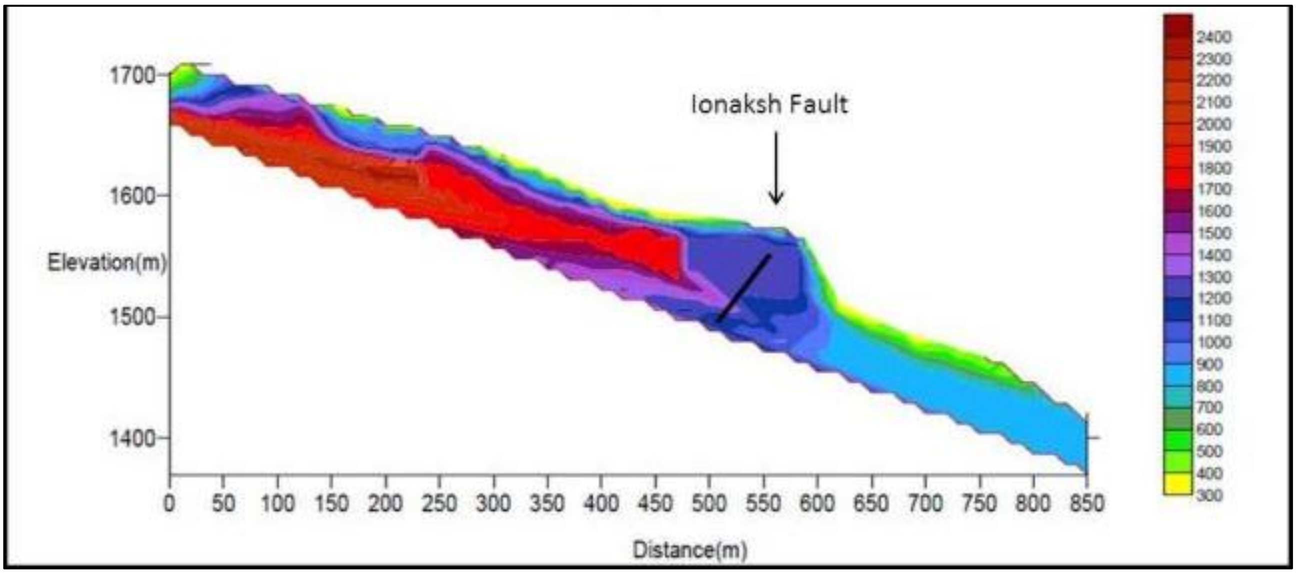

Illustration no. 20. Summary of refraction seismic results on Line 2, crossing the thick gypsum lens form the illustration above.

- The thickness of the fault zone, including crushed rocks, highly disturbed gypsum and fault breccia is well in the order of several tens of m (20 to 80 m in [1]).
- Observations in the grouting gallery in the Right Bank tend to confirm the watertightness of the hanging wall (downstream side) of the fault zone in the lower part of the abutment.
- According to a few tests only, carried out in boreholes IF1 and WRB2 at the upper elevations, the permeability values are variable: low in the undisturbed setting in the dam abutment (IF1), moderate to high in the overturned section (WRB2).
- According to [1], the cumulative offset of this fault is 1000 m.

Pumping and dissolution test has been recently carried out for the purpose of the TEAS. The results are commented in a separate report, dedicated to the salt dome.

<u>Gulizindan Fault</u>

This fault is comparable to Ionaksh fault in nature, attitude, size and order of magnitude for the slip displacement rate. Illustration n. 21 shows the fault in the right bank of Obi-Shur valley. No disturbance is visible in the recent scree deposit sealing the fault.

Unlike Ionaksh Fault, Gulizindan does not cross the dam foundation. In turn, it connects the reservoir with the downstream side of the dam. Downstream from the canyon, it runs through the left bank of Vakhsh River, where it is covered by thick alluvium deposits.

One adit, 2 boreholes with permeability tests and geophysical surveys investigated this fault reported. The findings of these investigations were the following:

- salt wedge only found at significant depth, 50 m below the depth of the wedge on Ionaksh fault

- low permeability values and results converged in showing the watertightness of the fault zone.

- seismic velocities of P waves in the range of 6000 m/s, which is extremely high for a rock mass dominated by sheared mudstone and gypsum.

The high elastic waves velocities were interpreted as a proof of the high state of compression of the rock mass along and near the fault.

Illustration n. 21. Gulizindan Fault in the right bank of Obi-Shur valley.

Fault no. 35

Fault no.35 is near perpendicular to the river valley, which it crosses about 100 m downstream from the dam axis. Its attitude is 35-45°/330-340°, i.e. dipping towards upstream.

According to [1], the cumulative offset of this fault is 120 m. In both banks, the fault comprises two branches, the width of the tectonic wedge being of 60-70 m. The same width is assumed near the foundation of the underground caverns ([1]). Field observations suggest that the maximum offset could attenuate significantly along the strike of the fault, in particular in the RB of the dam. Illustration no. 22 shows the fault in the Left Abutment. Tectonic lenses including highly sheared materials are several meters wide. In the Right Abutment, the two branches of the fault are more like a saw-cut, delimiting a wedge with increased fracturing degree but no crushing zone similar to that in the opposite bank. Further towards downstream, the fault becomes untraceable when it reaches the atypical zone with overturned sequence.

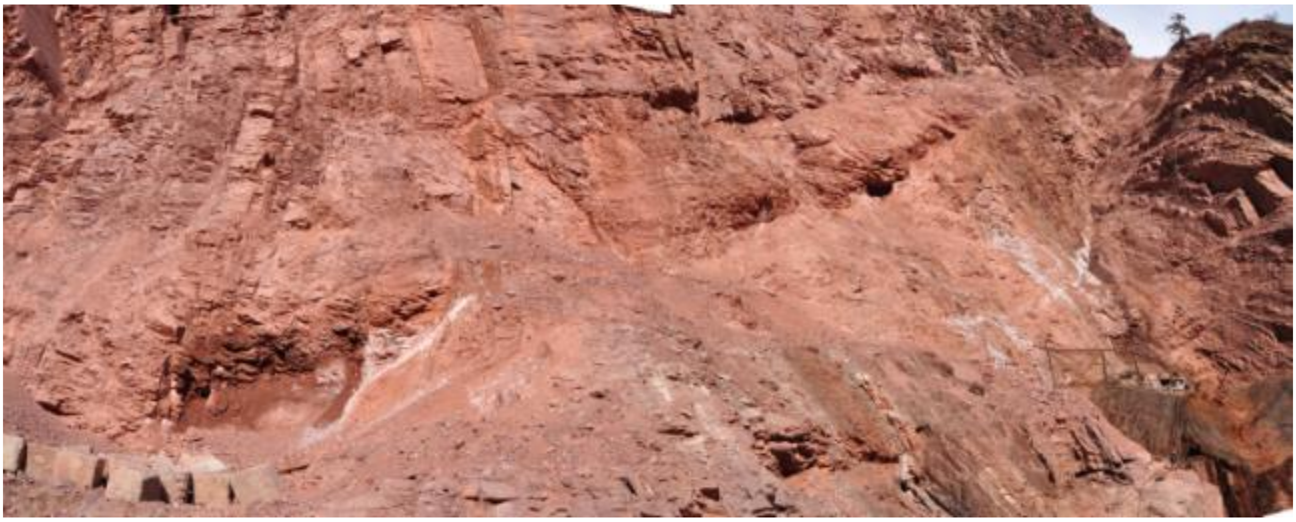

Illustration no. 22. Fault #35 in the Left Abutment of the dam.

Several other major joints, with orientation similar to the Fault no. 35 but with low or no offset, cross the river valley and the dam foundation (Illustration no. 23, Illustration no. 24 and Illustration no. 25). The spacing between these discontinuities varies mainly between 20 and 60 m. The width of fault breccia and clay infill would be mostly of several centimeters, but can reach 0.3 to 0.5 m (conclusions of geological report in [1]. Among them, no. 70 is reported to have a cumulative offset of 10 - 15 m. It should be noticed that in the Right Bank, these joints do not seem to cross the Ionaksh Fault.

As will be discussed further in the report, these faults and major joints are part of the joint family S4. Apart from the main faults described individually, the major fractures of this family are the most conspicuous and persistent, generally over hundreds of meters.

Illustration no. 23. Series of discontinuities of F#35 family I the Right Abutment.

Illustration no. 24. Discontinuities of F#35 family, dipping upstream, in the Left Abutment.

Illustration no. 25. Faults in the upper Left Abutment.

Fault no.28

This fault runs in the area of the outlets of the diversion and spillway tunnels. It is oriented NE-SW with very steep NW dip (310°/80°), but the SE bloc is thrusting the NW one, the vertical offset being of 100 m. Its length is about 1,0 km between fault no.35 and the Gulizindan fault. Like the fault no.35, it is not traceable downstream from the boundary of the atypical zone.

Transversal faults

Faults with strike transversal to the main regional trend are well known in the Tien-Shan bloc. Some of them, however, seem to cross also into or near the project site. Among them, fault no.367 has been identified during early studies. It outcrops in the right bank of Vakhsh River near the upstream cofferdam and its attitude is NW-SE with steep SW dip. The amplitude of displacement is only roughly estimated in [1] in the range 150-200m. The width of the zone of crushed rock would reach 3 – 5 m, while the wedge of highly fractured rocks can reach up to 70 m wide. To the SE, it is cut by the Ionaksh Fault.

A discontinuity of the same family is inferred from alignment of morphologic elements along the NE boundary of atypical zone in the right bank. It had been identified at the FS stage as fault no. 24. Field observations, such as tight bending of the plastic layers and attenuation of offset in the lower part of the slope, do not confirm the presence of a fault or continuous surface rupture.

3.3.3. Discontinuity pattern

A considerable amount of structural readings have been reported in [1], with a summary of the joint pattern in Drawing 1174-03-78. Accordingly, the main joint sets are as showed in Table no. 6:

Table no. 6. Main joint sets at the dam site

Joint set	Orientation (dip azimuth / dip angle)
S1 (bedding)	130 °/ 65-70°
S2	32° / 20-28°
S3	220° / 45-55°
S4	345 / 45-50°

The main elements of the joint pattern based on reported data and recent field observations are discussed below.

<u>Joint set S1</u>

Joint set S1 corresponds to the bedding. It is naturally similar in both siltstone and sandstone and shows low dispersion. Bed over bed slipping or shearing is very common in folded sedimentary sequences. At large scale, Ionakhsh and Gulizindan fractures show similar attitude.

<u>Joint set S4 - Fault no.35 family</u>

Joint set S4 has roughly the same NE-SW direction as bedding, but the dip is opposite, NW, and the average dip angle is lower. Numerous major discontinuities, including faults no. 35, 70, 28 among others, are large scale illustrations of this joint set. Together with the bedding, this joint set is the most conspicuous at the dam site (Illustration no. 23 above).

Joints of this family are unfavorable in the downstream walls of the caverns. The major fractures mentioned above have the same attitude across siltstones and sandstones. The major fractures are mostly unfavorable for slope stability in the upstream part of the Left Abutment, in the area of the Diversion Tunnels. Shearing of the lining at the inlet portal of the diversion tunnels was probably caused by gravitational sliding on such surface. The risk of sliding along such discontinuities will increase with pore pressure during impounding or with significant fluctuation of the reservoir level.

<u>Subhorizontal and shallow dipping discontinuities</u>

Subhorizontal discontinuities are noticeable at many locations at the dam site. Their significance in the kinematic model is not completely clear, but decimetric offsets are often associated with such discontinuities, showing that they participate actively in the adjustment of the tectonic stresses. They are often, but not always, combined with the S4 discontinuities (Illustration no. 26, Illustration no. 27 and Illustration no. 28).

Illustration no. 26. Conspicuous joint sets at the dam site (here, in the lower part of the Right Bank).

Illustration no. 27. Offsets on subhorizontal and S4 discontinuities, upper part of the downstream ridge near the boundary of the atypical zone.

Illustration no. 28 shows very persistent subhorizontal discontinuities, which do not appear as second order offset accompanying S4 faults.

Illustration no. 28. Offsets on very persistent subhorizontal / shallow dipping discontinuities, Left Bank downstream.

The subhorizontal offsets show that the kinematic model is more complicated, in particular by diffuse deformation on numerous discontinuities. The positive implication is that deformation on individual discontinuities is lower. Such deformation has been monitored on the main faults and the order of magnitude of the slip rate has been determined (Ionaksh Fault, Fault#35). The drawback is that shearing could occur at unpredictable locations within the rock mass. Consequently, a prudent design will contemplate not only local treatment where the structures cross the main faults but treatment of the full development of the structures.

4. Slope stability

This chapter deals with slope stability issues in the area of the dam and appurtenant structures. The aspects related with slope stability in the reservoir area are discussed in chapter 6.

The Technical Design report [1] distinguished in the project area the following types of landslides:

- Landslides involving Quaternary deposits
- Rockslides related with dissolution of salt at the foot of the slopes. (This type of sliding is especially relevant for the reservoir area and will be discussed in the corresponding chapter.)
- Rockslides controlled by structural or stratigraphic discontinuities

The analysis of slope stability has been updated and reported in [13].

4.1. Landslides involving Quaternary deposits

Several zones were distinguished, as showed in Illustration no. 29.

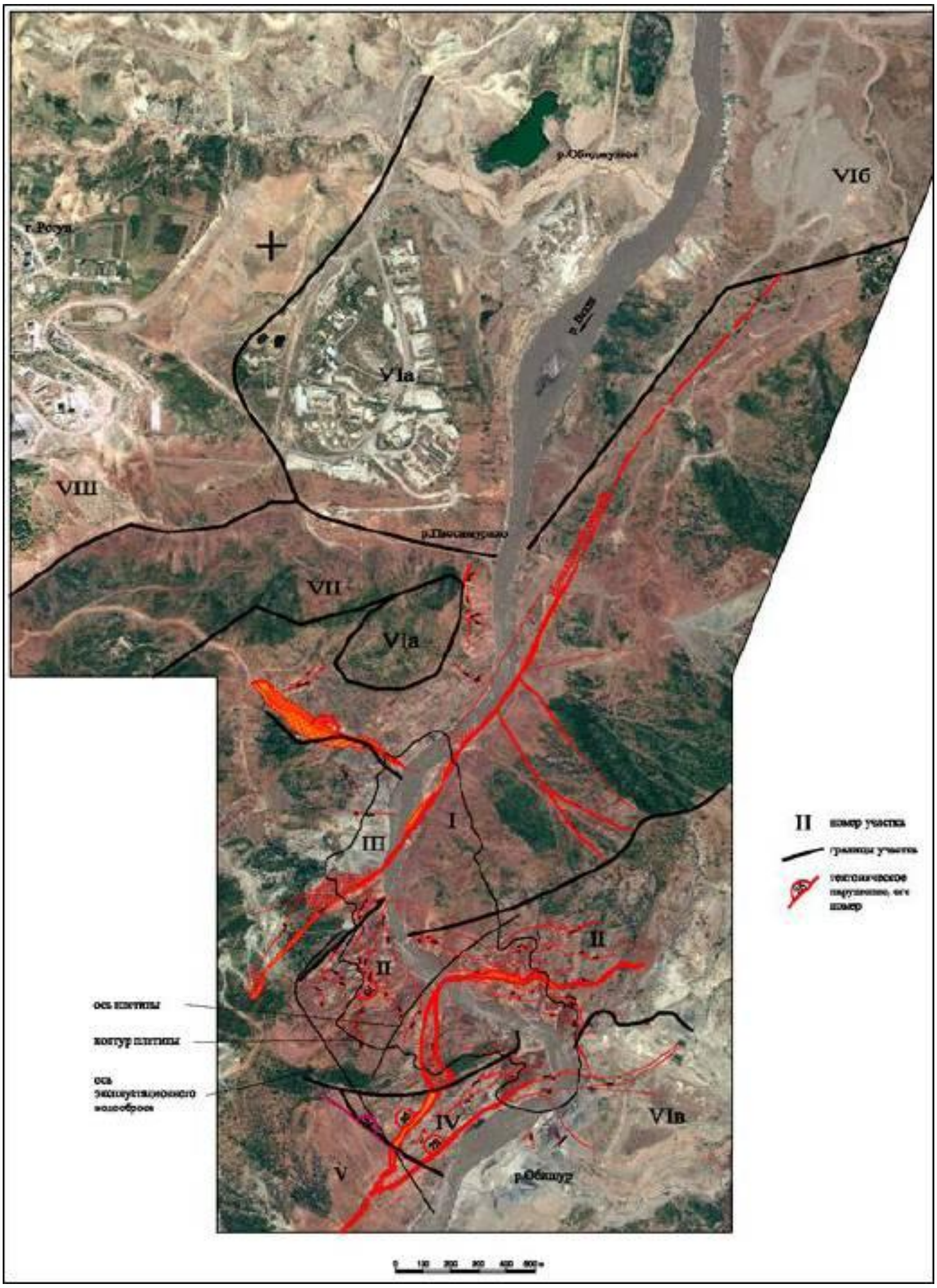

Illustration no. 29. Zoning of slope instability processes

According to the analysis in [13], the main areas with past and potential landslides of Quaternary terrains are:

- In 'zone I', accumulation of large volumes of scree deposits with thickness in excess of 10 m hang on the slope above the inlet structures (Illustration no. 30) the toe of these deposits lies below the reservoir level. They already constitute a threat during construction, but the probability of sliding will increase after impounding. Usual mitigation measures are recommended at this stage: reshaping of the slopes where possible, drainage, water collectors, retention structures.

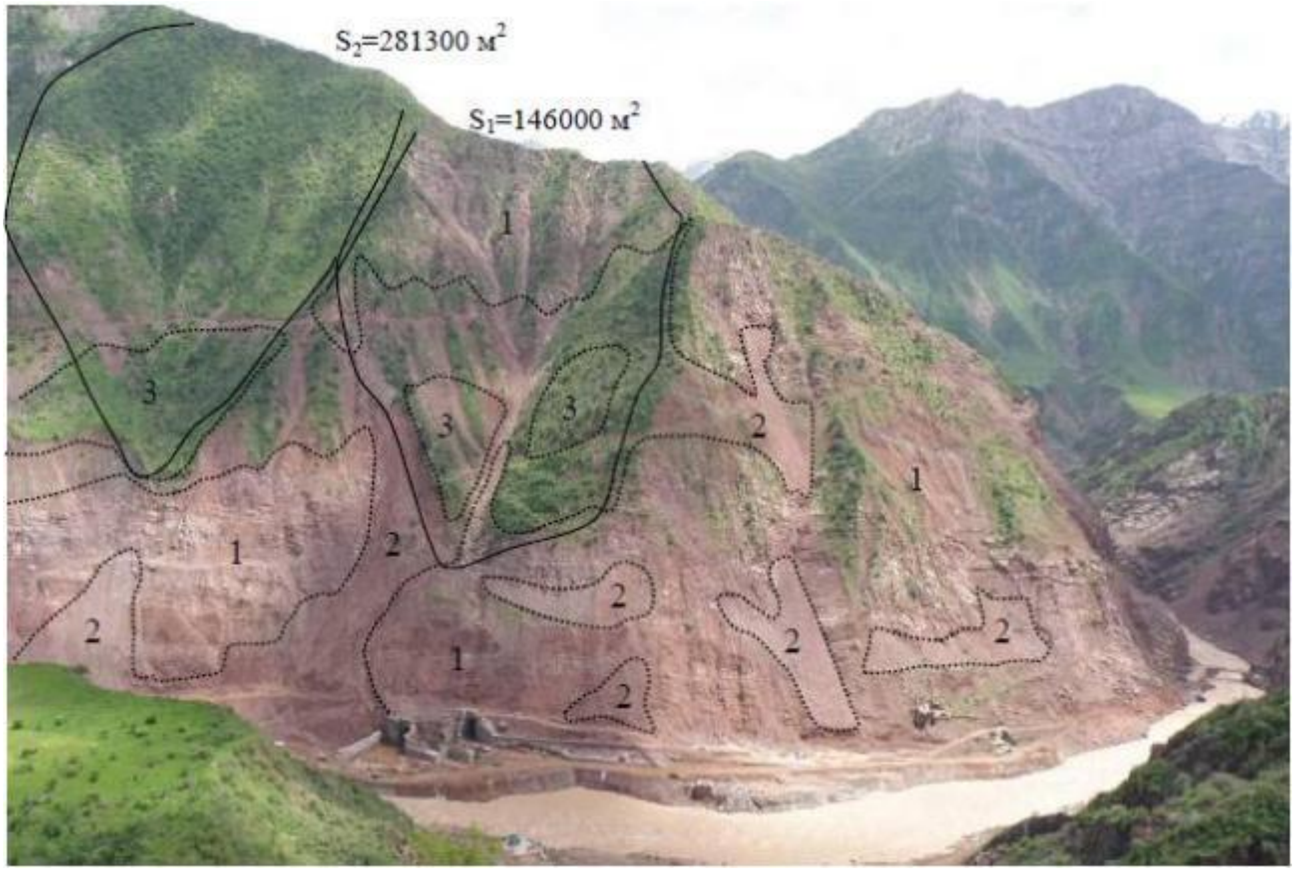

Illustration no. 30. Accumulation of thick slope deposits (3) in the upstream left bank.

- In ‘zone V’, which corresponds to the right bank slopes of the atypical area (Illustration no. 31). Thick accumulations of scree deposits are widespread on this slope. The slope also includes in its central part an ancient landslide (Illustration no. 32). The field inspection indicated that this landslide involved principally Turonian shales, the failure of which entrained subsequently the overlying massive limestone. The scarp within the frontal lobe of this ancient landslide indicates recent reactivation. Potential sliding volumes can reach up to 500,000 cubic meters and could dam temporarily the river valley. Drainage and reshaping of the slope are necessary in order to prevent or reduce considerably such instability and impact on the Rogun HPP structures during construction or operation. These measures are to be generalized to all potential unstable areas with considerable volume on this slope.

Illustration no. 31. Zoning of the slope of the atypical area.

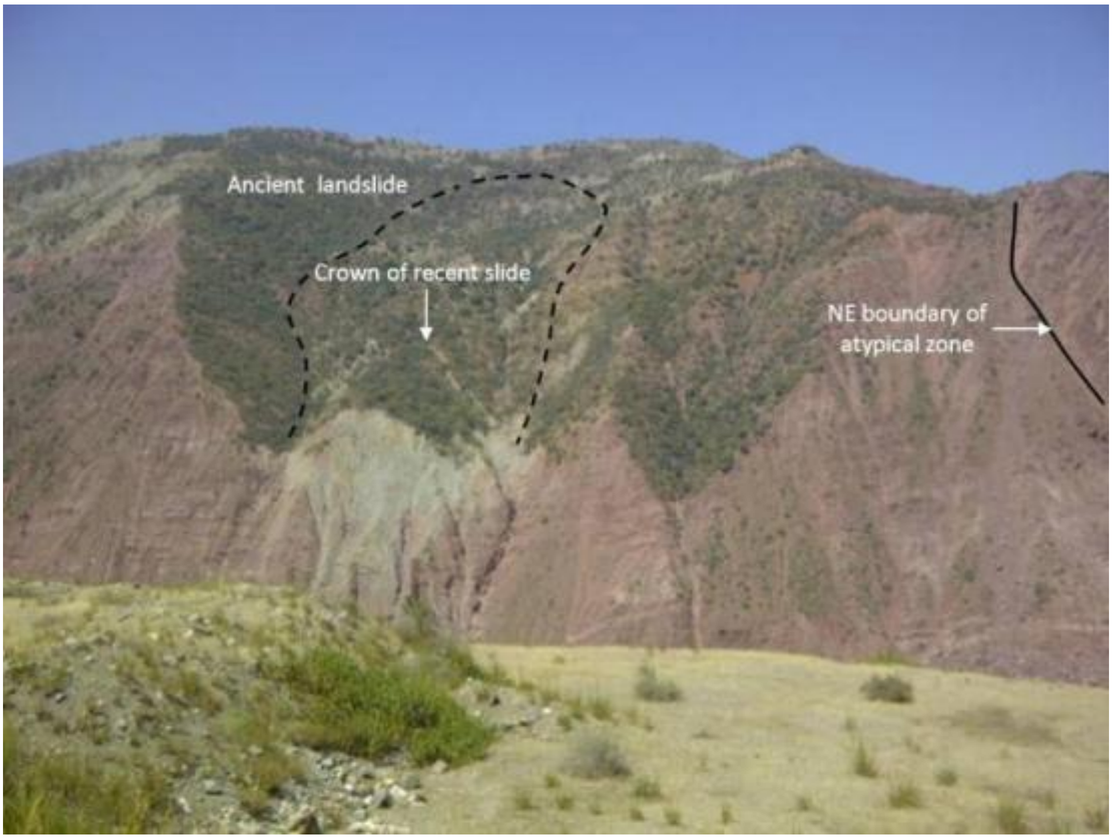

Illustration no. 32. Ancient landslide in the central part of the atypical zone.

- In 'zone VI', including the high scarps in alluvial terraces which lie in the left bank of the Vakhsh River especially upstream between the mouth of Obi-Djushon and the canyon, on one side, and starting from the mouth of Obishur downstream of the canyon. The scarps reach 20-50 m high and can be affected by slides subsequent to caving by river erosion at their base. The erosion is mostly expected to be progressive, unless dissolution of salt along the Vakhsh Faults does not trigger larger slides. Such occurrence is difficult to predict at this stage.

- 'Zone VII' comprises the right bank of Passimurakho valley. The landslides in this area are interpreted as adjustment of the slope in response to salt dissolution at the base. Considered in [1] as typical for ancient landslides common in the reservoir area, they will be described in the corresponding chapter.

- 'Zone VIII' comprises the area between Passimurakho valley and the right bank of the Obigarm valley. This area, which includes the city of Rogun and site installations, is special by rising of salt deposits, karst dissolution and numerous superficial instabilities. Damages to buildings in Rogun city have been reported in relationship with surface sinking, as discussed in the chapter relative to reservoir geology. As for 'zone VI', the sliding and creeping processes, mostly superficial, are expected to develop progressively during impounding. The impact of impounding on dissolution and subsequent instabilities should be considered.

- In addition to the above, it should be mentioned that in the upstream part of the Right Bank in the area corresponding to the Kirbitch syncline and adjacent to the Ionaksh fault, thick slope deposits could result in landslides of hundreds of thousands of cubic meters.

4.2. Structurally controlled landslides

Among the structurally controlled landslides, the TD report described an ancient landslide in the atypical zone in the Right Bank downstream of the site, with estimated volume of 500 million cubic meters. (According to recent reassessment in 2009 ([13]), the estimated volume of the ancient landslide would be 75 – 100 million m^3.)

The assumed mechanism is sliding of layers of a syncline limb along mudstone and gypsum interlayers. Recent investigations and observations during TEAS suggest that the configuration of this particular area results principally from tectonic deformation. The topic is presented in a separate report ([15]). The principal aspects are recalled below.

The atypical characteristics of the upper part of the Right Bank and more generally the RB slope downstream from the canyon have been identified since the earliest stages. Peculiar features include:

- A wide, relatively flat area (Illustration no. 33) at 1700 – 1750 masl, that is about 300 m below the ridge and 700-800 m above the Vaksh River valley.

- Bedding dip toward NW (upstream), as opposed to bedding dip toward SE (downstream) in the canyon. As a result, on the slope between the flat area and the river, the Mesozoic sequence is in reverse position, i.e. older formations overlying younger formations. The overturned sequence includes the Ionaksh Fault.

- Downslope offset of the formations, by tens of meters to more than 100 m, with respect to their normal position in the dam abutment (senestral offset).

Illustration no. 33. Atypical flat area.

At the Technical Design stage, the particular setting was explained by large scale slope instability, involving successive, massive landslides. While much of the slid rock masses piled up in the upper part of the slope to form the atypical flat area, significant masses also slid down to the river valley. Accordingly, the change of the bedding dip would have resulted from dragging of the layers' heads at the base of the slides (Illustration no. 34). In this 'landslide model', the downslope offset was interpreted as the result of tear-off along the eastern boundary of the landslide zone.

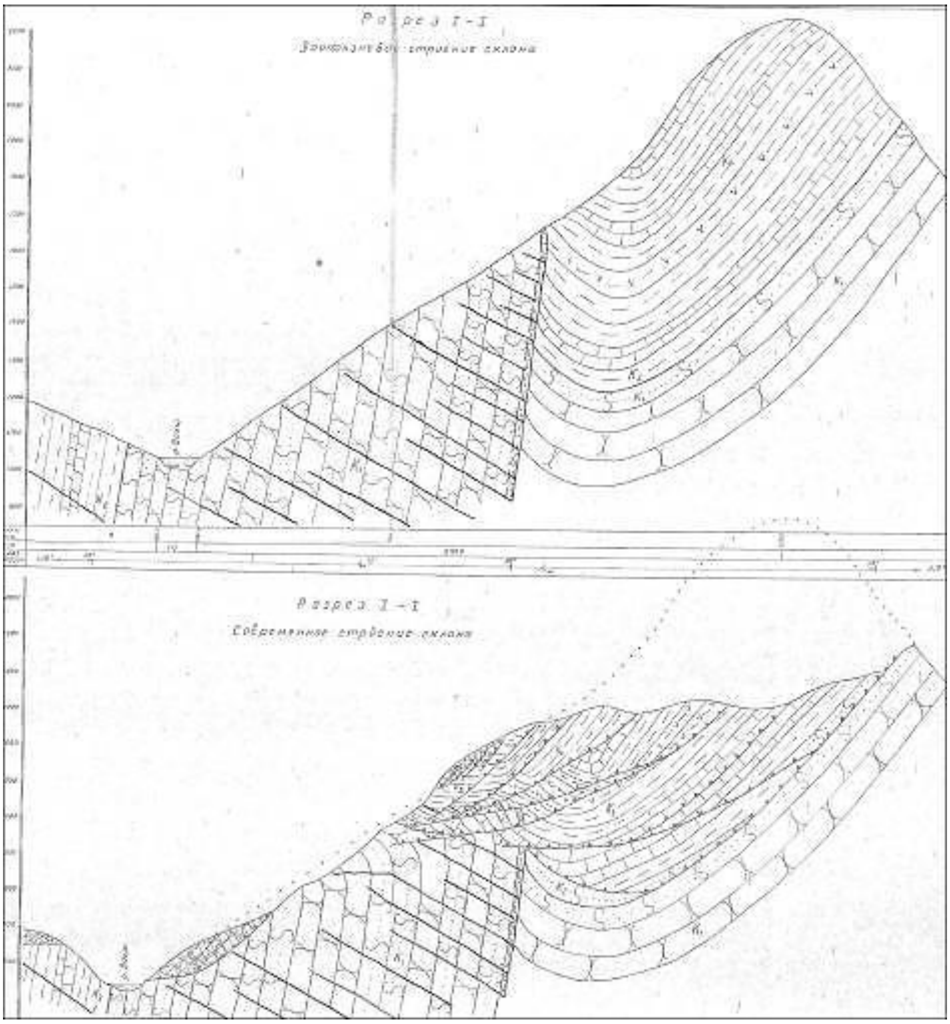

Illustration no. 34. Interpretive cross sections of the ‘landslide area’ (in [1]). View towards downstream (SW). Original setting at the top, post-landslide setting at the bottom.

The Technical Design 1978 report concluded that the ancient landslide zone is mostly stabilized. At present, only superficial landsides could result from failure of deposits from the body of the ancient landslide and from the disturbed layers on the slope. The maximum size of such potential landslide was estimated at ‘a few hundreds of thousands of meters’

<u>Additional field investigations in 2012</u>

The main findings of the investigations carried out during the TEAS were

The geological map, drilling reports, seismic refraction report and microgravimetry report are annexed to the report [15].

:

- The atypical geological setting extends beyond the area previously delimited and referred to as ‘ancient landslide’ zone. The study has been extended up to the Ararak valley, which is the first significant right-hand tributary downstream of the dam.

- Some of the Upper Cretaceous formations identified in the Ararak stream were found to include thick gypsum layers which exhibit numerous karst dissolution features (Illustration no. 35)

Illustration no. 35. Sinkhole in thick gypsum layer, left bank of Ararak stream.

Similar gypsum formations are involved as décollement level in the outstanding bubble wrap folds, typical of salt/evaporite tectonics, which are visible in the opposite bank of the Vaksh River (Illustration no. 36Illustration no. 36. Salt tectonics, bubble wrap folds in the left bank opposite to the atypical area.). It is concluded that in the area of the project, the tectonic stresses are accommodated by décollement not only in the Jurassic salt formation but also at other favorable levels above it.

Illustration no. 36. Salt tectonics, bubble wrap folds in the left bank opposite to the atypical area.

- Large scale folding and overturning of the Upper Cretaceous sequence including Cenomanian and younger formations was directly observed in continuity with the 'atypical setting' which had been formerly interpreted as 'landslide' of Upper Cretaceous layers (Illustration no. 37). The left bank of Ararak stream exhibits large scale bending and reversal of the Cretaceous sequence. Formations are younger from the left to the right. At left, normal position with bedding dip to SE. At right, reverse position with bedding dip to NW. Turonian black shales and massive limestone at the contact Turonian/ Cenomanian, as key beds, can be followed practically without interruption towards the dam site.

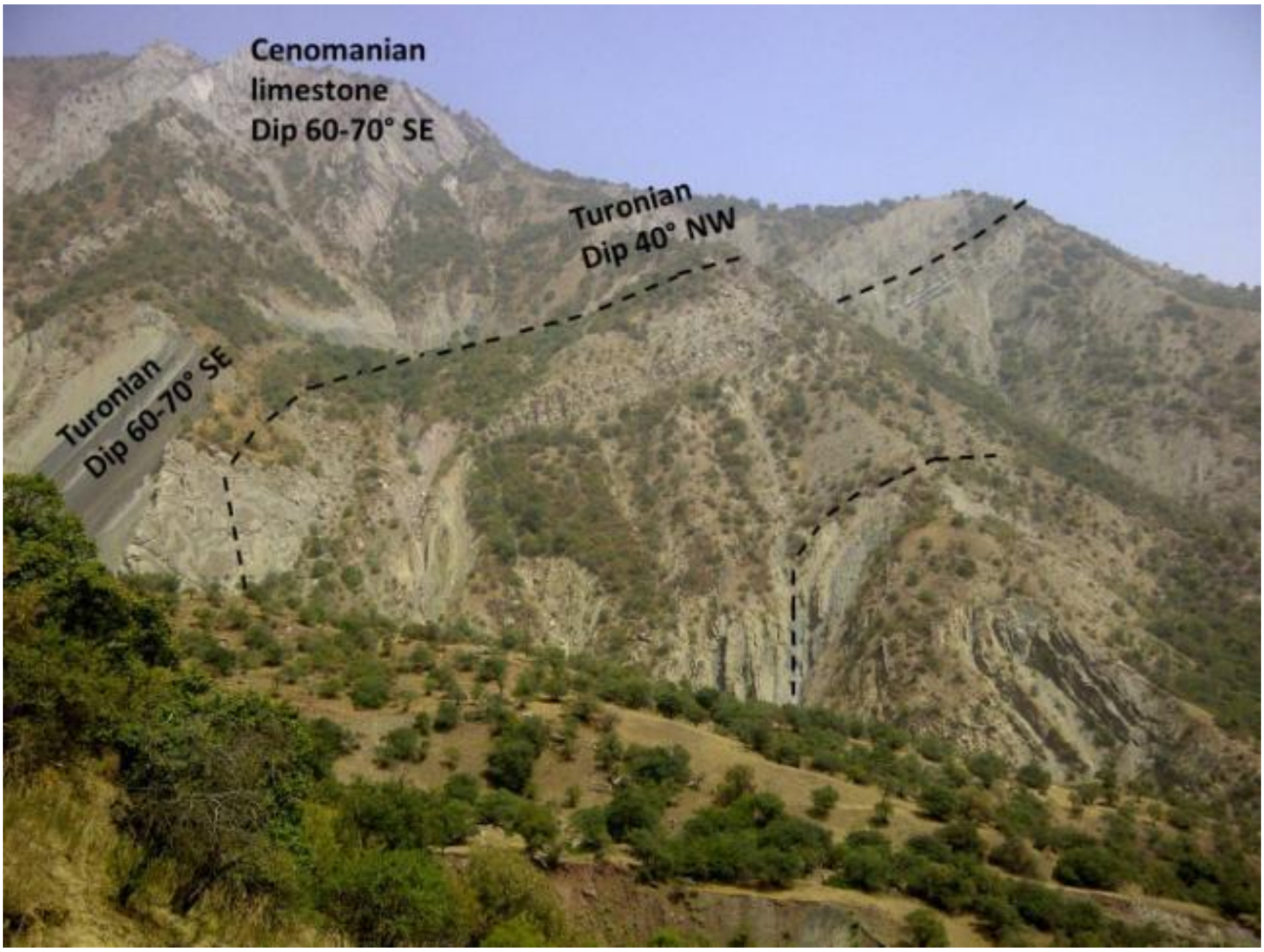

Illustration no. 37. Large scale folding in the left bank of Ararak stream.

- In the area of the eastern boundary of the atypical zone, field observations suggest that ductile deformation, as tight bending, is involved in the apparent senestral offset.

- The morphology of the wide flat area in the RB is complicated by numerous topographic depressions. They can be elongated parallel to the bedding, ENE-WSW (Illustration no. 38) but also of round shape. Their width is very variable, from a few meters to more than 100 m. The small sinkholes are very similar to those known in karst areas. The finding of 65 m thick gypsum/clay formation in borehole DZ2, near the permanent lake sheltered in one of these depressions supports the karstic dissolution origin of observed sinkholes.

Illustration no. 38. Sinkholes elongated parallel to bedding at the eastern part of the high flat.

- Seismic refraction investigations were carried out in order to estimate the thickness of overburden and to approach the characteristics of the bedrock by the variation of elastic wave velocity. The results confirmed the thickness of thick clayey overburden on the high flat area. Ionaksh Fault, in its overturned position (dipping NW), is well distinguished on the geophysical sections.

- The most significant anomaly outlined by microgravimetry measurements in the center of the investigated area has been interpreted as a low density mass reaching maximum depth in the order of 120 m. Its nature, either evaporitic mass (diapir?) or very deep sink area with clay fill, is uncertain. Irrespective of the actual nature, the base of the anomalous mass lies at least 200 m above the dam crest level, so that it is of little concern for the project.

Based on the available, previous and recent data, the geological setting of the atypical zone in the right bank is a result of tectonic deformation, as opposed to successive massive landslides and superficial creeping processes. The tectonic deformation could be related with décollement at evaporite layers located within the Upper Cretaceous sequence. One possible interpretation of the field observations is proposed in Illustration no. 39.

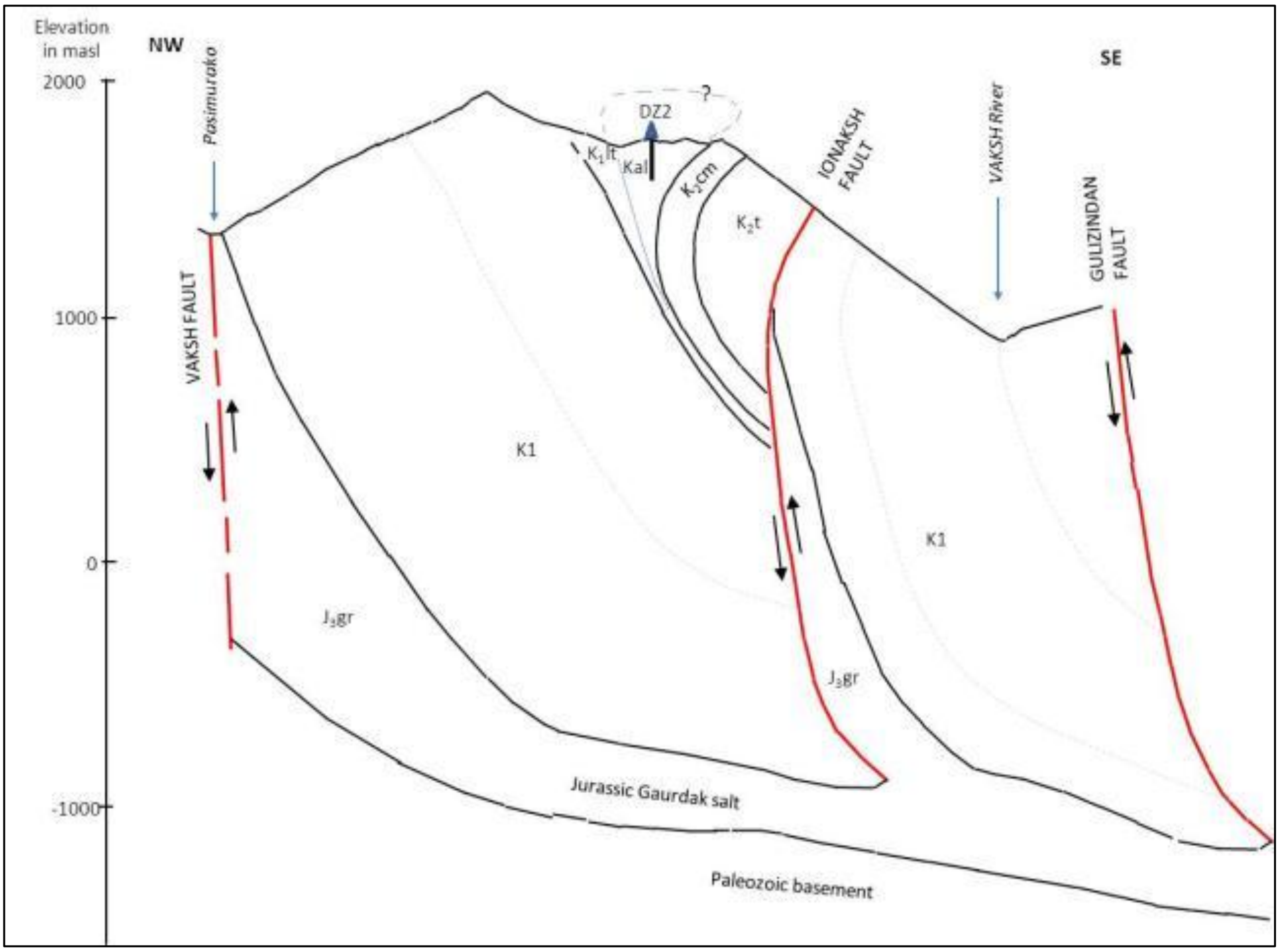

Illustration no. 39. Right Bank interpretive cross section, view from the SW.

Illustration no. 40 below shows, at small scale, a tight asymmetric bubble wrap fold the core of which is very similar to the fold core in the interpretative section.

Illustration no. 40. Left bank of Ararak stream. Tight folding in Coniacian layers.

This interpretation cannot pretend to reproduce accurately the reality, considering the complex setting and the paucity of the subsurface investigations. Nevertheless, it integrates field evidence of complex folding at large and at small scale, putting forward the model of tectonic deformation to explain the geological setting of the atypical area.

Superficial processes such as karst dissolution, sinking and landslides also concur to the reshaping of the slopes in the atypical zone. As discussed above, an ancient landslide is visible in the central part of the slope between 1700 m and the river.

The new interpretation implies two important corollaries:

- The overturned Mesozoic sequence is not a consequence of dragging by ancient landslides but of tectonic deformation. In the case of landslide dragging, the kink zone is a weak zone. Provided that the structural bending lies deep in the slope, as assumed at this stage, the tectonic origin is considered to be more favourable for slope stability.

- The NE boundary of the atypical zone (initially fault no.24), would correspond to tight bending as opposed to a sharp discontinuity or fracture zone. In detail, the setting can be complex, combining bending of the more plastic layers (argillite/gypsum) and brittle deformation of the more competent layers (sandstone). The nature and characteristics of this boundary are important for the layout and design of structures in this area. It can be concluded that, even if the bending is aligned with a fracture zone of tectonic origin, this could have the same characteristics as Fault #35, which the spillway tunnels are already designed to cross. In any case, additional investigations and monitoring are compulsory in order to provide reliable input data for the final design. Finally, it is highlighted that this issue can be regarded not as feasibility but as a design topic.

4.3. Rock falls

Even on slopes which are stable at large scale, rock falls are very frequent. During rain falls, they occur systematically. Based on the joint pattern, the size of the blocks varies mainly in the range 0.3 – 2 m. This is already considerable, but larger unstable rock masses are observed locally. The rock falls are a threat for the safety of the personnel and can sometimes cause damages to the structures. Standard mitigation measures are recommended in order to prevent such events: cleaning of the most unstable blocs, support with rock bolts, anchors, wire meshes.

5. Engineering geology

5.1. Weathering

At surface, differential weathering and erosion are obvious, especially for alternant sandstone and siltstone in Lower Cretaceous series and alternant shales and limestone or sandstone in Upper Cretaceous series. The layers of hard rocks (sandstone, limestone) form unstable ridges and this is one of the reasons of very frequent rock falls at the dam site.

Owing to the steep slopes, the products of rock weathering are progressively washed out, and the fringe of weathered rock is thin. Weathering only penetrates deeper along the open fractures.

Among the rock types, mudstones of Obigarm formation were reported to deteriorate fast after exposure. Fissures would develop within 8 to 12 hours and penetrate up to 0.5 m into the rock mass within one day. They also exhibit slaking in the surface exposures and the turbidity produced by some wetted samples would indicate the presence of dispersive clays.

Despite the sensibility to weathering, it is estimated that the mudstones are hard to excavate below 0.5 to 1 m. As for the mechanical behavior in the long term, they could be prone to softening and loss of strength.

Among the other rock types, the Jurrasic reddish mudstones, sheared and mixed with gypsum, overlying the salt wedge, but also the shales of the Liatoban and Turonian formations are probably the most sensitive to weathering and prone to softening.

5.2. Fracturing

At large scale, the bedding planes and the fractures of the S4 family form the most persistent and conspicuous discontinuities. These discontinuities have mainly planar surfaces. At small scale, the rockmass is affected by 3 or more joint sets of various directions.

The overall fracturing degree is high to moderate. In the zones of high fracturing density, the size of the blocks varies between 15 and 40 cm, it can reach up to 2 m in zones of moderate fracturing.

Accordingly, the rock mass is blocky to very blocky, with relatively well interlocked blocks. The interlocking is reflected in the steepness of the slopes.

Based on available data, the filling material for the large majority of the joints is gypsum, as very thin coatings. The clay fill was mapped in very rare occasions. The presence of gypsum, remobilized in high pressure zones and recrystallized on open joints is not surprising, given the amount of gypsum layers in the sequence. As for the clay fill, it could be observed during recent inspection of some galleries, that it is also present on numerous joints and in particular on the most persistent joints.

5.3. Hydrogeology

At the Technical Design stage, several hundreds permeability tests have been carried out. Given that the methodology was different from the current Lugeon test standard, it is difficult to assess the results in detail. However, the overall conclusion of those results in [1] shows globally that the rock mass at Rogun HPP has generally low permeability. Consequently, the error on correlation with current standards would not change the conclusions significantly.

The permeability values were integrated as a major parameter for the geotechnical zoning, discussed in the following paragraph. The typical values for the rock mass classes, from surface to depth, are summarized below:

- Class I, from surface to 7-40 m depth: 1.8 to 2.2 l/min per 1m under 1m water column, approximate equivalent 20 LU
- Class II, 15-25 to 40-50 m thick below Class I, 0.12 to 0.3 l/min, approximate equivalent 1 to 3 LU
- Class III, from 20-80 m depth to 60-140 m depth, with permeability in the range 00.2 to 0.08 l/min (0.2 to 0.8 LU)
- Class IV, with upper boundary at 60-140 m depth, permeability lower than 0.1 LU.

As reported in [1], high permeability values were recorded even at depths corresponding to Class IV rock mass, probably related with local open fractures.

The anisotropy commonly related with the sedimentary sequences has been little considered in this first assessment. Such anisotropy could be high in alternant sandstone / mudstone layers. However, at Rogun HPP site, the high horizontal stresses probably neutralize much of the anisotropic effect. Roughly, this effect is estimated around one order of magnitude and concentrated locally.

The results of recent permeability tests indicated the heterogeneity of the rock mass. In boreholes WRB1, which crossed principally sandstone, tested intervals yielded permeability values in the range 15 – 25 LU (Table no.7).

Prior to this TEAS, the number of piezometers in the dam foundation was very low, most of them being located near the Ionaksh Fault. A number of 19 piezometers have been installed during the present study. The analysis of the results showed that:

The groundwater aquifer flows generally towards the river. Due to steep slopes and rocks generally weakly permeable, the infiltration ratio is low, probably not exceeding 10% of the rainfall.

During summer when the river level is increased, the river charges the aquifer in the abutments, following a gradient of about 3%.

Table no.7. Summary of permeability tests results in borehole WRB1

Stage	Effective Pressure (in bars)	Permeability (in LU)
60-65	13	25
65-69.9	14	25
89.9-74.9	15	23
74.9-79.9	17	20
79.9-84.9	16	21
84.9-90	18	18
90-95	17	19
95-100	18	19
100-105	11	16
105-110	20	15

The infiltration, hydraulic conductivity and groundwater gradient are generally similar in both dam abutments. However, due to the presence in the Right Bank of gypsum and limestone in the Upper Cretaceous layers, the hydraulic conductivity is estimated to be slightly higher in this bank.

The particularities of the aquifer of the Ionaksh Fault, as well as the issues related with the salt dome are discussed in a separate report.

5.4. Engineering geology zoning

According to the original geotechnical zoning, 4 classes of rock mass are distinguished:

- Class I corresponds principally to the upper fringe of the foundation, where mudstones are weathered and clay infill is found on joints in sandstone. The thickness increases upwards from 7 m to 40 m. It is also characterized by:
    - intensive fracturing
    - high permeability (equivalent of approximately 20 LU)
    - uniaxial compressive strength: 10 to 90 MPa
    - low deformation modulus (1.2 – 2.5 GPa)
    - low seismic wave velocity, in the range Vp=1.6 – 2.2 km/s.
- Class II rock underlie the Class I. The thickness varies from 15-25 m near the river level to 40-50 m in the upper slopes.
    - Permeability reduced to 1 to 3 LU
    - UCS: 110 MPa for sandstone, 60 MPa for siltstone

- Deformation modulus of the rock mass: 1.5 GPa for the fractured zones or tectonic lenses, 3,5 to 4.5 GPa for standard rock mass.

- Class III rock and Class IV correspond to the deep seated, slightly weathered and fractured rock mass. The upper boundary lies at 20 to 80 m below the surface for Class III and at 60 to 140 m for Class IV.
    - Bloc size is in the order 15 to 25 cm
    - Permeability significantly less than 1 LU, but open fractures with high water inflow are still found.
    - Deformation modulus of the rock mass: 2 GPa for the fractured zones or tectonic lenses, 4 to 8 GPa for standard rock mass.
    - Velocities Vp can exceed 4 km/s, in Class IV.

5.5. Dam foundation

The excavations of the impervious core trench had already started, but during the long stand-by period, the right bank side has been partially filled by shallow slope instabilities. Meanwhile, the exposed rocks were affected by additional weathering. These excavations will have to be resumed anyway and they will have to be ripped down to the level where the great majority of discontinuities are tight.

The impervious core is located judiciously in the mudstones of the Lower Obigarm formation. This thick sequence of mudstone layers has naturally low permeability, in particular in the Class IV type of rock mass. For this reason, the proposed depth of the grout curtain (Illustration no. 41) seems, at this stage, adequate. On the contrary, it is estimated that the lateral extent, especially in the Right Bank, cannot be designed before determining the characteristics of the boundary of the atypical zone and carrying out additional permeability tests.

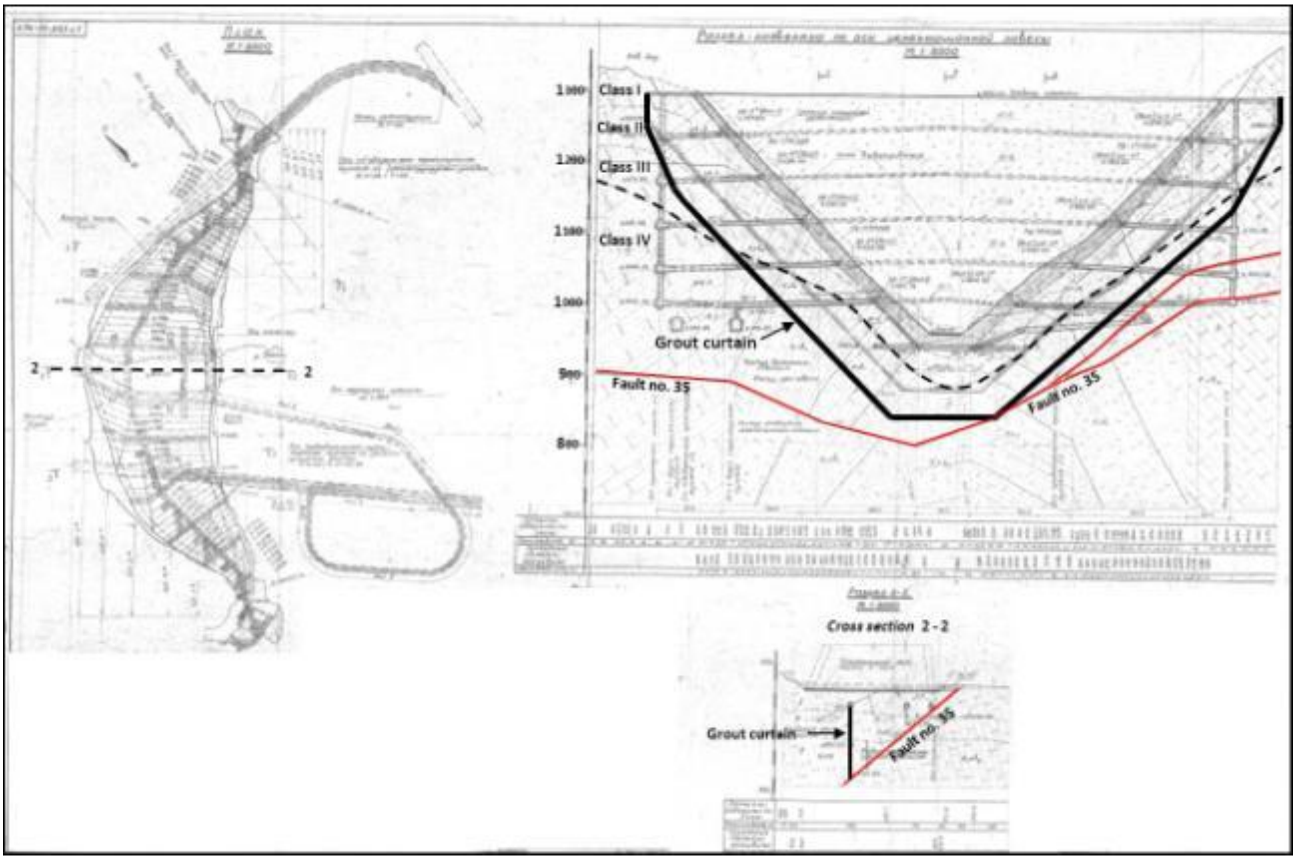

Illustration no. 41. Grout curtain extent (in [1]).

5.6. Power House and Transformers Hall caverns

- Location

The location of the two caverns has been selected so that to be hosted principally by sandstones and subordinately by siltstones. This choice is naturally judicious, and measured convergences showed actually showed that the deformability of siltstones is significantly higher than that of the sandstones.

The location lies deep within the slope, away from the superficial influence and within the zone of steady in situ stress. One of the matters of concern, also pointed out in [13], is the proximity of the zone of influence of Fault no.35.

- Joint pattern

In 2009, a detailed analysis of the joint pattern has been carried out ([13]). This analysis was based on existing including structural mapping carried out in 1978-1980 in short branches driven from exploratory gallery no 1030 near the location of the caverns of the power house and of the transformer hall. The attitude, persistence and conditions of joints have been integrated in this analysis. The main findings of this study are recalled below.

<u>Joint pattern in siltstones of Lower Obigarm Formation</u>

The siltstones of Lower Obigarm Formation form 30% of the host rocks of the Power House cavern and 20% of the pile between the two caverns. Strong convergence has been measured on the walls comprising these rocks.

The joint orientation data was recorded in the branch excavated from station 0+287 of gallery #1030, with azimuth 226° and a length of 10 m. The following synthetic joint plot (Illustration no. 42) is based on 718 readings.

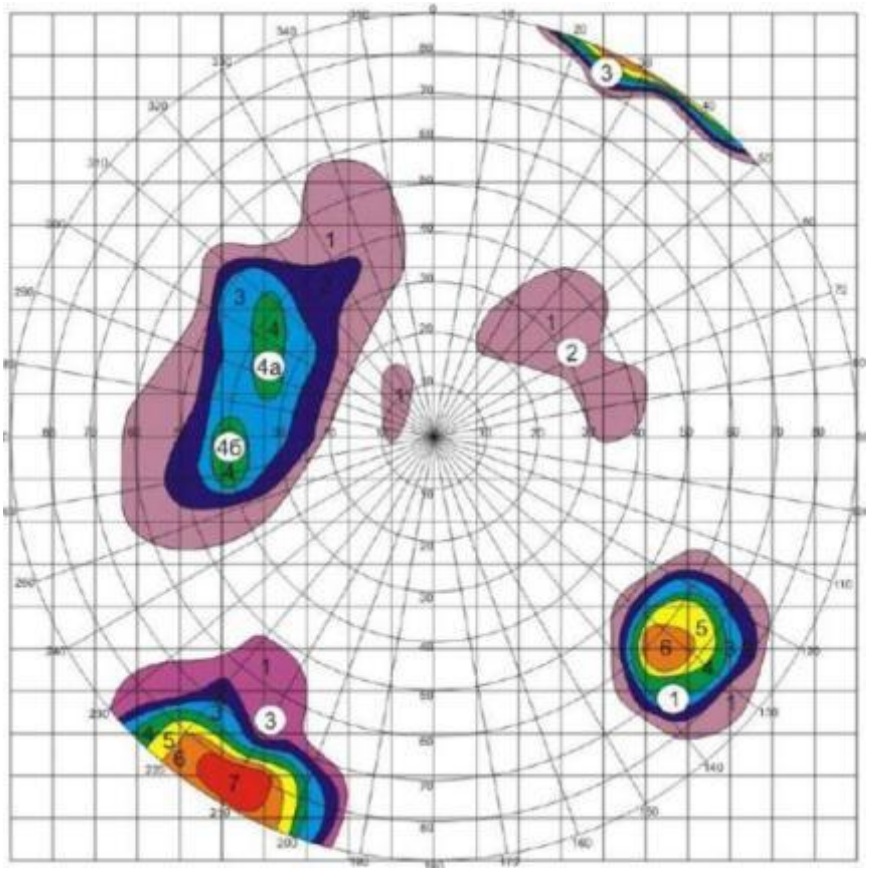

Illustration no. 42. Joint pattern plot in siltstones of Lower Obigarm formation.

The characteristics of the joint families are summarized in Table no. 8.

Table no.8. Joint sets and their characteristics in Lower Obigarm siltstones.

Joint system	Dip azimuth / Dip angle	Width (mm)	Persistance (cm)	Filling
S1	115-145° / 50-85°	0.1-0.2	20 to >3000	Gypsum, clay only for the most persistent
S2	35-92° / 19-41°	0.1-2.25	10-50	Gypsum
S3	195-232° / 52-90° 15-50° / 80-90°	0.1-0.5	10-160	Gypsum
S4a	280-350° / 25-60°	0.1-0.5	10-90	Gypsum
S4b	245-280° - 22-62°	0.1-0.95	15-115	Gypsum

Based on the orientation of the joints, the analysis highlighted the following potential unstable wedges (Table no.9):

Table no.9. Potential unstable wedges in Lower Obigarm siltstones.

Joint systems	Orientation of the edge	Unfavorable location
S1 / S4a	49° / 18-22°	Downstream wall
S2 / S4a	30-40° / 28-30°	Downstream wall
S1 / S2	50-60° / 26-28°	Downstream wall
S1 / S3	130-200° / 45-48°	Upstream wall

Joint pattern in sandstone of Upper Obigarm formation

The sandstones of Upper Obigarm form much of the foundation of the two caverns.

The data was recorded in the branch excavated from station 0+540m of gallery #1030, with azimuth 223° and a length of 10 m. The synthetic joint plot (Illustration no. 43) is based on 372 readings.

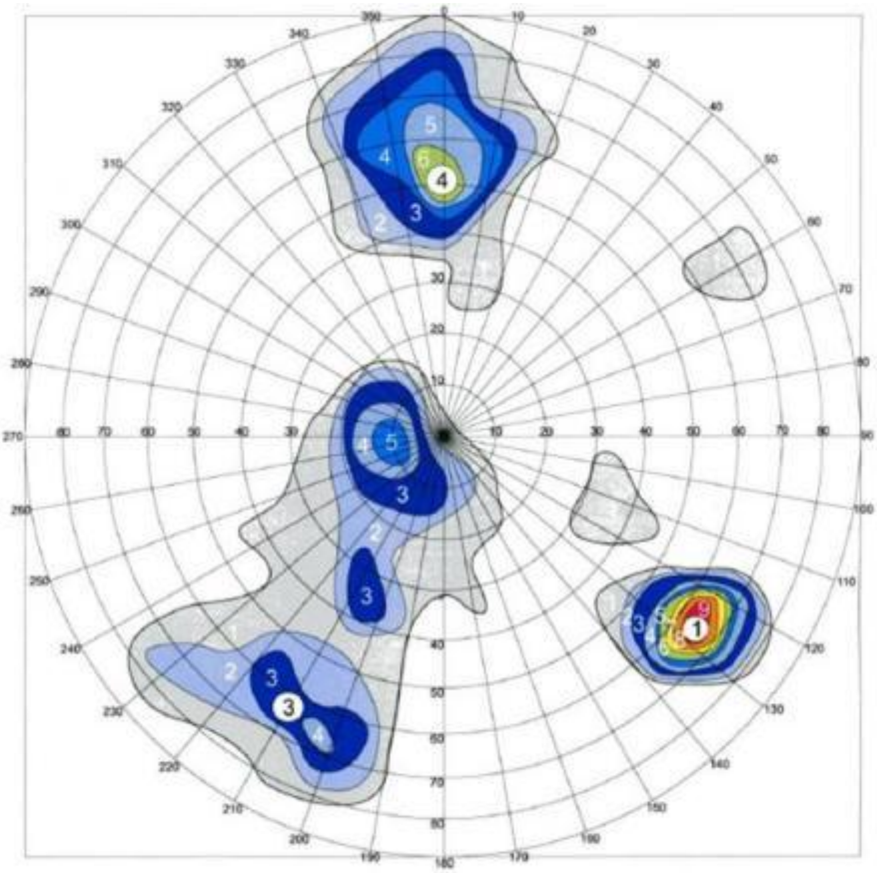

Illustration no. 43. Joint pattern plot in sandstones of Upper Obigarm formation.

Table no.10. Joint sets and their characteristics in Upper Obigarm sandstones.

Joint system	Dip azimuth / Dip angle	Width (mm)	Persistance (cm)	Filling
S1	110-140°/ 49-74°	0.1-0.25	5-140	Gypsum, very rare clay
S2	29-70° / 52-90°, 80-90°	0.2-0.4	10-60	Gypsum
S3	184-265° / 44-90°	0.1-0.45	5-70	Gypsum
S3a	160-278° / 26-50°	0.1-0.3	15-105	Gypsum, very rare clay
S4	310-360°, 0-29° / 29-90°	0.1-0.4	10-150	Gypsum, very rare clay
S5	Dip<25°	0.1-0.3	10-150	Gypsum, very rare clay

Potential unstable wedges are presented in Table no.11:

Table no.11. Potential unstable wedges in Upper Obigarm sandstones.

Joint systems	Orientation of the edge	Unfavorable location
S1 / S4	55° / 30°	Downstream walls
S2 / S4	358° / 52°	Downstream walls
S3 / S4	293° / 20°	SE end wall
S1 / S3	65° / 58°	Upstream walls

- Monitoring data

The main engineering geological aspects related with the caverns are highlighted by the monitoring of deformations of the walls. The main findings are:

- In 1999, the convergence of the walls in the PH cavern reached 120-160 mm in sandstone and 300-330 mm in siltstone. The overall convergence was 280 and 630 mm, respectively.
- Up to 2002, the convergence continued with rates of 1 mm/year for sandstones and 15 MM/year for siltstones.
- During inspection of the cavern in 2009, in the area of units 5 and 6, the concrete lining of the downstream wall between elevations 977 and 985 exhibited a series of cracks parallel with the joint set S4.

These observations show: (i) the low strength of the siltstone rockmass and (ii) the impact of joint set S4.

- Additional investigations and testing

Following the assessment of the powerhouse and transformers hall caverns complex, a possible set of stabilization measures was identified. However, the parties involved in the project agreed that further investigations of the rock mass parameters have to be performed, in view of the final design of the stabilization works. Thus, specimens of the siltstone rock mass surrounding the powerhouse cavern were collected, through Triple Core Barrel (TCB) Samples and Double Core Barrel (DCB) Samples. Also, cubic samples were obtained by using a saw machine.

The samples have been sent to rock mechanic laboratories, for performing tests including classification tests, triaxial compression tests, direct shear tests, triaxial multistage tests on saturated specimens and triaxial creep tests.

The tests are presently under finalization. According to a preliminary scrutiny, the results obtained so far seem to confirm the rock mass parameters adopted in the implemented 2D model of the Powerhouse complex.

5.7. Tunnels

Based on abundant data from investigations galleries and constructed tunnels, the types of rock mass and the geological structures have been already described in detail. At the present stage, the following aspects are considered relevant for the assessment of the geological conditions:

- The analysis of the disorders which affected the lining of existing tunnels
- The nature of the NE boundary of the atypical zone

➢ **Disorders in the lining of the tunnels**

Several disorders in the area of the inlet portals can be imputed to the weakening of the rock mass due to proximity of the Ionaksh fault zone.

In 2009, several shear fractures, dipping toward the inlets, could be observed in the concrete lining of both diversion tunnels: up to 70 m from the inlet in the Diversion Tunnel I and up to 90 m from the inlet in Diversion Tunnel II (Illustration no. 44).

Illustration no. 44. Shearing of concrete lining and opening of construction joint in Diversion Tunnels I (above) and II (bottom).

In the local geological setting, the dip direction suggests that the shears can be caused by gravitational sliding on S4 discontinuities, parallel to fault no.35. According to [13], a significant weak zone, of increased tectonic deformation and fracturing, would coincide with the 'tectonic lens' squeezed between fault no.35 and discontinuity no.111. The extrusion rate of this wedge would be twice higher than movement along fault no.35, averaging 2.1 mm/year over 3 years. Both tunnels cross the weak zone of fault no.35, which is related with major disorders in DT I at chainage 7+77 – 8+25.

The collapse of the lining occurred in the DT II at chainage 4+27 – 4+76 does not seem directly related with any identified fault or major discontinuity. The tentative explanation in [13] involves anomalous high stress levels, concentrating tectonic fractures in Kiziltash sandstone near the contact with Lower Obigarm siltstones.

These incidents in different geological contexts pointed out to the need of investigating the thickness and condition of the lining by means of geophysical investigations. Such investigations have already been carried out at selected locations. They should be extended for the entire development of the tunnels.

- **Nature of the NE boundary of the atypical area**

The data regarding the NE boundary of the atypical zone is not sufficient for an accurate assessment of its nature and characteristics.

Interpretation of aerial images suggests that it might correspond to a fracture lineament, while field observations suggest that surface rupture would not affect, at least, the more plastic layers. The same field observations suggest the attenuation of deformation from the upper slopes to the river valley.

Based on field observations, the deformation along this lineament would be lower than the rupture across fault no.35. Consequently, if tunnels are designed to cross fault no.35 they could as well cross this boundary. If the design considers this alternative, the excavation of an exploratory gallery at the designed elevations is compulsory, in order to inspect the boundary lineament and to install monitoring devices.

6. Geological conditions in the Reservoir area

6.1. Introduction

At the Technical Project stage [1], the investigations of the reservoir area included:

- engineering geology surveys at 1:25 000 scale (300 km^2) and 1:5 000 scale (5 km^2)
- drilling: cumulative 220 m
- exploratory pits: cumulate 70 m

Regional geology features are discussed in chapter 2 of this report. It is recalled that the reservoir stretches over a length of 70 km along the Vakhsh River valley, which runs between the two regional faults, Illiak-Vakhsh in the left bank and Gissar-Kokshal in the right bank.

The engineering geological classification of terrains in the reservoir area are showed on Drawing 1079-03-183. The main features having potential influence on the design are discussed below.

6.2. Evaporite masses and karst

In the left bank of the river, some foothills of the Vakhsh Ridge are formed by evaporite rock masses aligned on the Vakhsh Fault. The visible part of these rock masses, with volumes in the order of several million cubic meters or more, comprises principally gypsum, but the presence of salt at depth cannot be excluded. They were also identified in the valley of Passimurakho, which is the extension along strike of the Vakhsh Fault lineament. A salt diapir would underlie the interfluve between Passimurakho and Obi-Djushon valleys.

All these occurrences exhibit intensive karst dissolution features. Dissolution and formation of sinkholes can be accompanied by superficial landslides. Such processes already lead to sinking of inhabited areas in the city of Rogun, causing damages to buildings (Illustration no. 45).

Illustration no. 45. Surface sinking causing damage to the buildings.

6.3. Seismic scarps

Evidence of Upper Quaternary and modern age earthquakes have been identified in the reservoir area. Analysis of aerial photographs carried out in [11] highlighted the presence of numerous features interpreted as seismic scarps spread over a segment at least 15 km long at the foot of the Vakhsh Ridge. Some of the typical ones are recalled below:

- between Talkhakchashma and Roguni-Bolo, distinct scarps (or steps) reaching several meters high and shifting recent streams (Illustration no. 46)

Illustration no. 46. Recent thrusts (arrows) near the foot of the Vakhsh Ridge in the area of Liabidar village.

- between Tagikamar and Khodzhaalisho streams, a 15-20 m high scarp has been interpreted as outburst of a basal surface of a large rockslide, the slope above the scarp showing features of anomalous displacements. The frontal part of the slide would coincide with the thrust fault plane (Illustration no. 47). Long arrows indicate the thrust bench, short arrows indicate sliding features. Interpretive cross section AB is presented in the lower part of the illustration. The analysis concluded that the rockslide, with a volume roughly estimated at 10 to 15 million cubic meters, could be (re)activated as water level rises above elevation 1250m.

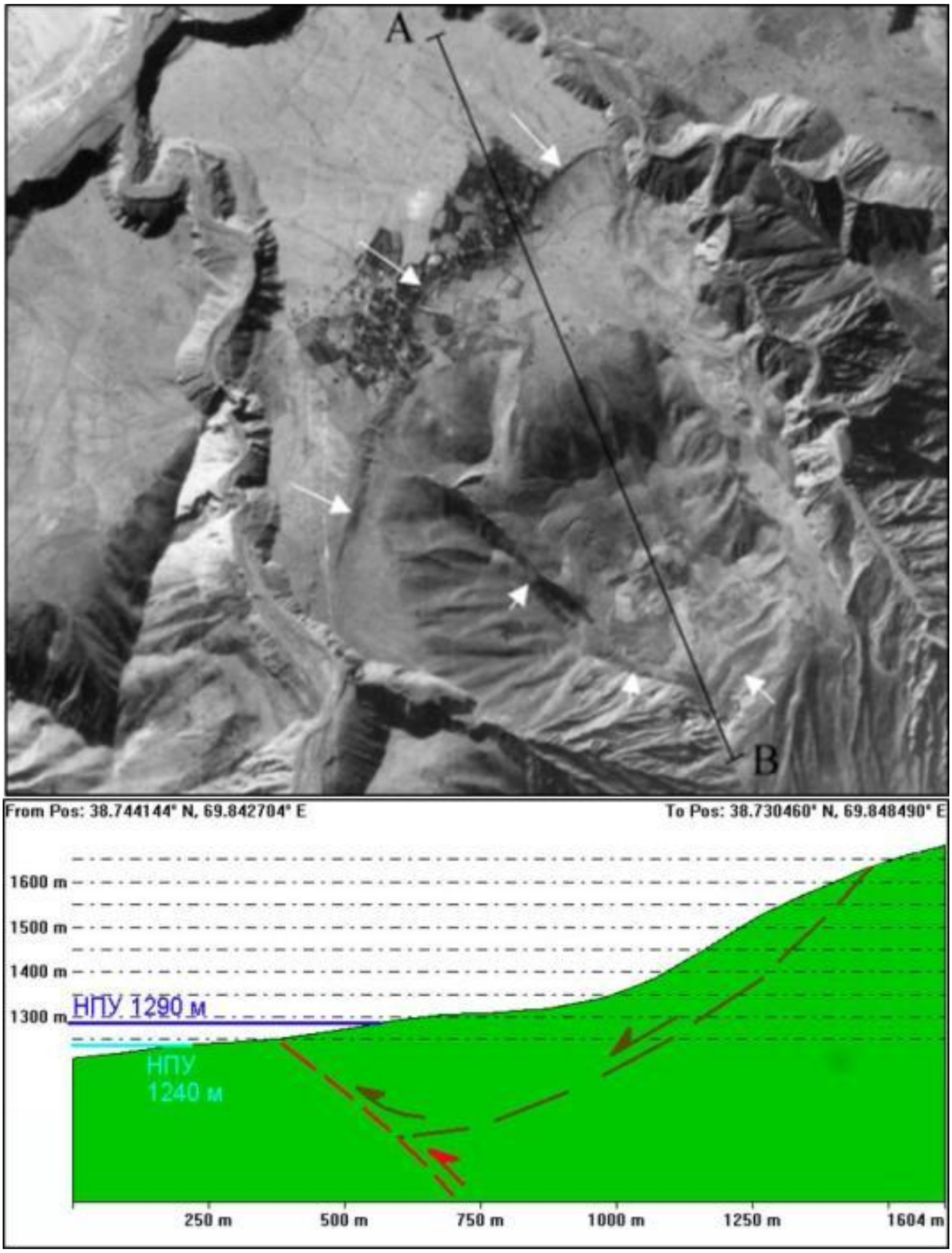

Illustration no. 47. Recent thrust and assumed landslide near the foot of the Vaksh Ridge between the Khojaalisho and Tagikamar valleys (grouped figures from [11]).

- Westwards from Talkhakchashma village, a young scarp crosses the Tanakba gully. No scarp is visible in the continuity of this lineament in the right bank of the Vakhsh River (Illustration no. 48). Landslides and karst processes occurring in the valley of Passimurakho could conceal the virtual evidence.

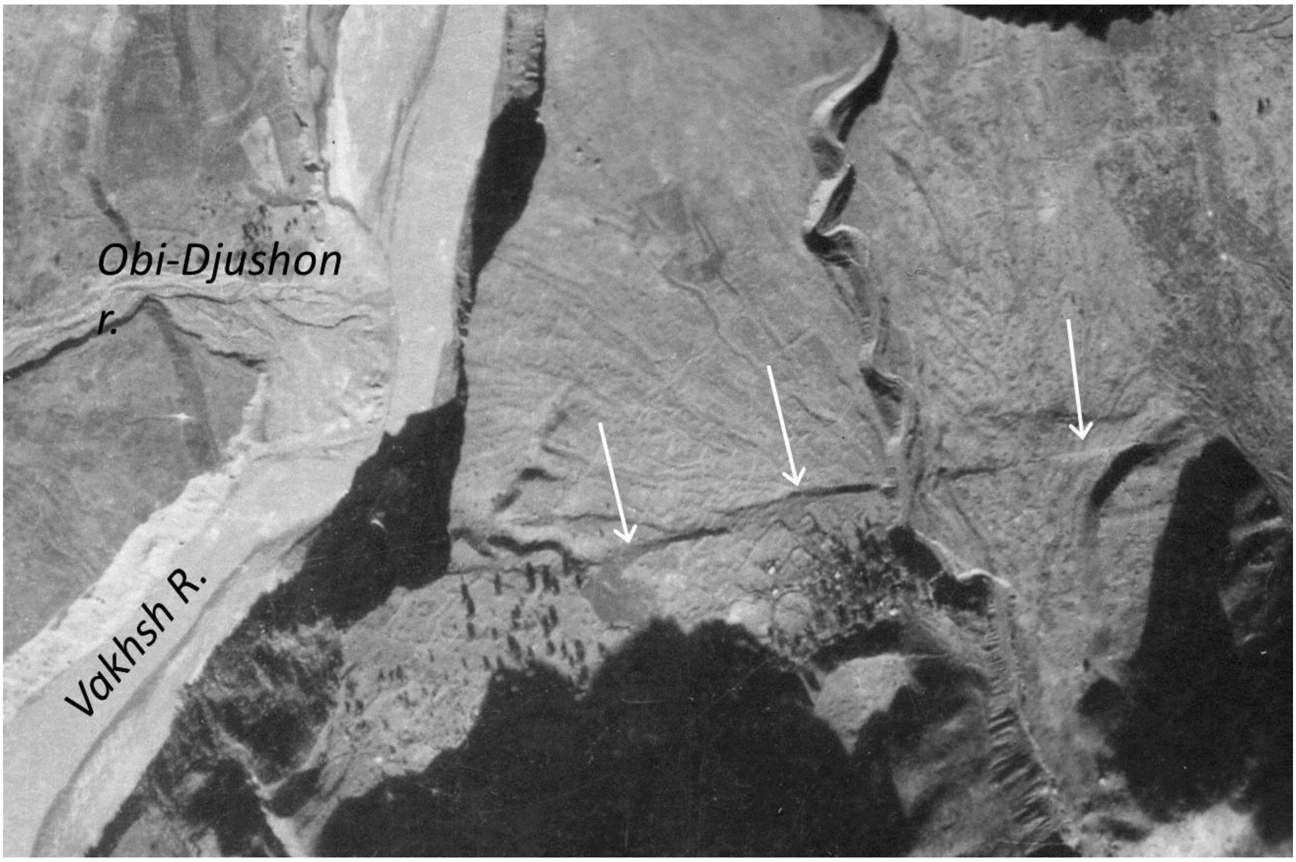

Illustration no. 48. Recent thrust rupture at the foot of the Vakhsh Ridge, crossing Tanakba gully.

The recent scarps discussed in [11] are most likely of seismic origin. The question could be raised if some of them, especially the less persistent or isolated, could result from upward creeping of evaporite.

6.4. Slope stability

According to [1], landslides are very common throughout the reservoir area. The following types were distinguished:

- Landslides of Quaternary cover deposits of up to 1 million cubic meters

and

- Landslides involving the Mesozoic rocks, which can reach several hundreds of millions of cubic meters for the major ones and 10 million cubic meters for the common ones. Triggered by dissolution of salt at the toe of the slope, the landslides would mostly occur in the left bank, along discontinuities with attitudes similar to the F#35, dipping 40°-60° towards the valley. Based on the observation that the overall structure of the rock masses is well preserved, it is inferred that the landslide developed at low rate, similar to creeping. The two landslides in the right bank of Passimurakho, with estimated volumes of 20-30 million cubic meters are given as examples (Illustration no. 49).

Illustration no. 49. The downstream landslide in the right bank of Passimurakho

According to recent evaluation of slope instability in the reservoir area (in [11]), the most significant potential slides would be:

- in the canyon, where rockslides were identified in both banks
- the right bank of the reservoir, near the mouth of Lugur river, with estimated potential volume of 1 million cubic meter
- on the left bank of the reservoir, between Tagikamar and Khodzhaalisho gullies, with estimated potential volume of 10-15 million m^3
- on the left bank of the reservoir, near Khufak village, where the base of a rockslide slope would be flooded for reservoir level FSL=1290m.

6.5. Seepage from the reservoir

Vakhsh River being the regional drainage base level, lateral seepage from the reservoir can be excluded.

Gulizindan Fault, which bypasses the dam on its left side, crosses through the Vakhsh Ridge and connects the reservoir with the Vakhsh valley downstream of the dam. It would therefore be the main potential waterway for leakage from the reservoir. As recalled above in this report, the results of geological and geophysical investigations carried out in the right bank of the Obishur valley indicated that the fault is watertight. Taking into account this condition, it has been considered that a 1 km grouting gallery running along the Obishur valley would be an adequate measure to prevent leakage from the reservoir along this fault.

It is recommended to implement these measures and to excavate the gallery in anticipation of the impounding.

7. Hazards related with the geological conditions

7.1. Salt extrusion and dissolution

The issues related with the salt dome along Ionakhsh Fault are discussed in a separate report.

7.2. Seismic and aseismic deformation

At Rogun HPP site, the regional tectonic stresses are adjusted by deformation which is both seismic, i.e. involving sudden co-seismic rupture, and aseismic, mainly by creeping probably related with regional tectonic stress but also with extrusion from depth of salt and gypsum. This creeping, which is permanent, takes place principally on the main faults, namely Ionakhsh and Fault no.35, where monitoring was implemented for measuring the deformation rate.

Based on the monitoring data and the update of the seismotectonic analysis, the following values are available for the design:

MCE co-seismic displacement

- Ionaksh and Gulizindan faults: 1m
- Fault no.35: 0.1-0.2 m

Creeping slip rates

- Ionaksh Fault: 1.8 mm/year
- Fault no.35: 0.7 mm/year
- Uplift of tectonic bloc between Ionaksh Fault and Fault no.35: 2 mm/year

The underground workings are crossed by Fault no.35 and other major discontinuities with similar attitude. They are well individualized and identified by mapping. Special protection measures are at study and have to be designed at crossing all major discontinuities with evidence of significant shear. Nevertheless, two observations call for refining the kinematic model:

- The shearing and damage of the support of diversion tunnels occurred at different locations. Some of them involve indeed S4 discontinuities, either as gravitational sliding at the inlet portal area (as discussed below), or as tectonic displacement on fault #35. Other damages occurred in different settings and the explanation assumed weak zones related with fracturing degree and major lithological contact between rock types with contrasted mechanical behavior.
- Offset of decimetric order along subhorizontal or shallow dipping discontinuities has been observed at several locations. Often apparent, the relationship with S4 faults could not be systematic. These offsets tend to show that the adjustment of tectonic stress is partially transferred by diffuse deformation to discontinuities different from the main faults. Shearing of these subhorizontal discontinuities is not in contradiction with the current orientation of regional stress.

If diffuse decimetric shearing related with creeping adjustment of tectonic blocs is confirmed, the location of shearing of underground structures would be unpredictable and reinforced support measures would have to be extended to the entire development of the structures. It is recalled that the completion of the design studies in 2009 also concluded on the insufficient level of data to explain the incidents occurred in the underground workings.

Additional investigations are recommended to verify the cause of damages to support at all identified locations. Only if the cause is ascertained can reliable mitigation measures be designed. If necessary, the rock mass should be exposed for inspection and installation of monitoring devices. Monitoring of displacements along the main faults should be resumed and additional devices installed. In addition, monitoring should be extended to the major discontinuities showing offset which is consistent with present-day stress orientation. In this respect, the anomalous results obtained for the orientation of the principal stress components should also be verified by additional tests. Taking into account the complex tectonic setting, these tests should be also carried out at different locations into the abutments.

Formerly interpreted as a tearing-off landslide boundary, the NE boundary of the atypical zone could be crossed by spillway tunnels in some layout alternatives. Excavation of exploratory gallery and monitoring of deformation are compulsory in order to determine the nature and characteristics of this lineament.

7.3. Risk of landslide

Potential landslide risk has been identified in the following areas:

- Left Bank in the upstream part of the dam
- Right Bank downstream
- At several locations in the reservoir

Left Bank in the upstream part of the dam

This area includes the slopes above the diversion tunnels and water intake. Damage of lining already identified could be explained by gravitational sliding on such discontinuities. It is recommended to identify precisely the persistent joints which daylight on the slopes and to carry out stability calculations taking into account the effect of increasing pore pressure upon impounding and fluctuation of reservoir level.

Right Bank downstream

Based on available data and field observations, there is no evidence for the existence of unfavourable tectonic discontinuities which could cause massive structural controlled landslides.

Materials resulting from ancient instabilities are concentrated in the central part of the main slope, below the flat area (Illustration no. 50). These deposits could be progressively involved in future landslides, as shown already by the crown of the landslide initiated, most probably in the last years, in the frontal lobe. Without mitigation measures, the volume of this next landslide could vary between 100,000 and 500,000 cubic meters. Other landslide involving slope cover deposits can be expected. They are not considered a major threat for the feasibility but mitigation measures are compulsory to prevent the risk during construction and operation.

Illustration no. 50. Zone of ancient landslide in the central part of the slope. The arrow indicates the crown of recently initiated landslide.

Regarding the failure of rock masses, there is one major positive aspect, namely the favourable structural position of the bedding, which is by far the main discontinuity set. In addition, the bedrock includes numerous thick sandstone layers. Favourably oriented, they grant overall good strength to the entire sedimentary sequence and to the slope. As a result, the slope is relatively steep, approaching 1:1 over a height of several hundreds of meters. This slope can be expected to evolve by progressive instabilities of small scale.

The recent data showed that the geological setting results from slow, tectonic deformation. When compared with the initial landslide model, the present interpretation is more favourable to slope stability, taking into consideration that the rock mass is less damaged during slow deformation. In particular, the assumed bending of the layers due to dragging by landslides would form a weak zone where potential failure could be initiated.

The increasing of pore pressure locally within the ‘atypical zone’ cannot be discarded, considering that the following conditions characterize this area: (i) high inflow on the wide plateau, including karstic formations and (ii) heterogeneous underground flow which can be anticipated from the interlayering of highly and low permeable formations. Further investigations of the piezometric levels and of the permeability during the early stages of the construction will help designing adequate drainage measures which can reduce such risk considerably.

In order to detect and follow-up any slope movements in the atypical zone, 30 geodetic stations have been installed (including three older stations which have been rehabilitated). The targets have been scattered on the upper part of the slope below the plateau. Readings will be performed from 2 base stations located on the opposite bank (Illustration no. 51).

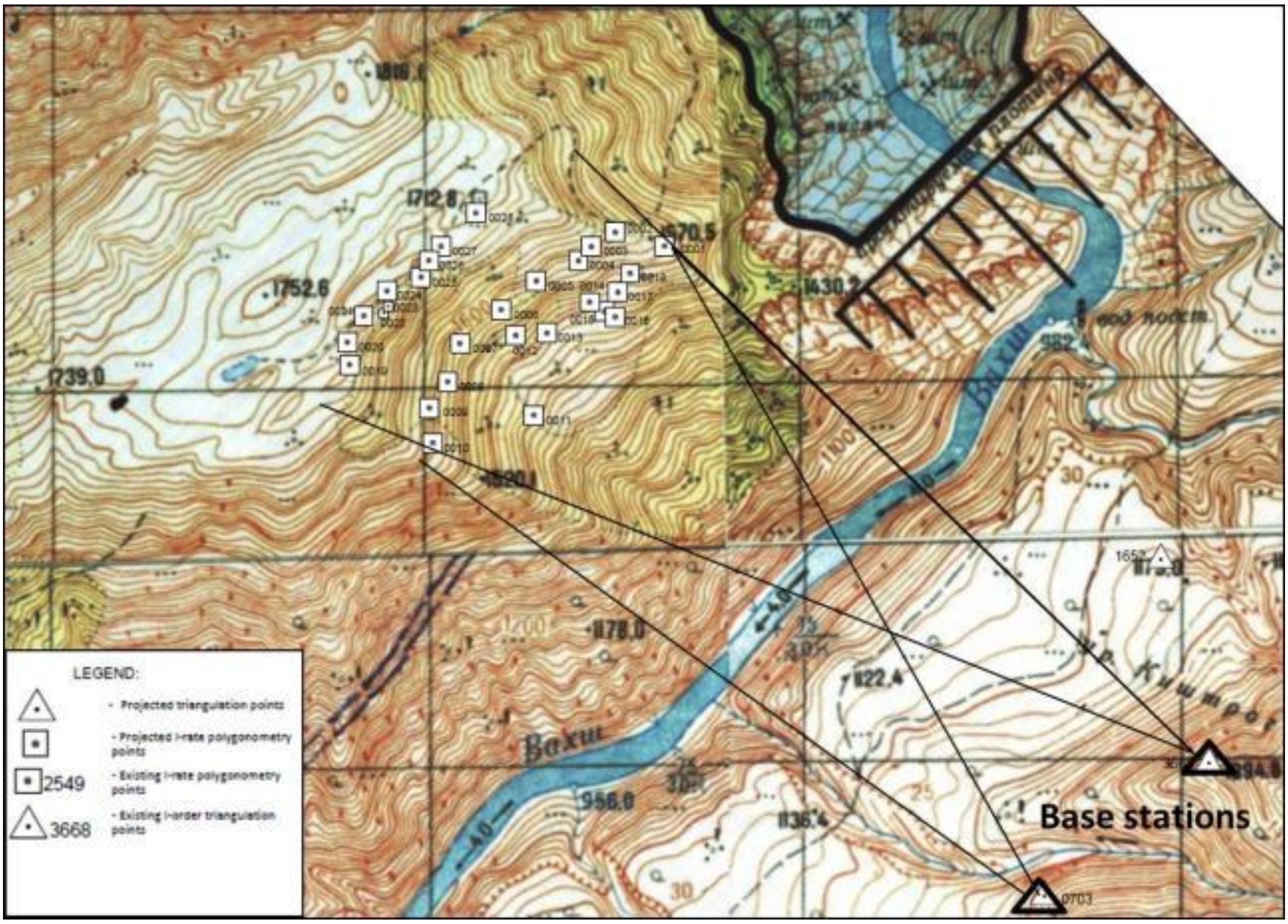

Illustration no. 51. Location of the geodetic monitoring system.

<u>Landslides in the reservoir area</u>

Numerous minor instabilities are anticipated during impounding. They have been thoroughly inventoried and discussed, most recently in [11] and [13].

Regarding the major instabilities, two cases can be distinguished: (i) reactivation of ancient landslides and (ii) triggering of landslides by dissolution of evaporite at the foot of the slopes.

The potential landslide on the left bank of the reservoir, between Tagikamar and Khodzhaalisho gullies, with estimated potential volume of 10-15 million m^3 belongs to first case. The evidence described in [11], has to be verified by investigations. The risk seems manageable, but only based on additional data can detailed impact be assessed and mitigation measures be designed.

Regarding the landslides triggered by dissolution of evaporite at the foot of the slopes, according to [1] such slides with large volumes were frequent in the past. The closest to the dam site are still developing in the right bank of the Passimurakho valley. Illustration no. 52 shows the extent of Jurassic salt at the foot of these slopes.

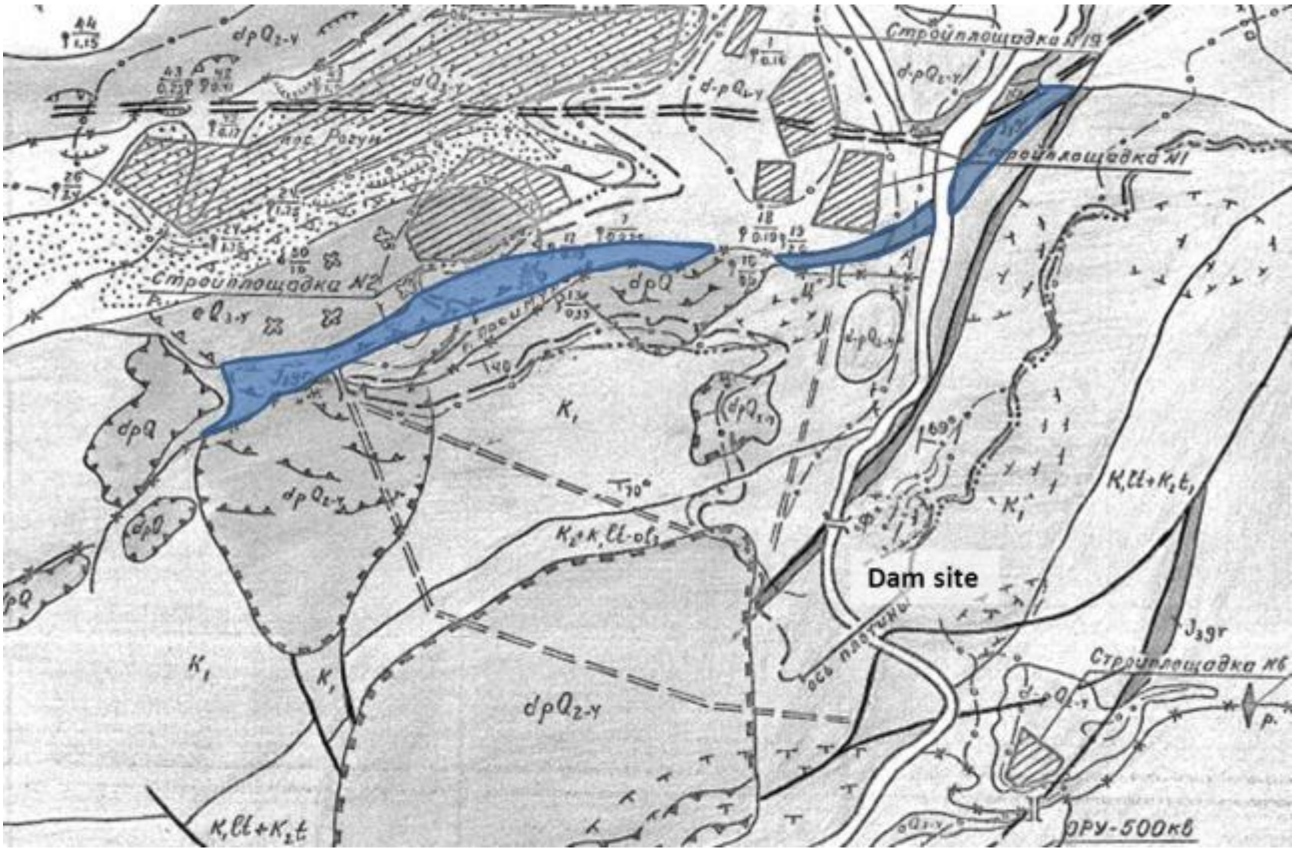

Illustration no. 52. Jurassic salt in the valley of Passimorukho.

Further upstream in the reservoir, the evaporite masses outcrop at elevations higher than the reservoir. However, their lower part still lies below the reservoir level, covered by alluvial deposits. The probability of occurrence of massive sudden landslides seems low. Even if in the past the processes were slow, the impounding and the fluctuations of the reservoir level will mark rapid changes of the natural conditions. Consequently, it is recommended to assess the response to these changes, in particular for the slopes in both banks of the Vakhsh River near the entrance in the canyon of the dam site, where salt occurrence was identified.

The landslides are preceded commonly by several months by progressive opening of cracks on the upper slopes. For this reason, the first recommended measure is to implement a program of monitoring of the slopes by visual inspection.

7.4. Debris and mudflows

These flows are relatively common in the area of the project and the risk has been studied since the Technical Design, when the construction of a retention structure on Obishur valley had been considered. Severe floods have been recorded along this left hand tributary, leading to temporary damming of the Vakhsh River and rising of the river level by up to 10-14 m.

Most of the mud flows occur during the rainy months of May and June. Between 1971 and 1991, they occurred at least once a year. Maximum volumes were estimated around 3.100 million m^3 in 1983 and 1.185 million m^3 in 1992.

Recent mudflow on Obishur occurred the 19th-20th of May 2009, triggered by strong rainfalls. The level of the Vakhsh River increased by 5 to 7.3 m at different gauge stations. Estimated flow in the project area was around 2000 m^3/s.

The retention structure on the Obishur stream, as well as deflection walls for deviation of the flow towards downstream are under construction.

Given the high frequency of these mudflows, the study is being updated since 2009 for the streams with the highest potential risk: Passimurakho, Obi-Djushon, Daraikamak, Obigarm and Obishur. The first elements of analysis are:

- Mudflows on Passimurakho stream can carry up to 100,000 m^3
- Mudflows from Passimurakho can dam temporarily the Vakhsh River (recently recorded for 5 minutes in 2009) and cause increasing of the river level by several meters.
- Mudflows on the Obi-Djushon stream are apparently less voluminous. They could lead to rising the river level only in conjunction with flows on Passimurakho
- The mudflows on the Obigarm river would have little impact on the project.
- Mudflows on Daraikamak stream, 15 km upstream from the site, could result in rising the river level in the construction area by 1 to 2 meters.

As reported in [13], a comprehensive program for mudflow risk assessment is being conducted.

8. Conclusions and recommendations

8.1. Investigations

The amount of existing investigations is considered sufficient to assess the feasibility of the project.

However additional investigations are recommended to address specific issues and for the completion of the detailed design:

- Nature of the boundary of the atypical zone: exploratory gallery, monitoring of the boundary zone underground and at surface. To finish the rehabilitation of gallery #1034. If major fracture zones are crossed, both these galleries could be equipped with devices for monitoring the deformation.

- Piezometric levels – in particular in the upper part of the Right Bank, for the design of the grout curtain, and on the downstream slope for designing drainage system to control the pore pressure : drilling with permeability tests and installation of piezometers.

- Geotechnical characteristics of construction materials

- Monitoring of slopes and fault displacements.

8.2. Seismic and aseismic deformation

At Rogun HPP site, the regional tectonic stresses are adjusted by deformation which is both seismic, i.e. involving sudden co-seismic rupture, and aseismic, mainly by creeping probably related with regional stress but also with extrusion from depth of salt and gypsum.

The seismic hazard is discussed in a separate report.

The slow deformation, which is permanent, takes place principally on the main faults, namely Ionakhsh and Fault no.35, where monitoring was implemented for measuring the deformation rate.

The field observations and examination of damage on support of underground workings call for refining the kinematic model, to account for diffuse decimetric shearing related with creeping and adjustment of tectonic blocs. If diffuse shearing is confirmed, the location of shearing of underground structures would be unpredictable and reinforced support measures would have to be designed and extended to the entire development of the structures.

Additional investigations are recommended to verify the cause of damages to the supports at all identified locations. If necessary, the rock mass should be exposed for inspection and installation of monitoring devices. Monitoring of displacements along the main faults should be resumed and additional devices installed. In addition, monitoring should be extended to the major discontinuities showing offset which is consistent with present-day stress orientation. In this respect, the anomalous results obtained for the orientation of the principal stress components should also be verified by additional tests. Taking into account the complex tectonic setting, these tests should be also carried out at different locations into the abutments.

8.3. Risk of landslide

Potential landslide risk has been identified in the following areas:

- Left Bank in the upstream part of the dam
- Right Bank downstream
- In the reservoir

Left Bank upstream

In the Left Bank, in the upstream part of the dam including the slopes above the diversion and water intake tunnels, the risk is related with gravitational sliding on daylighting discontinuities of S4 family. It is recommended to identify precisely the persistent joints and to carry out stability calculations taking into account the effect of increasing pore pressure upon impounding and fluctuation of reservoir level. Among the possible mitigation measures for increasing the shear strength, already implemented for similar risks in other projects, are mentioned galleries filled with reinforced concrete across the discontinuities.

Right Bank downstream

Based on available data and field observations, there is no evidence for the existence of unfavourable pre-existing discontinuity which could cause a major structural slope failure.

Landslide involving slope cover deposits are not considered a major threat for the feasibility but mitigation measures are compulsory to prevent the risk during construction and operation.

The assessment of the risk of failure due to exceeding of the strength of the rock mass as a whole can be based on the following elements:

- The structural setting is favorable for stability
- Slow tectonic deformation, which is privileged in this report over the ancient landslide model, is more favorable to slope stability
- The conditions for raising pore pressure locally in the atypical zone could be met. It is therefore recommended to design adequate drainage system for the main slope downstream of the dam site. For this purpose, additional investigations are recommended to determine the permeability and he ground water level. These investigations should comprise a line of minimum 5 boreholes in the atypical zone, starting at elevation 1350 m, 100 - 150 m deep or sufficient to intercept the ground water level, spaced at 100 m.

Accordingly, the geological setting is rather favorable for slope stability. The risk of rock mass failure could be increased if mitigation measures for controlling the pore pressure are disregarded.

Risk of landslide in the reservoir

Potential rockslides could be triggered by dissolution of salt in the foot of the northern slopes of the Vakhsh Ridge and Surkhku Ridge. Near the dam site, such slides are still developing in the right bank of the Passimurakho valley.

Further upstream in the reservoir, the evaporite masses outcrop at elevations higher than the reservoir but their lower part lies below the reservoir level, covered by alluvial deposits. The probability of occurrence of massive and sudden landslides seems low. Even if in the past the processes were slow, the impounding and the fluctuations of the reservoir level will mark rapid changes of the natural conditions. Consequently, it is recommended to assess the response to these changes, in particular for the slopes in both banks of the Vakhsh River near the entrance in the canyon of the dam site, where salt occurrence was identified.

The landslides are preceded commonly by several months by progressive opening of cracks on the upper slopes. For this reason, the first recommended measure is to implement a program of monitoring of the slopes by visual inspection.

8.4. Summary of major hazards related with geological conditions

- Salt dome

This issue is discussed in a separate report.

- Gravitational sliding on S4 discontinuities

This risk is manageable provided that appropriate mitigation measures are designed after detailed assessment is carried out.

- Diffuse shearing

This risk is mostly difficult to assess accurately. The assessment should be based on resuming monitoring of the main faults and extending monitoring to other major discontinuities. In the absence of convincing data, conservative design should be conceived and implementation of reinforced measures extended to the entire development of the structures.

- Downstream landslide

The risk is manageable provided mitigation measures are implemented for (i) preventing slides of slope deposits and weathered rock and (ii) controlling the pore water pressure in the rock mass.

- Landslides triggered by dissolution of salt

The probability of occurrence seems low, but cannot be disregarded without assessment, although the assessment is difficult. The risk is most probable just upstream of the canyon up to the mouth of Obi-Djushon, where salt rock masses will be certainly in touch with the reservoir.

9. ANNEXE

Annex 1. Site geological map (HPI Moscow)

ANNEX 2. Geological map of the Right Bank (2012).