TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

PHASE II: PROJECT DEFINITION OPTIONS

Volume 2: Basic Data

Chapter 2: Geology

Part B - Geological Investigation in the Right Bank

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1 Extent of this report

The present report is only a part of the general assessment of geological conditions of Rogun HPP. This document presents the results of the geological investigations carried out in 2012 with the purpose of refining the assessment of the geological setting in the right bank of the Rogun dam site and in particular of the atypical zone in the right bank at large. While most of the overall Rogun site assessment is based on previous, abundant data and documentation, the results of the 2012 investigations are a major contribution as fresh input basic data.

2 List of main abbreviations and definitions

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

FS: Feasibility study, used for the technical design report issued in 1978

HPI: Hydroproject (Gidroproyekt) Institue

IF: Ionakshski (Ionaksh) fault

LI: Lahmeyer International GmbH

LU: Lugeon Units (unity measure for permeability of rock mass)

mgal: unity measure for the gravity field

RB: Right Bank; when referring to the Rogun dam site, it designates the area delimited by the River Vaksh and its tributaries, Ararak and Pasimurako.

Salt tectonics: in this report, the term designs the particular deformation resulting from extrusion, doming, creeping of salt or gypsum; it can result in local folding which can reflect or be totally different from the folding vergence related with regional tectonic stresses.

TEAS: Techno-Economic Assessment Study, used for the present study, commissioned to the Consortium composed of Coyne et Bellier, Electroconsult and IPA.

3 Background

List of main references relevant for the atypical zone in the Right Bank

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

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

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

[4] 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

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

[6] 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

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

[8] 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 proposed Rogun project. HPI, 2009.

[9] Conception of project completion, HPI, 2009.

[10]TEAS for Rogun HPP, Inception Report.

Geological context

- ***Brief regional context***

As the entire dam site area, the Right Bank lies within the structural domain of the Tajik Depression. The site lies more precisely very near the northern boundary of this unit, along which it collides with the Tien-Shan bloc (Illustration no.1).

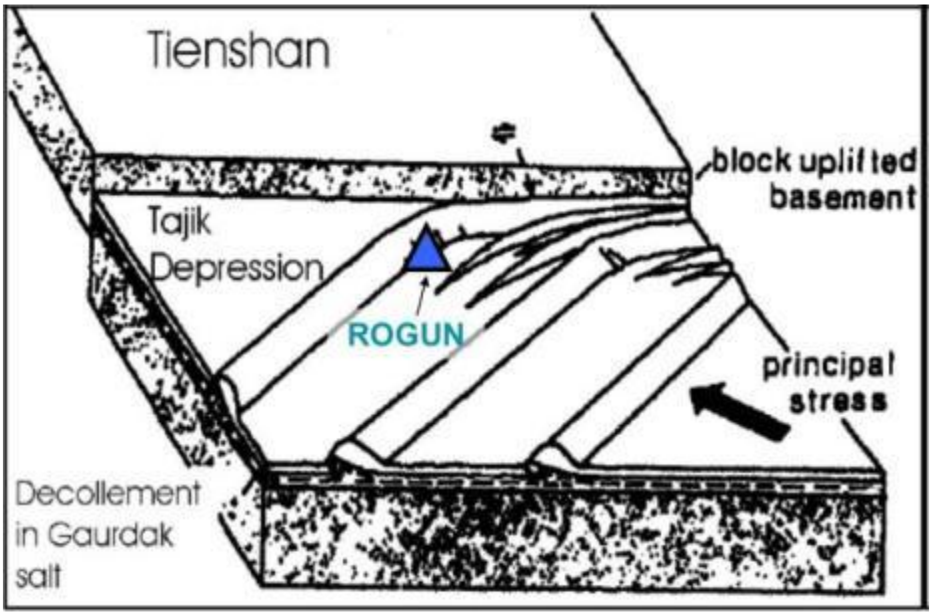

Illustration no.1. Schematic regional setting near the zone of contact between the Tajik Depression and Tien-Shan

As a consequence of high compressive stresses and regional uplift, the Mesozoic sedimentary sequence, formerly deposited above the Paleozoic basement in the Afghan-Tajik basin, is now exposed in young mountain ranges.

The considerable shortening of the sedimentary cover in response to compressive stresses is mainly accommodated by a series of thrust sheets. The main base décollement level where the thrusts initiate is the thick Jurassic salt layer identified as the Gaurdak Formation. One of these regional thrust faults, Ionaksh Fault, runs precisely through the RB of the Vakhsh River at the dam site.

- ***Lithological sequence***

Table no.1 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), Table no.1 shows ranges of variation. While the high precision can be adequate for a small area at the dam site, the range of variation seems more representative for larger areas, which is the case for the extended Right Bank.

The approach initiated in the 1978 FS, which consisted in distinguishing groups of formations, is more adapted to the 1:5 000 scale of the complementary mapping of the RB presented in this report. Those groups are: (i) Jurassic evaporitic formation, Lower Cretaceous continental sequence and (iii) marine sequence, mainly 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 IF and the other regional thrusts are rooted, around 2000 m below the river level (Illustration no.2).

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.

Lower Cretaceous continental sequence

This group, recognizable by 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.

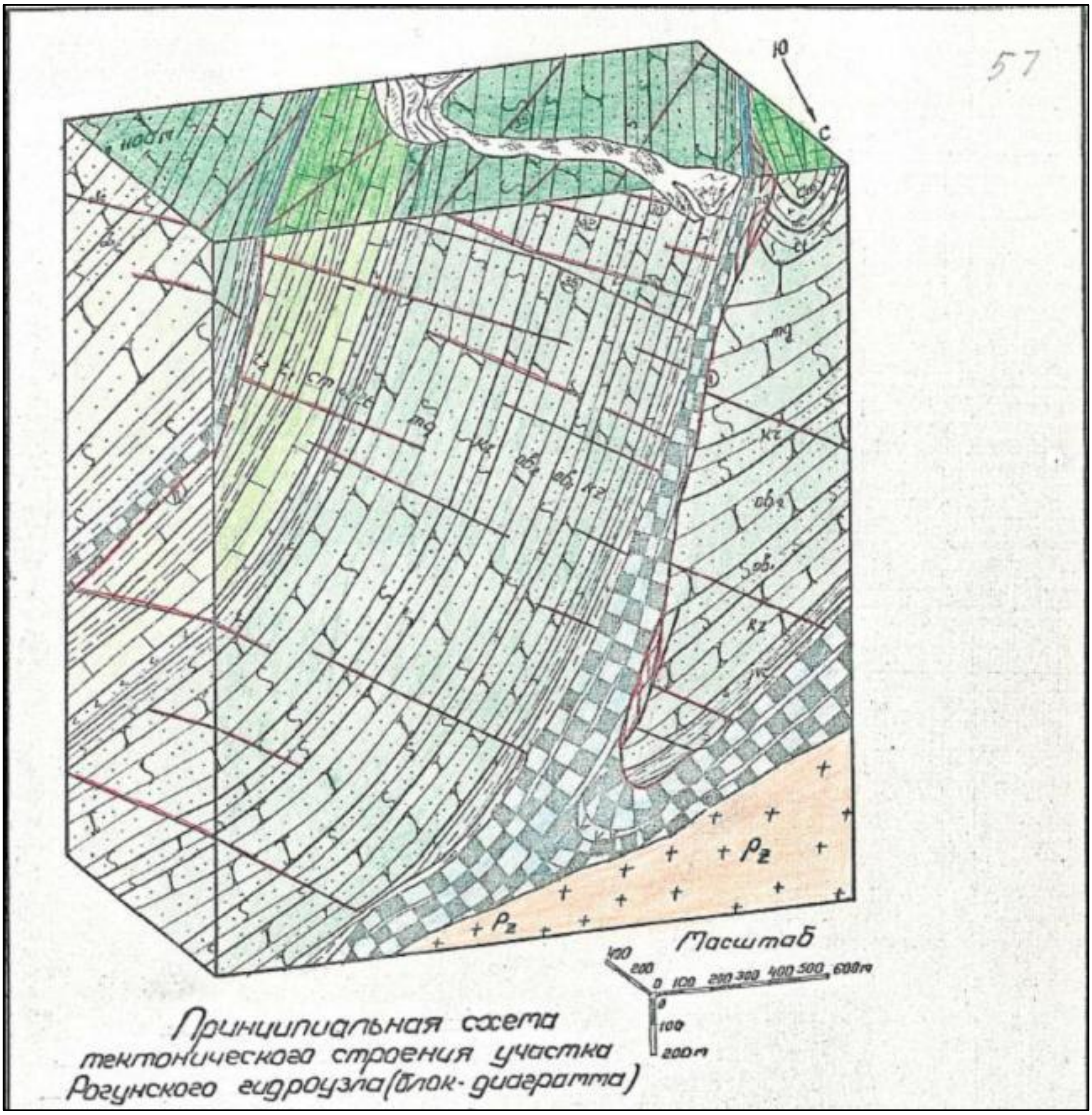

Illustration no.2. Interpretive bloc-diagram of deep dam foundation (from FS 1978). The root of the Gaurdak salt layer would lie about 2000 m below the river level.

Table no.1. 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

- ***Main geological structures***

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 IF and 60° for the bedding of the monoclinal sequence downstream of IF.

➢ ***Particular features in the RB: the atypical zone***

Away from the dam abutment, the geological setting of the Right Bank is marked by lateral changes. The most outstanding peculiar features are:

- A wide, relatively flat area 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, in the atypical zone, on the RB slope, the Mesozoic sequence is in reverse position, i.e. older formations overlying younger formations. The tilted sequence includes the Ionaksh Fault (IF), which is a major thrust contact between the Jurassic and the Cretaceous layers
- Downslope offset of the formations, by tens of meters to more than 100 m

The peculiar features mentioned above lead to distinguish, from the earliest stages, an 'atypical' zone.

➢ ***Geological model of the atypical zone***

At the FS stage (1978 report), the particular setting was explained by large scale slope instability, involving successive, massive landslides with a volume estimated initially in the FS at 900 million cubic meters.

As represented on the geological map, of which an extract is presented in Illustration no.3, the downslope offset was interpreted as the result of tear-off along the eastern boundary of the 'landslide zone'.

Illustration no.3. Extract of the 1978 geological map. Enhanced geological contacts and bedding structural positions highlight the inferred offset and the sharp change of bedding dip.

The ‘landslide boundary’ was also indicated on the map of the left branch of the gallery 1034 which had precisely targeted this feature (drawing 1079-03-99, FS 1978). However, the extrapolated map at the floor level of this gallery shows only bending of the layers (Illustration no.4).

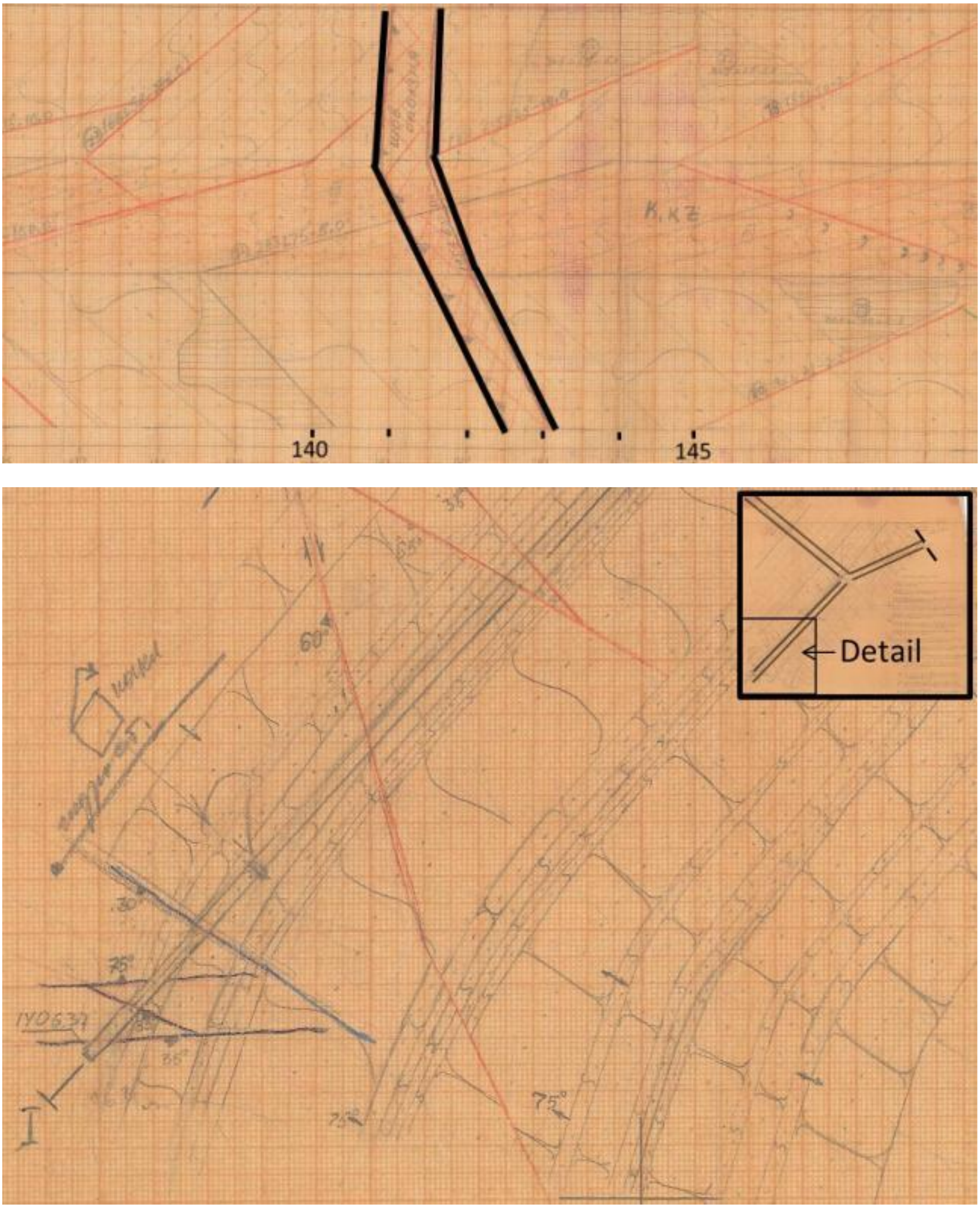

Illustration no.4. Extract from original mapping, with landslide boundary enhanced (top) and extrapolation at the floor level of gallery 1034 (bottom), at the end of the left branch. Several fractures are mapped, NW-SE and E-W, but the bedding is represented as only bending instead of being offset.

As explained by the landslide model, 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.5).

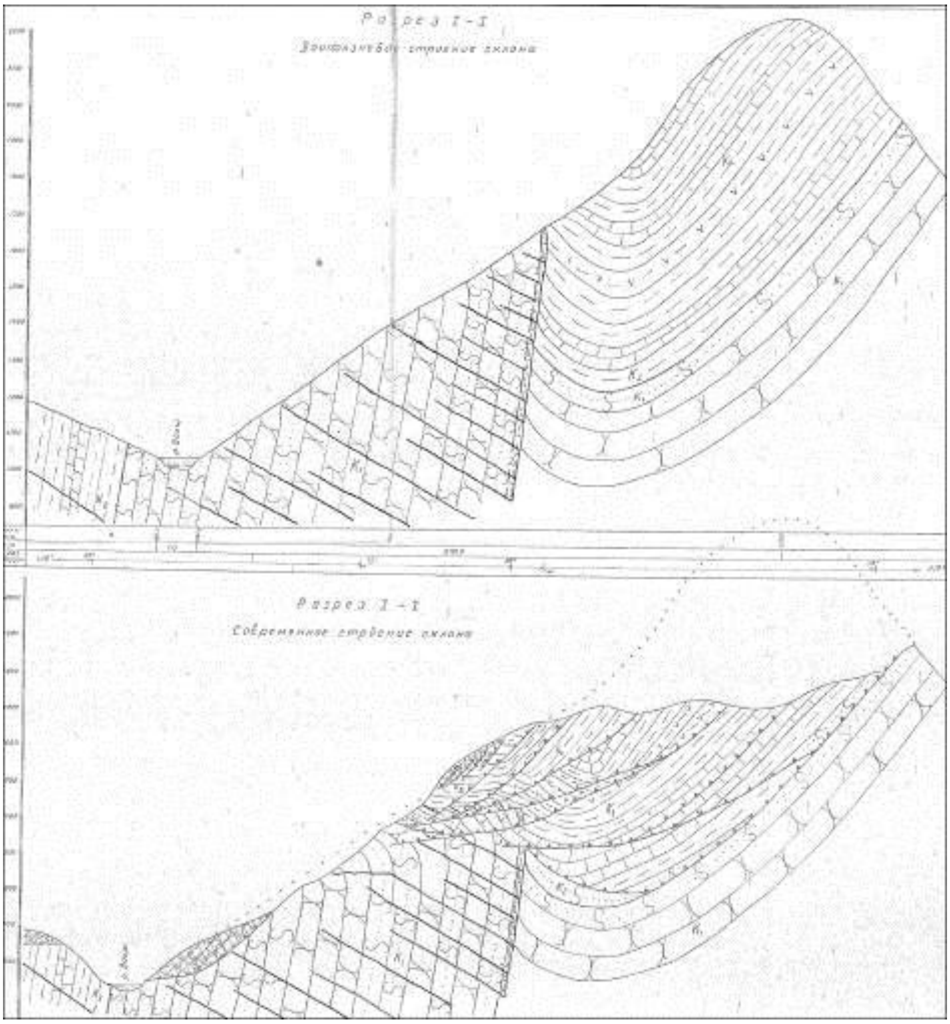

Illustration no.5. Interpretive cross sections of the 'landslide area' (from FS 1978 report). View towards downstream (SW). Original setting at the top, post-landslide setting at the bottom.

The FS 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'.

Subsequent to the first interpretation presented in the FS report, the total volume of assumed landslides has been re-evaluated. The most recent reassessment dates from 2009 (Ref. [8]), when the total volume of the landslide was estimated at '75 – 100 million m^3'. The risk of reactivation as massive landslide is also considered as very low. The new analysis integrated results from refraction seismic and electric resistivity sounding investigations carried out in 2006 principally on the plateau at 1700 m. The plan view of the atypical zone and the interpretive cross section are reproduced in Illustration no.6.

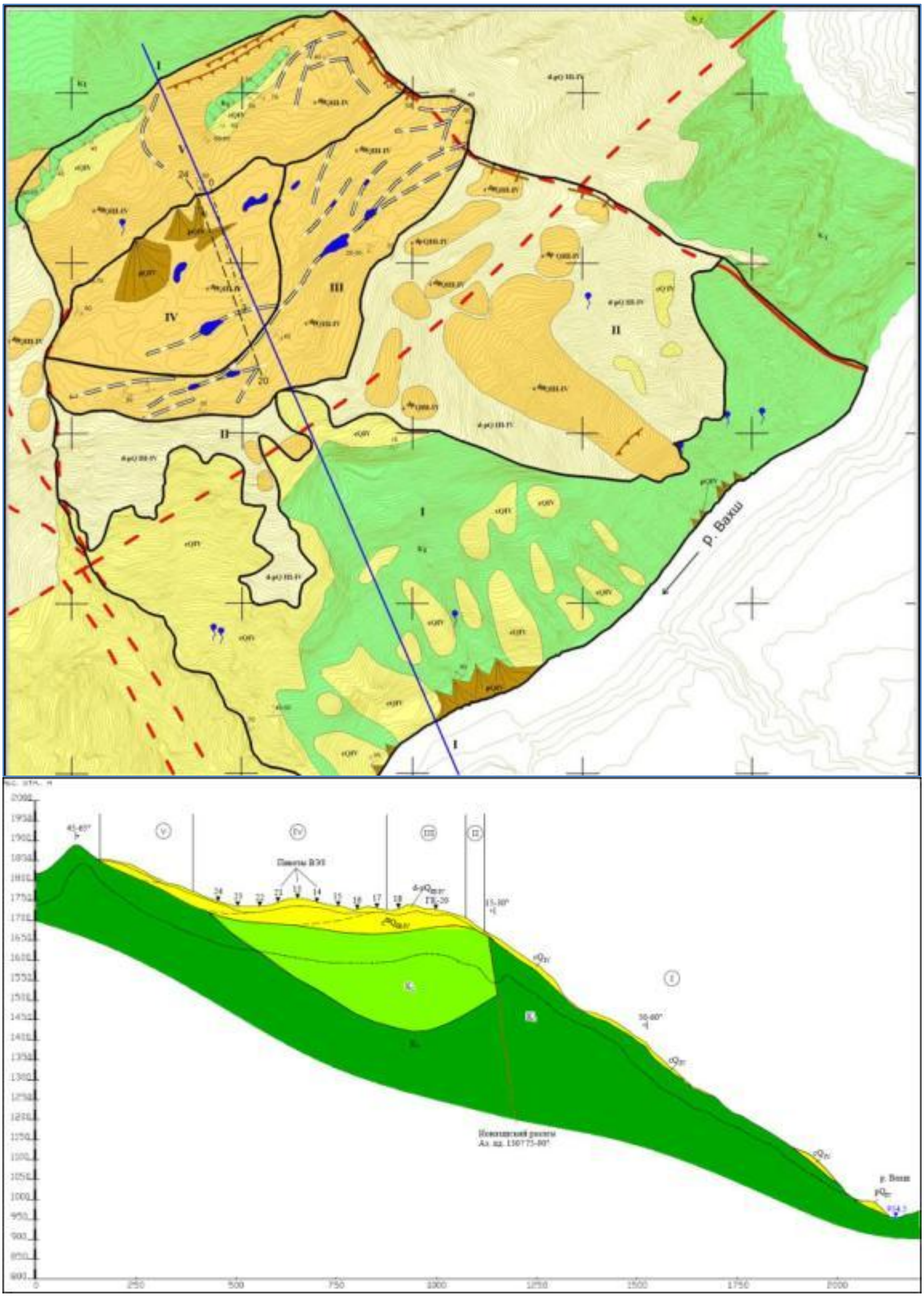

Illustration no.6. Plan view and cross section through the atypical zone (reproduced from Ref [8])

4 Additional field investigations in 2012

At the beginning of the TEAS, it has been considered that the 'landslide' model had not been verified by sufficient subsurface investigations. In addition, the presence of salt domes and of folds typical for salt tectonics in the project area suggested that alternative scenarios could explain the atypical configuration.

In order to reduce the uncertainties related to the geological setting and in particular with the risk of massive landslide, additional geological investigations were recommended. The investigations completed in 2012 consist of:

- Surface geological mapping, 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, cumulated length 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

The results of investigations and the main findings relevant for the assessment of the right bank are discussed in the following paragraphs.

Surface geological mapping

Based on analysis of aerial images and on field observations, the atypical morphology and geological setting appeared to extend beyond the limits of the available detailed geological map. It was therefore decided to complete the geological mapping at 1:5 000 scale, within the area delimited as follows:

- to the east and to the south, by the Vakhsh River,
- to the west, by the Ararak stream, first right hand tributary d/s of the dam site,
- to the north, by the Pasimurako stream, right hand tributary u/s of the dam site.

The area of interest is indicated in Illustration no.7. This block has clear geomorphological boundaries. It can be considered as the natural extension of the Right Bank of the dam site, for instance for the purpose of hydrogeological modeling.

Illustration no.7. The white frame indicates the area of interest in the right bank.

The geological map is presented in Annex 1. The English translation of the field notes is joined in Annex 2.

The main findings of the complementary mapping and geological walkovers are recalled here below.

- Extension of the atypical setting

Mapping in a broader area showed that the ‘disturbed’ or ‘atypical’ geological setting extends beyond the area previously delimited and referred to as ‘ancient landslide’ zone. Basically, the geological setting is different from that at the dam site all the way and even beyond the Ararak stream.

- Gypsum layers, karst and décollement levels

In the Ararak stream, the Upper Cretaceous formations of Santonian, Coniacian, and Campanian-Maastrichtian were identified. Among them, the Santonian formation includes thick gypsum layers which exhibit numerous karst dissolution features (Illustration no.8).

Illustration no.8. Sinkhole in thick gypsum layer, left bank of Ararak stream.

Such gypsum is apparently responsible for the outstanding bubble wrap folds, typical of salt/evaporite tectonics, which are visible in the opposite bank of the Vaksh River (Illustration no.9). 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.9. Salt tectonics, bubble wrap folds in the left bank opposite to the atypical area.

- Direct observation of large scale tectonic folding

Large scale folding which turns normal sequence (young formations overlying old ones) with bedding dip SE in reverse position (old formations overlying young) with NW dip, was directly observed in continuity with the ‘atypical setting’ which had been formerly interpreted as ‘landslide’ of Upper Cretaceous layers. This observation is convincing evidence that the overturn of the bedding dip results from tectonic deformation (Illustration no.10).

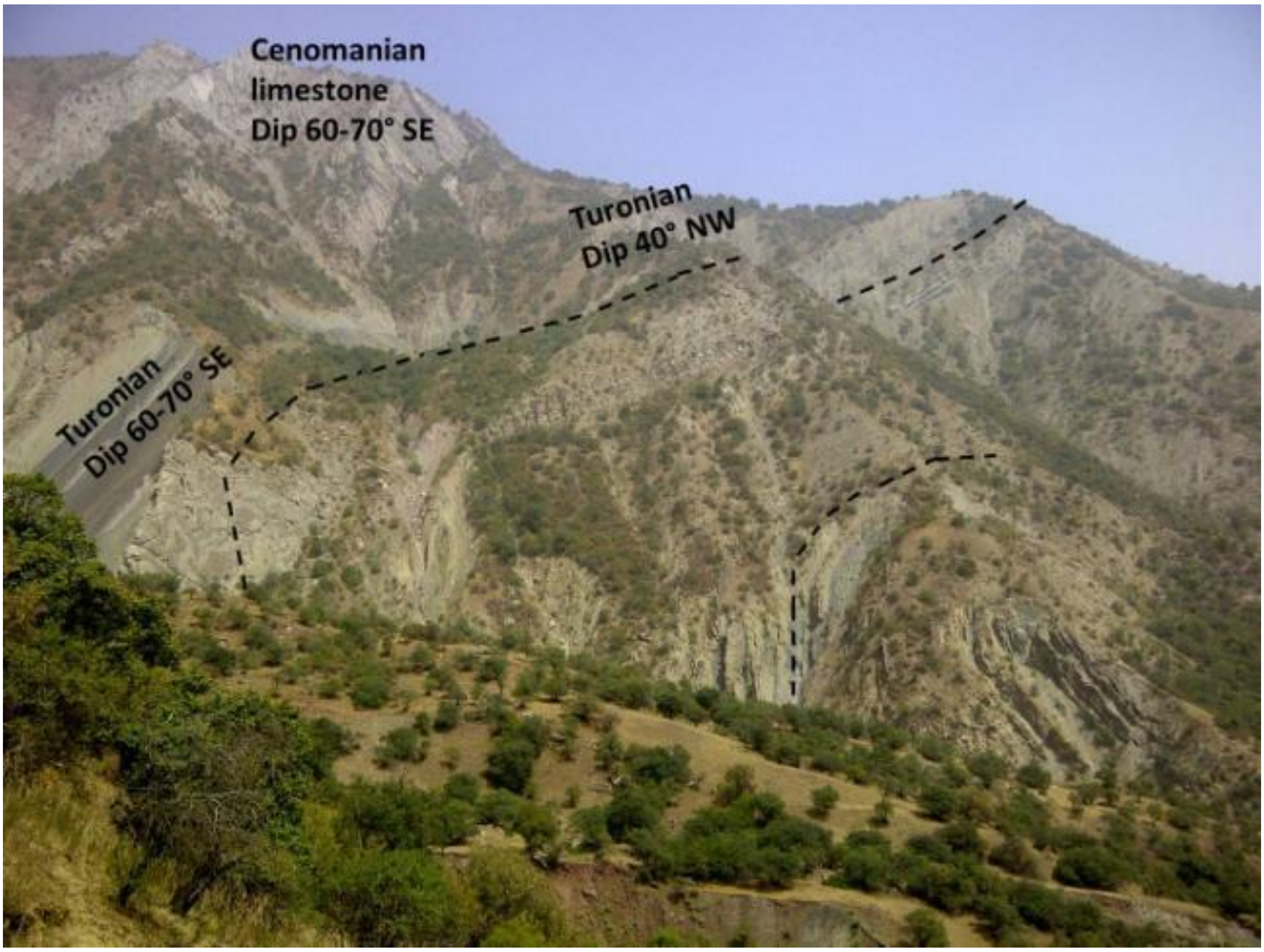

Illustration no.10. At the downstream limit of the mapped area. The left bank of Ararak stream exhibits large scale bending and reversal of the Cretaceous sequence. Formations are younger from the left to the right. At left, normal position with bedding dip to SE. At right, reverse position with bedding 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.

- Small scale folding

Small scale folding typical of salt tectonics was also observed (Illustration no.11).

Illustration no.11. Left bank of Ararak stream. Tight folding in Coniacian layers.

- Faults no. 35 and 28

Existing geological maps indicate that faults no.35 and 28 cross the boundary and continue into the reverse atypical sequence. Based on recent field observations, no evidence was found for such continuity.

- Nature of the Eastern boundary of atypical zone

In the area of the assumed Eastern boundary of the 'landslide zone', no evidence of NW-SE tear-off zone has been found. On the contrary, field observations rather suggest that the apparent senestral offset of the layers results from ductile deformation (bending) as opposed to sharp shearing (Illustration no.12). Other observations on the slope are also indicative of slow tectonic deformation (Illustration no.13).

Illustration no.12. Near the eastern boundary of the atypical zone. The structural position of this gypsum layer and adjacent shales, almost perpendicular to that in the undisturbed area, indicates bending instead of lateral offset across discontinuity.

Illustration no.13. On the steep slope of the atypical zone, in overturned Lower Cretaceous sequence. Brittle deformation of sandstone, next to ductile deformation of gypsum and mudstone. Remobilization of gypsum within the fracture which cross-cuts the bedding in sandstone layers is consistent with slow, tectonic driven deformation of this rock-mass.

- Sinkholes on the high plateau

The morphology of the wide flat area in the RB is complicated by numerous topographic depressions (Illustration no.14). They can be elongated parallel to the bedding, ENE-WSW, 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 largest ones can shelter permanent or temporary lakes. The one with the permanent lake lies just south of the borehole DZ2. As discussed in the next chapter, this borehole crossed about 65 m of clays which could be interpreted as residual infill of a large karstic sinkhole. The presence of limestone at outcrop and of thick gypsum/mudstone sequence in the borehole suggest that the sinkholes are related to karstic dissolution.

Illustration no.14. Sinkholes elongated parallel to bedding at the eastern part of the high flat.

- Cracks related with slope stability

Some elongated depressions were also observed on the thin ridge oriented NW-SE, which dominates the right abutment of the dam (Illustration no.15). The troughs lie on the side of the ridge which is opposite to the dam abutment. They can reach up to 20 m long, 5 m wide and 2 - 5 m depth. Lying entirely in sandstone-mudstone layers, they cannot be related with dissolution but with slope instability. There is no indication of very recent or progressive, continuing opening. Based on the morphological configuration, these features seem to reflect rather a sudden development, such as during an earthquake. Nevertheless, this ridge feeds the steep slope to the SW at least with rock falls. Due to the proximity to the upper lip of the slope, more voluminous failures along the cracks cannot be discarded.

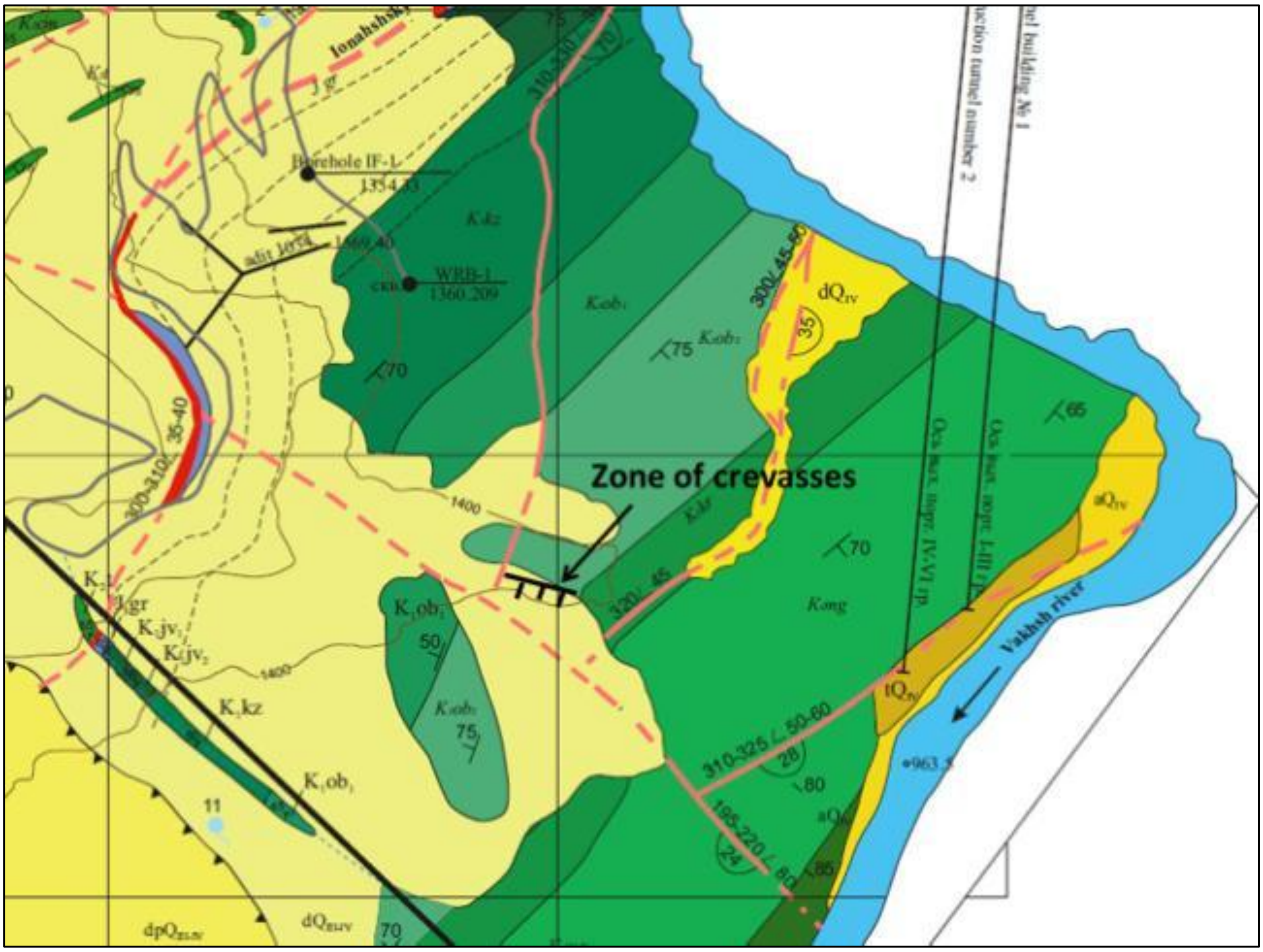

Illustration no. 15. Location of crevasses on the narrow ridge.

Drilling

Four boreholes were drilled, two near the dam foundation and two in the atypical zone. For each of these boreholes, the objectives and the main results are recalled in this chapter. Detailed information is presented in Annex 3.

- **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. 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 FS in these reaches. The following table summarizes the results of permeability tests.

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 107 – 112, where the permeability is very low. On the contrary, many stages in the upper part of the borehole yielded high values.

- **Borehole WRB1**

Location and length: upper part of the right bank near the dam axis, 110 m, vertical

Objective: to characterize the rock foundation in the upper part of the abutment near the dam axis, to carry out permeability tests at high pressure.

Main results: The borehole was driven principally through sandstone and mudstone. The rocks are moderately fractured, which is reflected also by the permeability values.

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

- **Borehole WRB2/DZ1**

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

Objective: 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 characterizd by sheared red mudstone and gypsum. 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.

- **Borehole DZ2**

Location: flat lying area in the atypical zone, 166.2 m long, vertical.

Objective: to investigate the geological structures, to calibrate geophysical measurements from 2012 and 2006 campaigns.

Main results: The borehole crossed:

- very thick clay overburden, with only rare rock chips, down to near 70 m depth
- 15 m of sandstone and siltstone and
- alternant gypsum and mudstone over about 80 m.

The thick gypsum-mudstone formation has been assigned to Albian, although it should be stressed that the gypsum layers are much thicker than described in existing documents. Taking into account the local context, including limestone at outcrop, abundant gypsum found in drilling and the morphology, the thick clayish overburden could be residual infill of a large karstic sinkhole.

Refraction seismic

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 location of the seismic lines is showed in Illustration no.16.

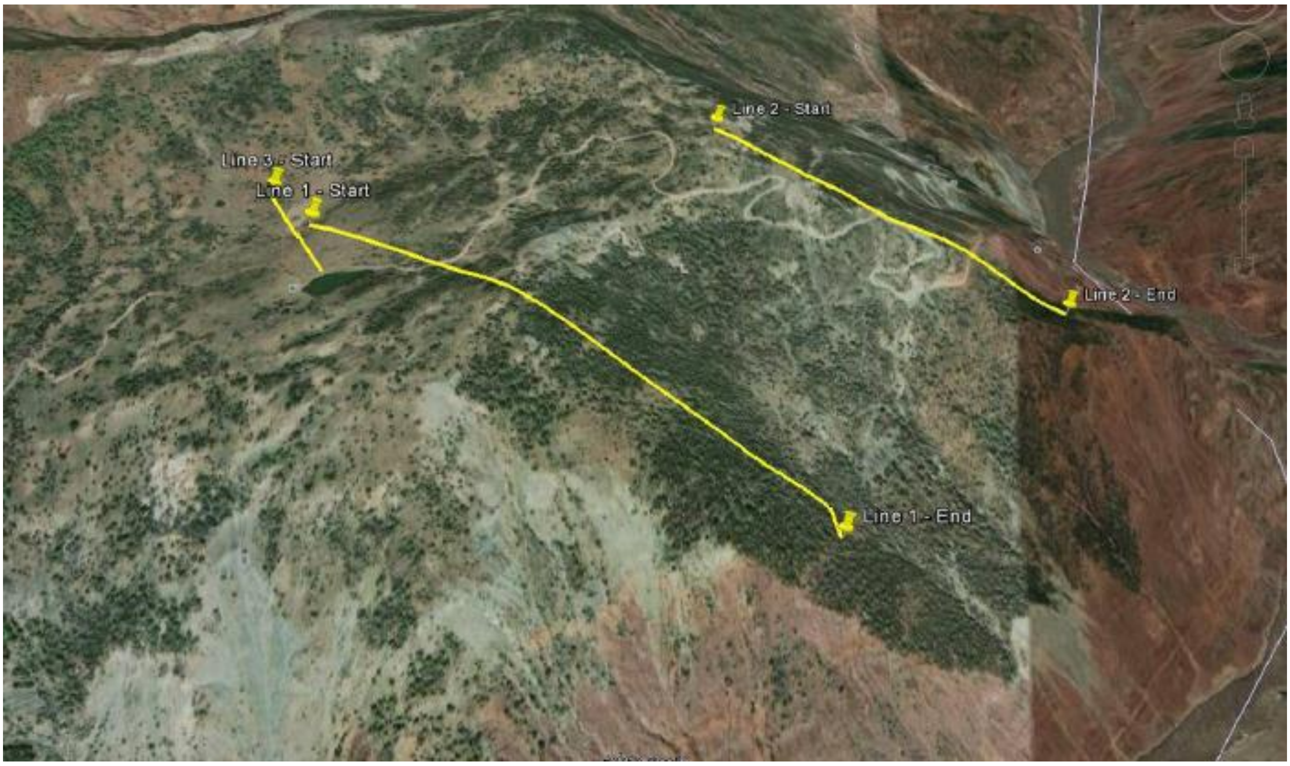

Illustration no.16 Location of the seismic refraction profiles.

The seismic lines are spread over the flat area and the slope below. Line 1 crosses the central part of the atypical area, running by the location of borehole DZ2. Line 2 runs near the eastern boundary of the atypical zone and near the borehole WRB2/DZ1. Line 3, only 230 m long, brings additional information on the flat area, passing through the location of DZ2.

The report is attached in Annex 4. The results are summarized here below.

Illustration no.17 presents the summary results for Line 1.

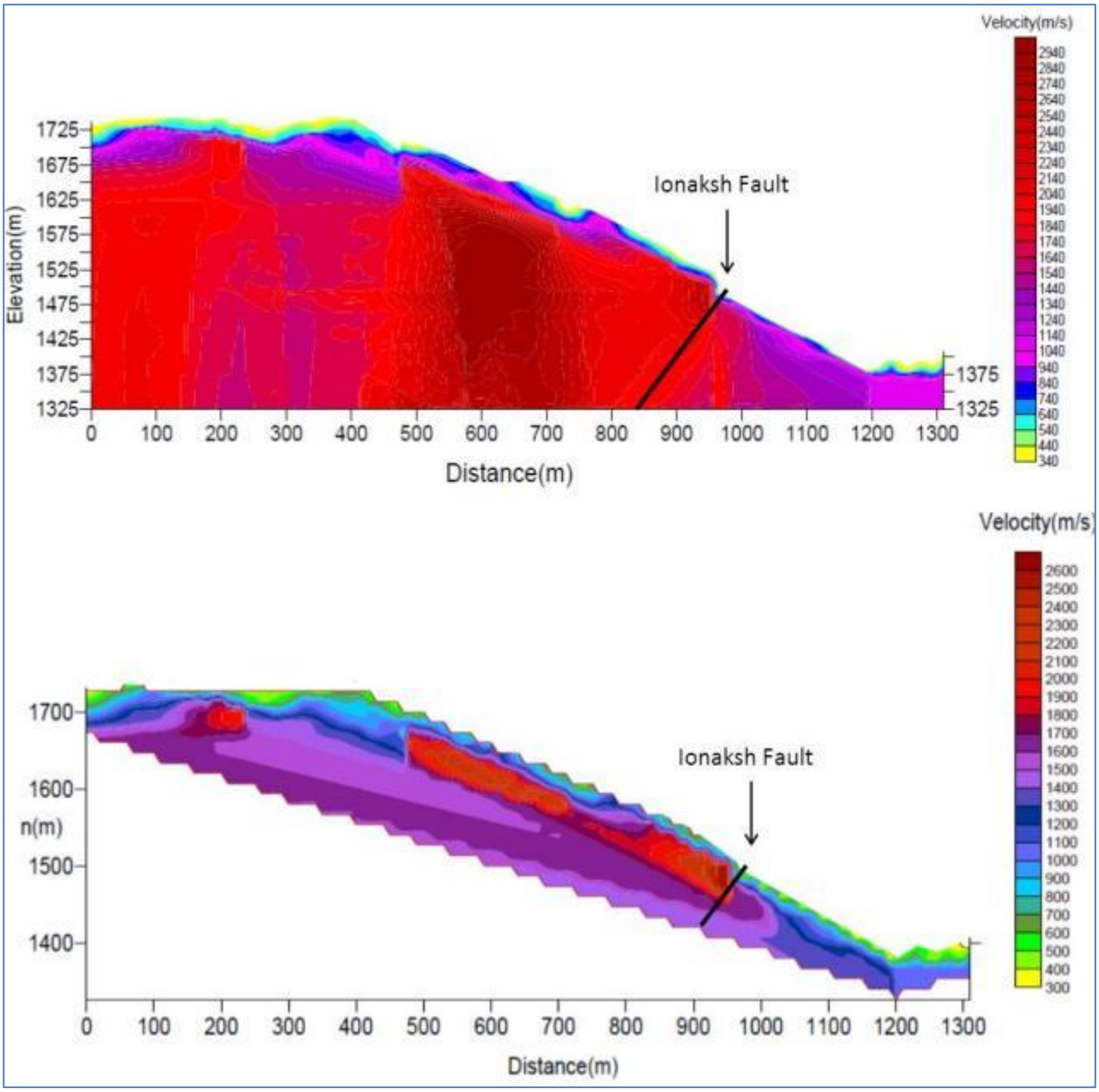

Illustration no.17. Summary of results on Line 1 according to two interpolation methods.

Both models show clearly:

- Very thick overburden on the high flat area, confirming the results of borehole DZ2, and lower thickness on the slope.

- Ionaksh Fault, reverse position (dipping NW) is well distinguished, separating two distinct domains: (i) upslope, the Upper Cretaceous, with relatively high velocities in the deep horizons and (ii) downslope, the Lower Cretaceous formations where velocities stay low, in the order of 1200-1500 m/s even at depth.

The results of Line 2 area summarized in Illustration no.18

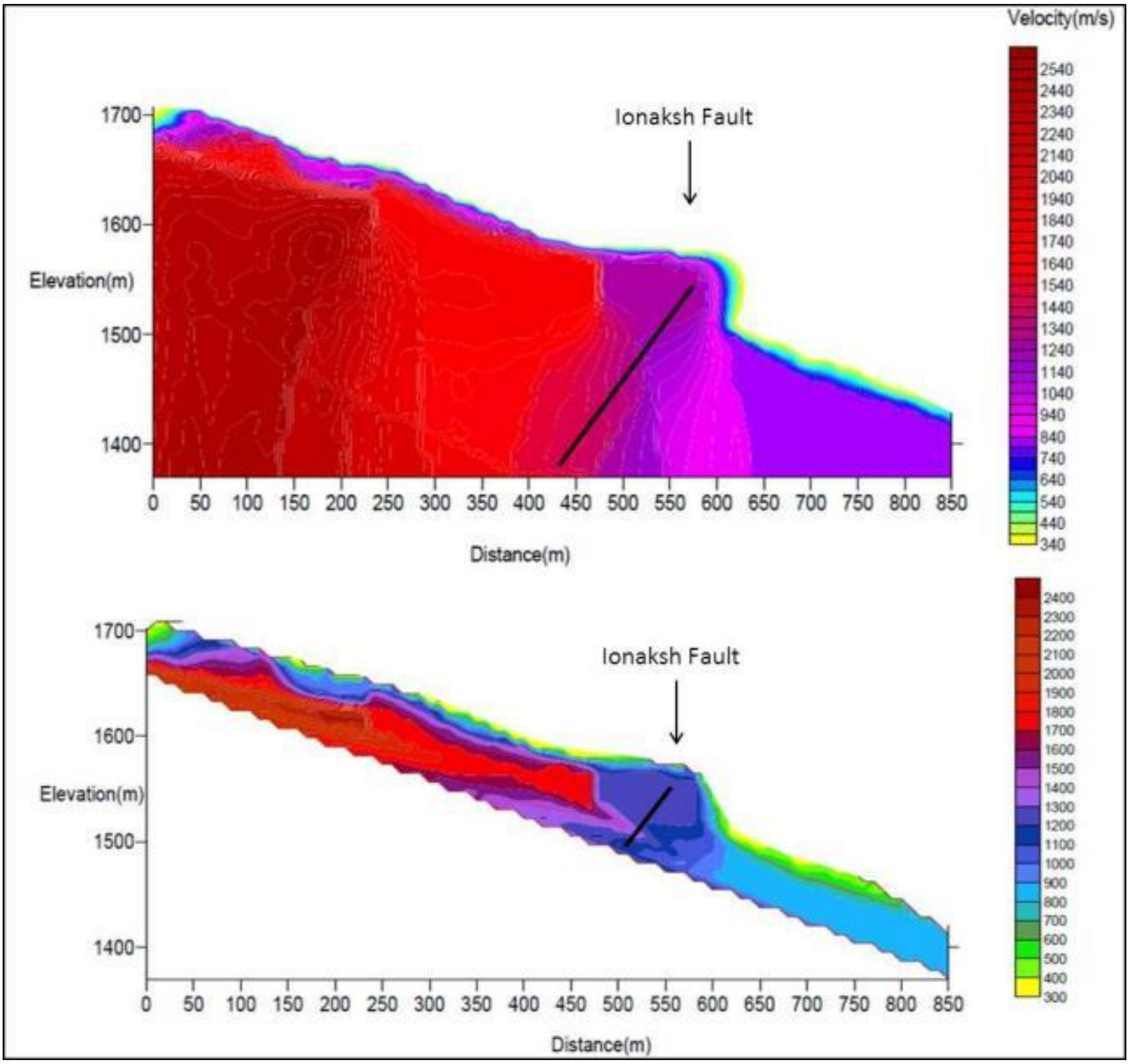

Illustration no.18 Summary of results on Line 2 according to two interpolation methods.

As for the Line 1, the results highlight the contrast on each side of Ionaksh Fault, itself in overturned position. The Upper Cretaceous bedrock is characterized by higher velocities than the Lower Cretaceous. The outstanding step at the IF location corresponds to the thick outcropping lens of gypsum visible in the access road cut.

The results of Line 3 confirm the considerable thickness of overburden on the high flat area, in particular in topographic depressions (Illustration no.19). In the local context, such features can be interpreted as clay filled sinkholes.

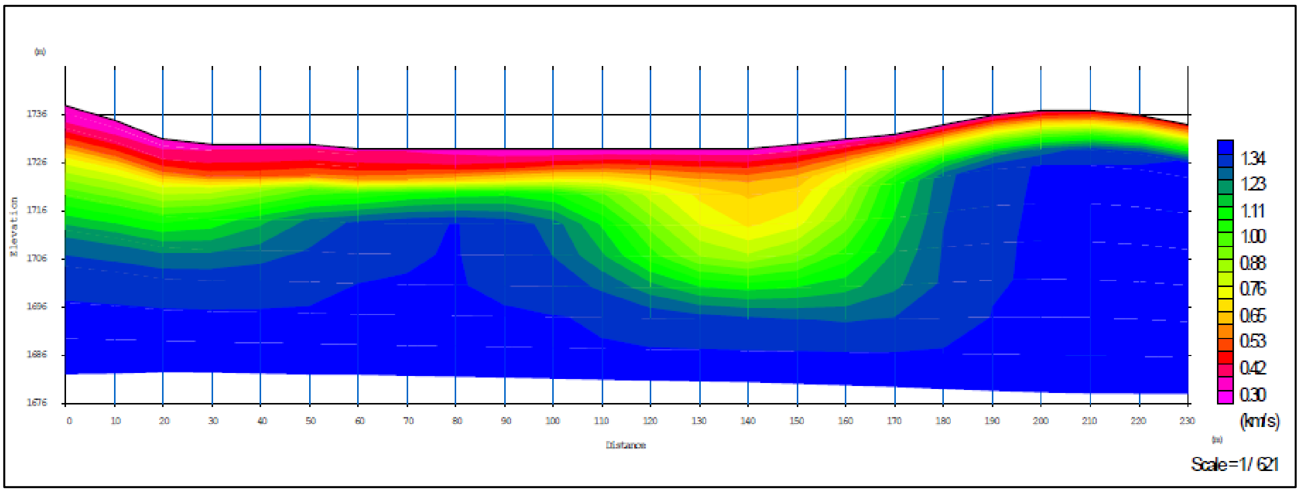

Illustration no.19. Seismic velocity model along Line 3.

Finally, it should be noted also that the results of 2012 investigations are comparable in respect of the velocity profile to the previous investigations (Ref [8]). However, integrating the results of borehole DZ2 and of microgravimetry, the present interpretation privileges the karst model.

Microgravimetry

The primary objective of microgravimetry measurements was to investigate the possible presence of large mass of salt or gypsum, given that such occurrence in the proximity of the dam site could have unpredictable impact on the project. Compared to refraction seismic investigations, which give reliable results for the shallow horizons, microgravimetry integrates the response of very deep anomalous sources. In addition, it can provide reliable information for the presence of cavities or sinkholes in the upper soil layers. In both cases, evaporitic rocks or cavities have lower density than the country rocks and would correspond to negative residual anomalies.

The report is attached in Annex 4. The main results are summarized below.

The investigated area corresponds roughly to the flat area of the high plateau (Illustration no.20). This is the area of most interest and also the area of most favorable topography.

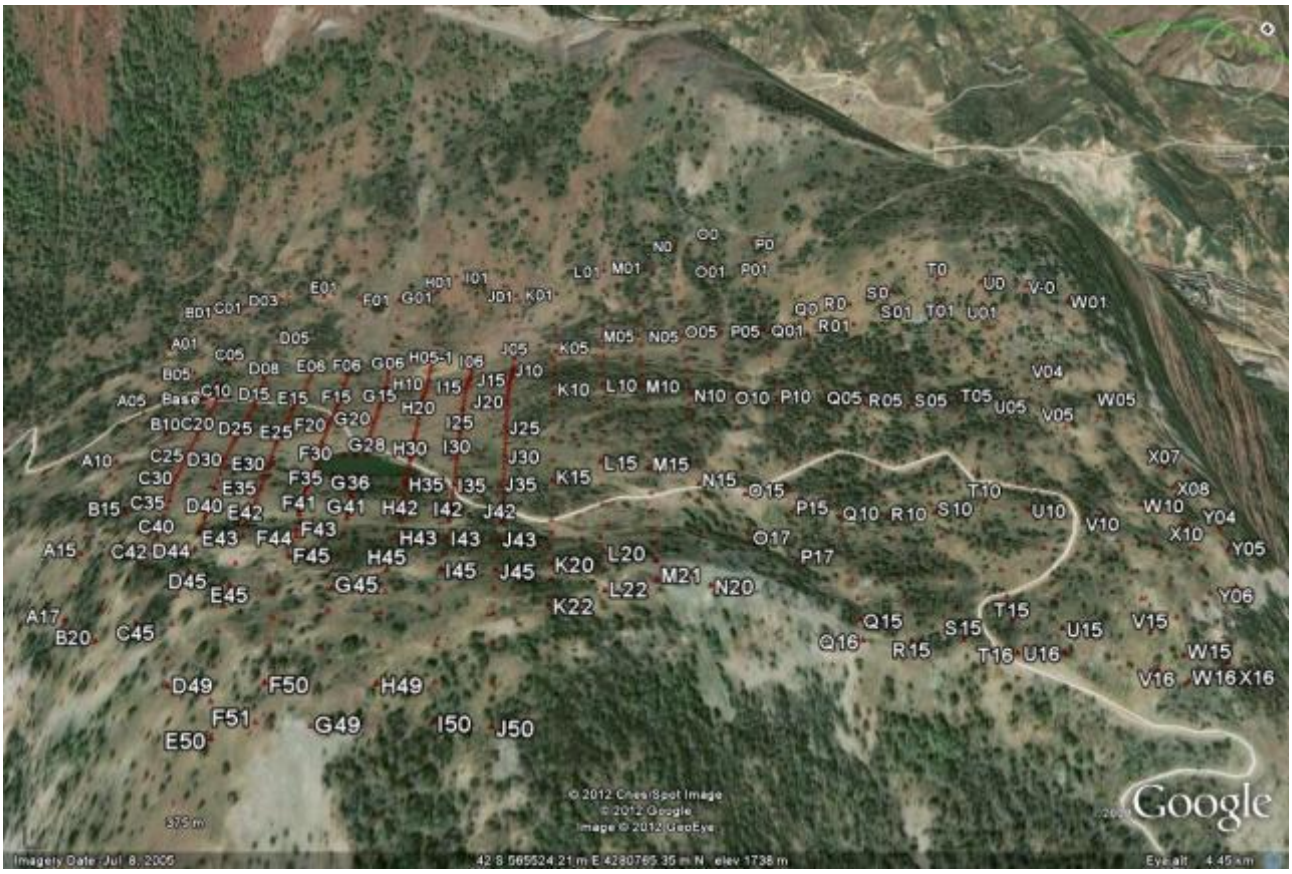

Illustration no.20. Location of the measurement stations.

Illustration no.21 presents the main results, as residual anomaly at surface and at a depth of 120 m. Among the outlined anomalies, the ones near the boundaries of the study area could be more influenced by topography. Although they can not be considered meaningless, their interpretation would not be reliable without extending the area of investigations on steep slopes with even higher topographic influence.

After treatment and geophysical modeling, the source of the anomaly no.1 in the center of the investigated area has been interpreted as low density mass reaching maximum depth in the order of 120 m. Its nature, evaporitic mass (diapir?) or very deep sink area with clay fill, is uncertain. Based on analysis of all available data, the evaporitic mass seems the most probable (see also interpretive geological section in Illustration no.23). However, since the plateau lies at least 350 m above the dam crest level, as long as the anomalous mass does not extend deeper, it is of little concern for the project.

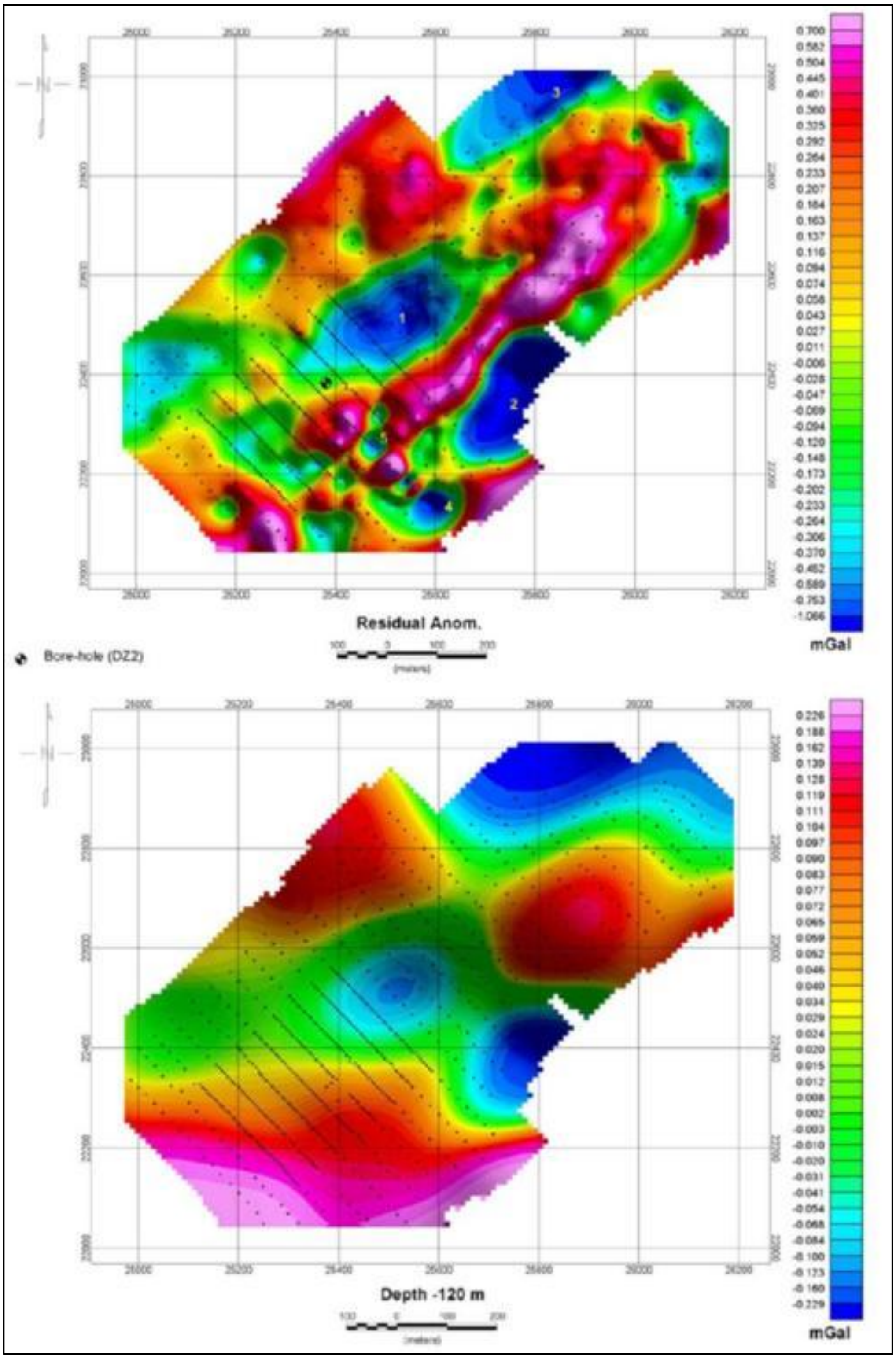

Illustration no.21. Summary of microgravimetry results: Residual anomaly at surface (top) and extrapolated to 120 m depth (bottom).

Inspection of gallery 1034

Among other field activities, the inspection of the gallery 1034 offers valuable insight in the zone of the 'landslide boundary'. As discussed above, the left branch of this gallery had been specifically designed to investigate the boundary of the assumed landslide zone. The workings for rehabilitation progress with difficulty beyond 145 m counted from the bifurcation of the branches. At the end of the rehabilitated section, and also in the ceiling of the collapsed area beyond, no major changes in the bedding orientation could be observed.

The rehabilitation is continuing and should be completed. The updated observations will be taken into account in the final design, for which the nature of this zone, bend or break and offset of layers, is important.

5 Geodetic monitoring

In order to detect and follow-up any slope movements as early as possible, 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.22).

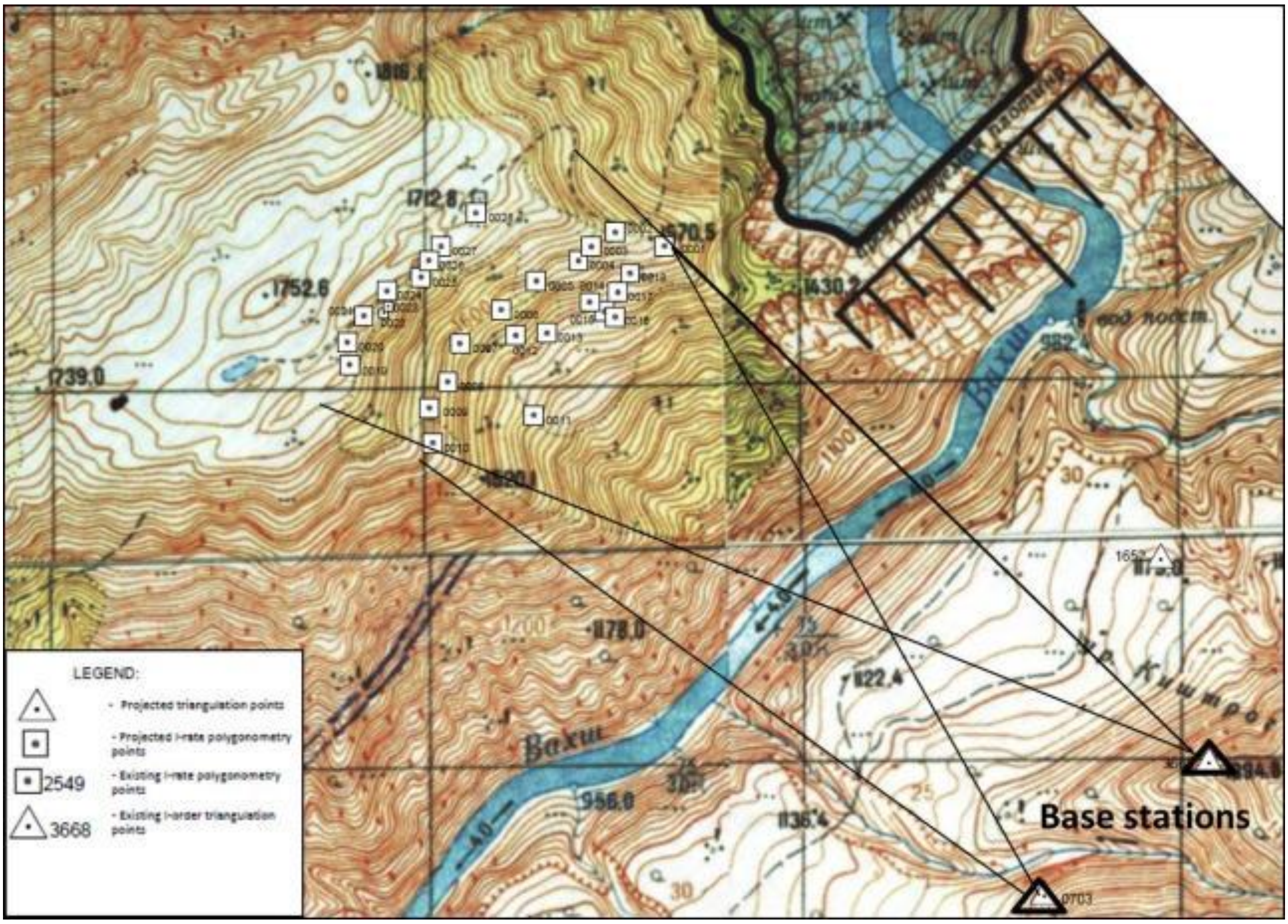

Illustration no.22. Location of the geodetic monitoring system.

6 Discussion of the results

Geological setting of the atypical zone

Based on the available data, the geological setting of the atypical zone in the right bank results from the combination of the following elements:

- Local deformation related with salt/evaporite tectonics
- Karstic dissolution
- Superficial landslides

➢ *Local deformation related with salt/evaporite tectonics*

The most convincing evidence is the direct observation of large scale folding leading to overturning the bedding position. The fact that the oldest Lower Cretaceous formations are involved in the reversed sequence could suggest that the *décollement* responsible for this deformation took place at the level of the Jurassic Gaurdak Formation. However, having noticed the presence of other décollement levels in younger formations, other scenarios could also be investigated. One possible representation of field observations and regional data is showed in Illustration no.23.

The current active tectonics in the study area, near the crustal boundary with the Tien-Shan block, determines its particular context. The deformation takes place on the older, major thrusts such as IF. However, in response to the increased intensity of tectonic stresses, the shortening of the sedimentary cover could be accommodated by (i) new ramps initiating in the Gaurdak layer but also by (ii) décollement at the level of evaporitic layers which are frequent in the Upper Cretaceous formations. The tectonic context can be further complicated by diapir movement of large masses of salt or gypsum. Such recent deformation can take over the older features.

In such complex environment and with only a few subsurface data, it is difficult to build the precise structural setting. Nevertheless, if the uncertainties of a detailed model persist at this stage, the observation of complex folding at large and at small scale positively promote the tectonic deformation against the landslide model.

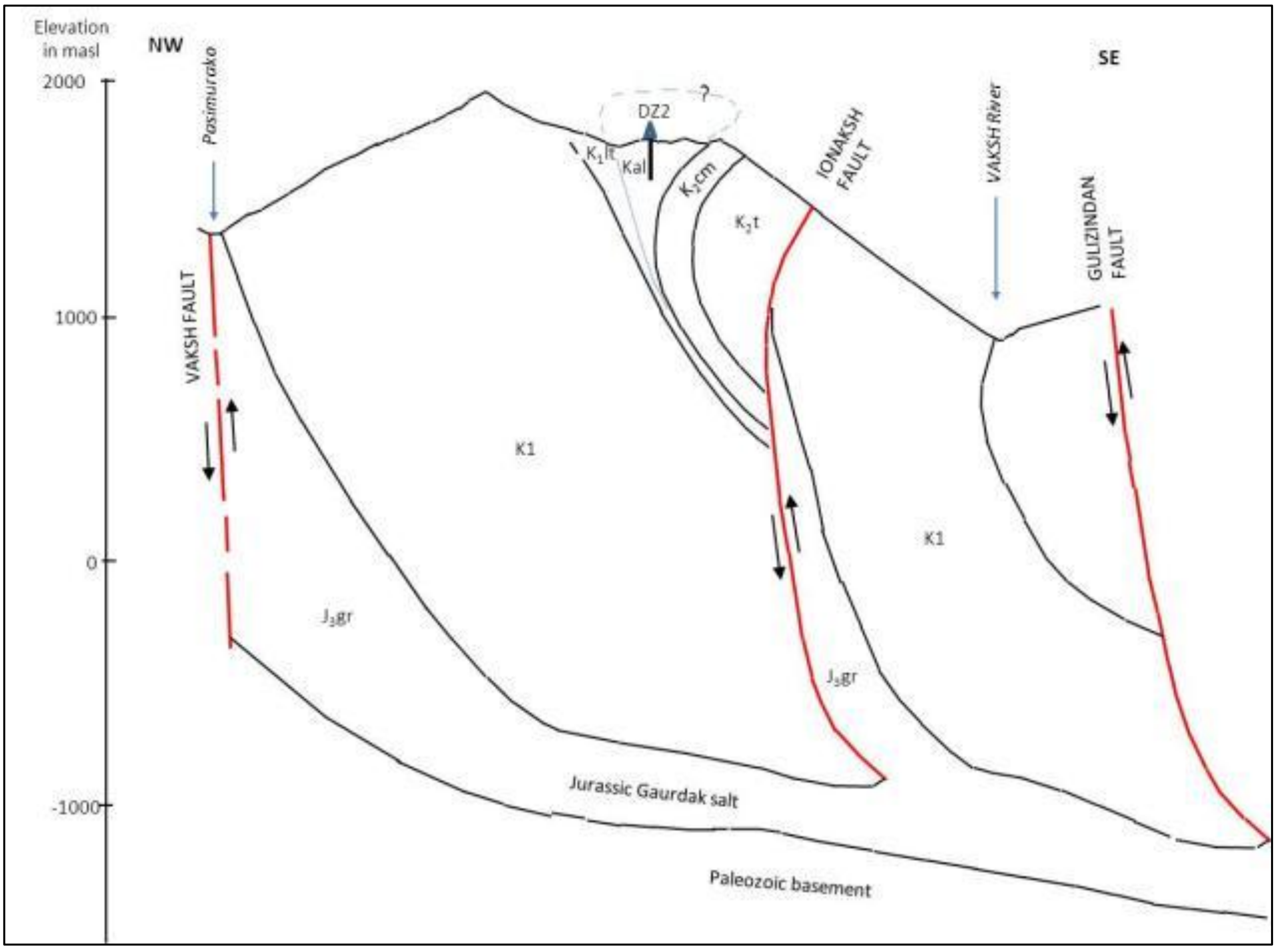

Illustration no.23. Right Bank interpretive cross section, view from the SW. The extrusion of evaporates inferred at the top recalls the small scale fold in Illustration no.11 above.

- *Dissolution*

Borehole DZ2 showed the presence of thick interlayers of gypsum, assigned so far to the Upper Albian formation. The thickness of these gypsum layers is significantly higher than observed in the Upper Albian at the dam site, indicating a considerable lateral variation of facies. Such feature is not uncommon in evaporitic environments. The presence of thick gypsum layers, but also of limestone and sometime dolomite, is characteristic for the Upper Cretaceous formations. All in all, the results of recent investigations suggest that dissolution of gypsum and/or limestone/dolomite layers could occur within 100 – 150 m from the surface below the flat area, with subsequent settlement of the natural ground level. This assumption is mainly supported by the thickness of clay encountered in borehole DZ2, right above the bedrock comprising thick gypsum layers. Gravimetric anomalies also suggest that the lower limit of low density source of the main local anomaly would lie at 120 m depth. In addition, karst dissolution could explain the remarkable topographic depressions found on the plateau.

- *Superficial landslides*

The chaotic accumulations of large scale limestone blocs in the eastern part of the flat area are indicative of landslides. The 30 m thick overburden crossed in borehole DZ1 is also interpreted as landslide deposits, possibly reworked on the slope.

On the contrary, the assumption of large scale sliding down the whole slope and subsequently washed-off by the river is not supported by field observations. Actually, there is no evidence in the river valley for such past event, which commonly dams the river. Even if most of the slid deposits are washed progressively, there are always some very large blocs left to witness for an ancient landslide.

Risk of landslide

When large scale landslides are contemplated, the following cases can be distinguished:

a) Structural failure along pre-existing, unfavourable discontinuity

b) Failure when the strength of the soil or of the rock mass as a whole is exceeded

With respect to the first case, based on available data and field observations, there is no evidence for the existence of such unfavourable discontinuities.

The second case needs more discussion. In the atypical area, on the slope below the flat, the fringe of weathered rock is generally thin. As a result of intense tectonic stress, the fracturing degree of the rock mass is relatively high. However, owing to the high rate of uplift, the slope angle is high and the superficial, highly weathered and fractured rock horizons are progressively dislocated and washed-off down the slope. As a consequence, the volumes of weathered, soil-like materials hanging on the slope in unstable position is limited.

Materials resulting from ancient instabilities are concentrated in the central part of the main slope, below the flat area (Illustration no.24). The field inspection indicated that these instabilities involved principally Turonian shales, the failure of which entrained subsequently the overlying massive limestone. These deposits are expected to evolve progressively 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. Mitigation measures, such as reshaping of the slope and drainage are recommended and can considerably reduce the risk.

Illustration no.24. 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 presented in this report 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 risk of sliding is always increasing with the pore pressure. The increasing of pore pressure locally within the 'atypical zone' can not be discarded, taking into account 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.

7 Conclusions and recommendations

General geological setting

The atypical setting results from tectonic deformation as opposed to major landslide. The overturned Mesozoic sequence which forms the RB slope downstream of the dam is not the consequence of dragging by ancient landslide(s), but the result of salt tectonics. In both cases, but especially 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 estimated more favourable for the slope stability.

Another important consequence of the present interpretation is that the eastern boundary of the atypical zone 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. If the landslide tear-off is discarded, spillway tunnels could be designed to cross this lineament. 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 recommended in order to provide reliable input data for the final design. Finally, it is highlighted that this is not a feasibility but a design issue.

The comparison with the previous interpretation is summarized below.

Atypical element	Previous interpretation	TEAS interpretation
Flat morphology	Piled-up, successive, large scale landslides	Combination of: shallow to moderate bedding dip, karst dissolution and shallow landslides
Bedding dip NW	Dragging by landslide	Tectonic deformation
Apparent offset of the layers	Tear-off discontinuity at the boundary of the landslide	Tight bending in response to tectonic deformation

Risk of landslide

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.

The volumes of weathered, soft materials hanging on the slope in unstable position is limited, the failure of such materials is not considered a major threat for the feasibility of the project. However mitigation measures (reshaping of the slope, drainage) are recommended in the areas with evidence of future instability.

The assessment of the stress-controlled global stability of the slope 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 in the atypical zone could be met. It is therefore recommended to design adequate drainage system for the main slope downstream of the proposed dam site.

Accordingly, the geological setting is rather favorable for the slope stability. Although this is not a feasibility issue, but a design constraint, mitigation measures must be implemented in order to control the risk linked to the pore pressure increase during the life of the project.

Recommendations

- Follow-up monitoring of the geodetic system implemented

- In order to clarify the nature and the characteristics of the eastern boundary of the atypical zone, it is recommended:

    - to finish the rehabilitation of gallery 1034

    - to excavate an exploratory drift around elevation 1100 masl across this lineament

    If major fracture zones are crossed, both these galleries could be equipped with devices for monitoring the deformation.