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Correlation between structural geological and geotechnical properties of the rock mass at the Lukovo Pole dam site

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Abstract

This paper presents the results from detailed geological investigations carried out at the Lukovo Pole dam site, and makescorrelation between the structural geological and geotechnical properties of the rock mass. This issue is particularly interesting in environments with a rather complex geological structure in which tectonics plays a significant role. By resolving the structural geological properties of the rock mass, we provide a proper way to direct the geotechnical investigations and have better understanding of the physical-mechanical characteristics of the rock.In this context, it is particularly important to know the reason for the formation of the terrain, the type of geological structure, and the nature of the discontinuities. The strike and dip direction of the foliation planes have essential role in defining the drainage character of the rock medium.

The Lukovo Pole Dam is located within the Western Macedonian province, which is distinguished as a separate geotectonic unit in Republic of North Macedonia. It is characterized by its complex lithological and tectonic composition, which is manifested by dominant presence of old paleozoic metamorphic rocks and intense folding. This kind of environment requires large scale of variable research methods and techniques. Therefore, for this purpose, numerous field investigations were carried out, consisting of: detail geological mapping, investigative drilling, water permeability tests, dilatometric tests, determination of joint strength testing with sclerometer, construction of investigative galleries, and geophysical tests. By this, the level of awareness for the lithological composition and tectonic impact of the rock mass was very high. These investigations were concentrated mainly along the axis of the dam, as well as the spillway and the diversion tunnel axis. The dam axis was analyzed as primary zone of interest where total of 14 investigative boreholes were performed. Additionally, side wise two investigative galleries were performed by which direct and detail overview for the geological structure was established.

As special zones of interest in these investigations are considered the sections where diabase intrusions and silification zones appear. What makes this research interesting is the water permeability data in these zones. Despite the high RQD values for both type of rock, water permeability in zones where meta-diabases appear is significantly higher compared to silification zones.

Keywords

Dam, Geology, Geotechnics, Research, Corelation.

1 Introduction

The Lukovo Pole Dam project is part of the Hydro Energetic System “Lukovo Pole” which is an integral partof system “KorabskiVodi”. This project is planned to be implemented in the near future and would complete the entire Korabski Vodi system. The Lukovo Pole dam is situated in the peripheral north-western parts of the Republic of North Macedonia, near the joint point between Kosovo, Albania and North Macedonia. The dam is located on the Crn Kamen River at an altitude of 1520 m on terrain that is part of the Korab mountain. According to the basic design dated from 1989, it has been planned to be arock-fill type of dam with height of 71m which makes the elevation of the dam crown to be 1591m. Maximum elevation of the lake is 1589m, and minimal 1540m. Total volume of water mass in the reservoir is $39x10^6m^3$, out of which life storage is $38x10^6m^3$. Investigations date from the early 70' of the past century and up to 2012 when the last investigations were carried out by the Civil Engineering Institute "Makedonija" J.S.C. - Skopje. During this 40-year time period, a substantial geotechnical documentation has been created that served as the basis for development of the Summary Elaborate for this object.

From a geological perspective, the Lukovo Pole dam is situated within the western Macedonian province, which is distinguished as a separate geotectonic unit in Republic of North Macedonia. Characteristic by its complex lithological and tectonic composition, this zone is manifested by dominant presence of old Paleozoic higly metamorphic rocks and intense folding. Dam site zone is composed of several types of sediments and most of all metamorphic rocks as well as intrusions that are to certain level influenced by metamorphism. Aside from this, the terrain is also characterized by quite distinctive structural-tectonic composition, manifested by fault structure created along the axis of old and eroded anticlinal structure. This complex structural-geological composition of the terrain has considerable influence on the overall engineering-geological characteristics of the terrain. As most significant are considered to be the results from the water permeability tests of the rock in zones where meta-diabase and silicified phyllites appear.

2 Performed terrain investigations

The overall field investigations at the Lukovo Pole dam site consisted ofvarious scope of field research: detailed geological mapping, investigative drilling, water permeability, piezometer installation, dilatometric tests, joint strength testing with Schmidt hummer, investigative galleries, and geophysical tests. For this paper as essential data, results from detail geological mapping, exploratory drilling, geophisical tests and water permeability tests were analyzed.

Geological mapping consisted of engineering - geological and hydro-geological mapping of terrain in the dam zone and the core from the exploration boreholes (Fig 1b). Due to the presence of sediments, the incisions used during the construction of access roads and drilling platforms were used as an auxiliary indirect method for determining the geological structure of the terrain (Fig.1a). By this, detail lithological composition and level of fracturing (RQD) was established on surface and in depth.



a) b)

Fig. 1 Geological mapping a) along an access road b) borehole core.

Drilling consisted of 27 vertical boreholes with total length of 1355m, out of which 14 at the dam axis, spillway tunnel 3, diversion tunnel 5, and river bed 5 boreholes. Their depth variates from 15min the river bed, up to 80m along the dam axis. Geophysical refraction seismic investigations in total length

of 2500m were performed along the diversion tunnel, spillway tunnel and dam axis, as well as perpendicular to the axes. By this sediment thickness and level of fissuring for separate lithological units were established. Water permeability test was performed in 13 boreholes, out of which 9 by "Lügeon" and 4 by "Lefranc" method. Although unusual for examining solid rock masses, the Lefranc method in this case showed quite interesting results for this geological environment.

3. Results and discussion

Based on detailed geological mapping of the terrain and the core from the boreholes, it has been determined that the terrain in the zone of Lukovo Pole dam site is composed of: alluvial and diluvial sediments, and philitic, chlorite-sericitic and meta-diabase as bedrock.

Alluvial sediments are noted within the riverbed and have maximum thickness of around 5m. They are composed predominately of coarse-grained gravel and cobbles with small presence of sand and boulders. In general, they are formed by erosion of the fluvio-glacial sediments situated sidewise in the valley (water accumulation area), and have relatively small transport by water. Diluvial sediments are detected on the right flank where they almost in total cover the metamorphic bedrock. Their thickness and composition are quite variable. Along the dam axis they go from 5m to 10m in thickness, but in some zones on the right flank (approx. 200 north), their thickness is up to 20m. In general, they cover most of the bedrock and make geological interpretation very difficult.

Bedrock formation is detected predominately by drilling and in smaller scale by detection via outcrops. This situation is result of very high fissuring level of the metamorphic rock complex in which the series of phyllites and chlorite-sericitic schist are dominant type of rock. All detected outcrops are presented by meta-diabase, quartz veins or silicified phyllites (Fig 2). These types of rock appear as more compact compared to the phyllites and chlorite-sericitic schist which are dominant in the rock massif. Low compressive strength and high fissuring level along and perpendicular to the foliation plane makes the series of phyllites and chlorite-sericitic schist to be defined as highly weathered. However, the phyllites situated on the right flank appear as most fissured. Their level of weathering is up to form of eluvial debris.

Meta-diabase outcrops are detected on two locations on the left flank of the dam site (Fig 3). They appear as irregular intrusions in the metamorphic complex and are engulfed by low level of metamorphism. Large outcrops of quartz veins are also noted on the left flank (Fig 3). Their formation is related to younger acidic intrusions which is probably younger than the meta-diabases. This conclusion comes by the fact that quartz veins are detected even in the diabase intrusions. However, the possibility for several stages of acidic intrusions is also an option. What makes them distinctive is the fact that they appear generally along the foliation planes of the surrounding complex of phyllites and chlorite-sericitic schist and rarely perpendicular to them.



a) b)

Fig. 2 Detected outcrops a) meta-diabase b) silicified phyllites with quartz veins.

Silicified phyllites are detected generally by exploratory drilling in various zones of the rock massif. Their appearance is related to zones where quartz veins usually appear. Together with meta-databases they present the relatively compact sections of the rock massif.

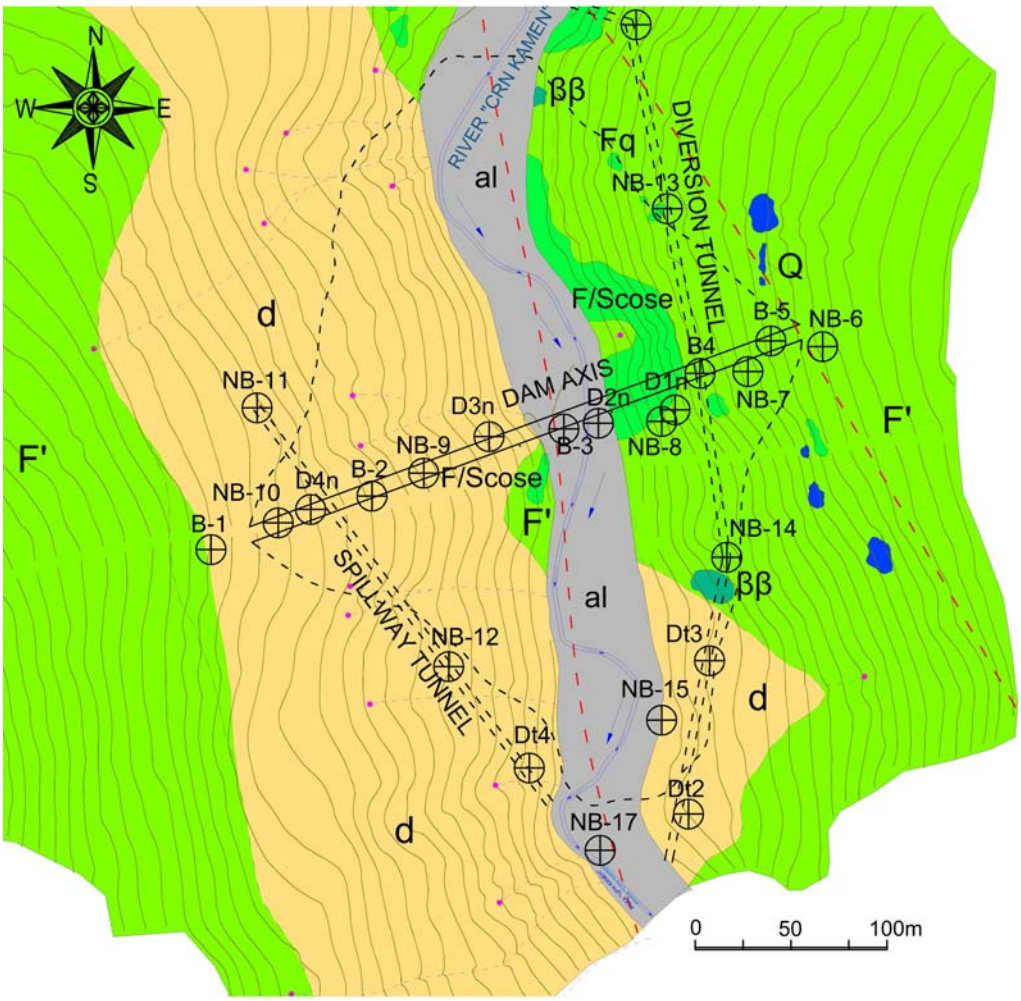
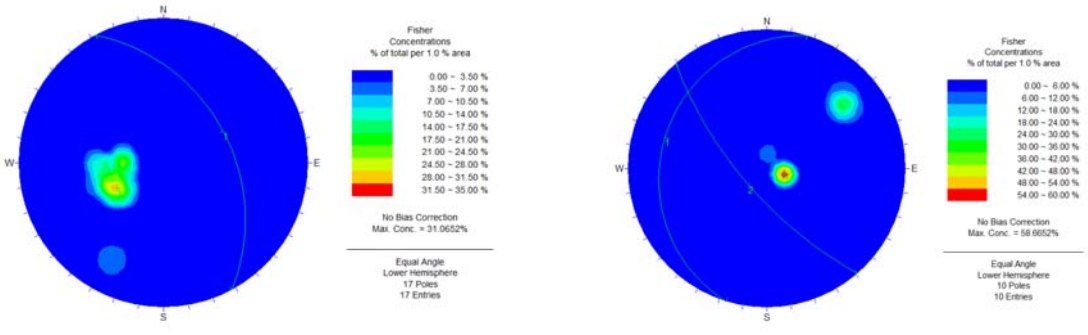


Fig. 3 Engineering-geological map of Lukovo Pole dam site.

Legend:**al**- alluvium, **d** - diluvium, **F'**- phyllites, **F/Scose** - complex of phylitic and chlorite-sericitic schists, **ββ** - meta-diabase, **Q** - quartz veins, B-1⊕ - borehole, _ _ _ _- fault (presumed)

By establishing the structural-geological data of the rock along the access roads, it was concluded that the dip of the foliation planes on both sides of the dam site have opposite dip direction and low to medium dip angle. On the left flank, general dip direction/ dip angle is 62/40°, and on the left flank 287/15° (Fig 4 &6). This situation indicates presence of eroded anticline structure along the axial plane which has perpendicular position towards the dam axis.



a) b)

Fig. 4 Stereo net plot of foliation data a) left flank b) right flank.

Most often in such cases the axial plane also represents a fault surface, i.e. during the formation of the folds, discontinuities appear along the axial plane. In this case, the hinge line represents the direction of the fault (Fig 5). Having in consideration that in our case all of the zone along the predicted hinge line is covered by alluvial sediments, the only logical possibility for defining the discontinuity in this case is as a presumed fault.

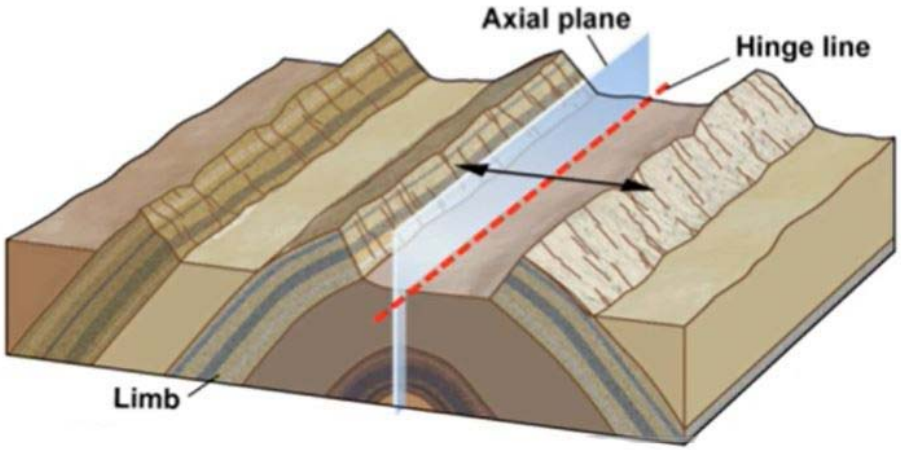


Fig. 5 Theoretical model of how the terrain was formed.

The linear occurrence of large outcrops of quartz veins on the left flank also provides indications of a possible faulting occurrence in that zone. This assumption is based on the fact that the linear sequence of quartz outcrops coincides with the direction of a fault determined north of the dam site (Fig. 3 & 6).

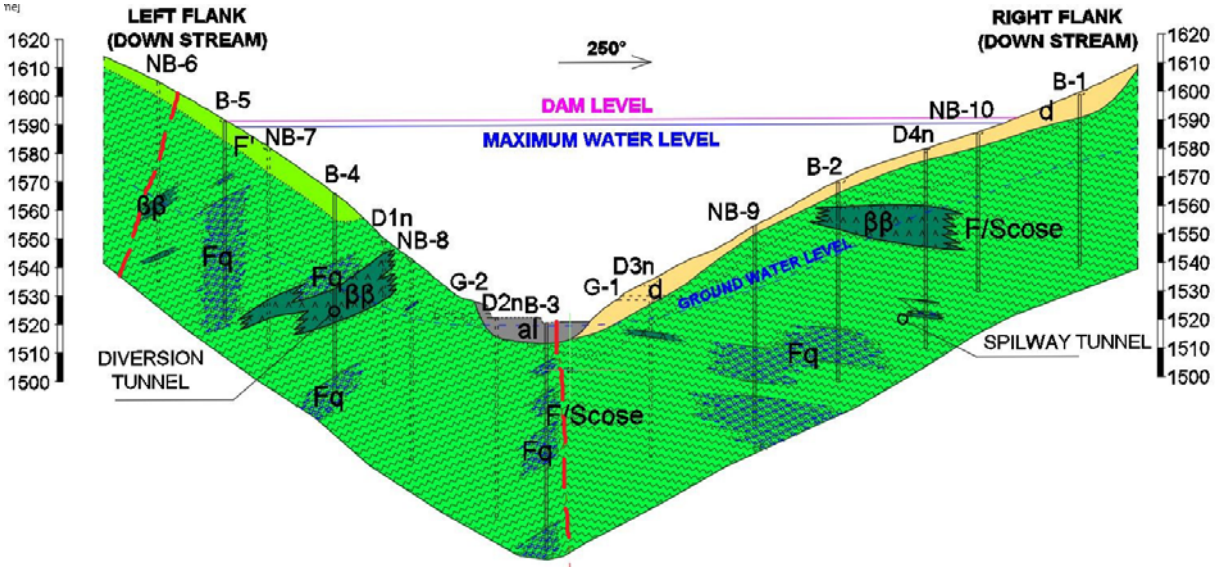


Fig. 6 Engineering-geological profile along the dam axis.

Legend:**al**- alluvium, **d** - diluvium, **F'**- phyllites, **F/Scose** - complex of phylitic and chlorite-sericitic schists, **ββ** - meta-diabase, **Fq** - silicified phyllites (quartz phylites), B-1 - borehole, _ _ _ _- fault (presumed)

In addition to the definition of the characteristics from laboratory examinations, and in combination with data from the field investigation analysis, systematization and classification of the acquired data was performed. Classification of the rock was done in categories (groups) with similar parameters i.e. geotechnical conditions for construction and work usage of the structure. For this purpose, categorization according RMR system of Bieniawski (1989) was performed (Table 1).

Nnecessary parameters were acquired from engineering-geology mapping of the area, mapping of the sampled core form investigation boreholes, as well as from laboratory examinations. Rating points are adopted as for separate parameters in the classification for each rock mass, as well as according the acquired RMR rating, (Table 1). The rating for the condition of joints for types of rock mass is performed according to detail classification of the discontinuities, where the length, opening, roughness, type of fill material and weathering level of the joint walls have been taken into consideration.

The correlation between structural geological properties and GSI and RMR values is based mainly on the genesis of the formation of the individual lithological members. Those that are relatively younger are more compact but with unfilled cracks, while the older phyllite shales are significantly more fractured but mainly filled with silty-clayey filler. This results in relatively higher water permeability mainly in metabasalts, and noticeably lower in phyllite schists.

Table .1 RMR classification of the rock at dam site zone.

P A R A M E T E R	**Rock type and points**		
	phyllite chlorite.-sericitic. schists (F/Scose)	**quartz phyllite (Fq)**	**meta-diabases (ββ)**
Uniaxial compressive strength	2	7	7
Rock Quality Designation (RQD)	3	8	13
Spacing between joints	5 - 8	10	10
Condition of joints	4 – 10	14	18
Underground water	7 - 10	4 - 7	0
Orientation of joints	-5	-5	-5
Rock Mass Rating(RMR)	**16 – 28**	**38 - 41**	**43**
Geology Strength Index (GSI)	24 – 33	49	58
Rock Mass Class	IV →V	IV → III	III

Geological Strength Index (GSI) was calculated as RMR - 5. In this case for RMR calculation 15 points for groundwater and 0 points for joint orientation ware established.

For adequate extrapolation from monolith to massif, the results from the rock mass classification were used for shear strength determination and the deformability of the massif. This extrapolation is done with the empiric non-linear criteria of failure criterion of Hoek & Brown:

$$\sigma_1 = \sigma_3 + \sigma_p \left(m_b \frac{\sigma_3}{\sigma_p} + s \right)^a \; ; \quad m_b = m_i \cdot exp\left(\frac{GSI-100}{28-14D}\right)$$

$$s = exp\left(\frac{GSI-100}{9-3D}\right) \; ; \quad a = \frac{1}{2} + \frac{1}{6}(e^{-GSI/15} - e^{-20/3})$$

σ_1, σ_3 – main perpendicular stress;
σ_p – pressure strength;
GSI – geology strength index according Bieniawski classification;
m_b, s, a – empiric constants deriving from GSI;
D – massif disturbance factor.

The value of the internal friction for the massif (φ_m), the cohesion of the massif (c_m) and the global strength of the rock massif (σ_{cm}) are acquired from the failure criterion of Hoek & Brown (2002), while the deformation modulus of the massif (E_{rm}) is calculated from the empiric formula of Hoek & Diederichs (2006). Results from the calculations are presented in Table 2.

Table 2. Estimated parameters for the shear strength of the rock.

Rock type	**σ_p [MPa]**	**GSI**	**m_i**	**m_b**	**s**	**a**	**γ [kN/m^3]**	**φ_m [°]**	**c_m [MPa]**	**σ_{cm} [MPa]**	**E_{rm} [MPa]**
F/Scose	10	28	6	0.195	1.00×10^{-4}	0.526	25.0	24.28	0.073	0.506	238.74
	10	27	6	0.078	1.57×10^{-5}	0.527	26.0	22.26	0.031	0.308	174.74
	2	24	5	0.134	3.97×10^{-5}	0.533	25.0	17.91	0.016	0.079	34.11
	10	33	7	0.288	1.00×10^{-4}	0.518	26.0	27.04	0.096	0.649	345.76
	8	24	5	0.134	3.97×10^{-5}	0.533	26.0	19.09	0.058	0.315	184.17
Fq	25	49	8	0.209	2.00×10^{-4}	0.506	26.0	33.48	0.129	1.490	1063.0
ββ	35	58	12	0.597	9.00×10^{-4}	0.503	26.0	43.09	0.266	3.625	2265.3
	35	58	10	0.498	9.00×10^{-4}	0.503	26.0	41.44	0.263	3.321	2265.3

Geophysical refraction seismic profiles were performed along and perpendicular to the axis of the dam, spillway and diversion tunnel. According to the obtained velocities of spreading of the elastic waves, three characteristic media were distinguished. Along the axis of the dam site, the first distinguished elastic medium has values of the waves ranging from 400 to 970m/s, and mainly refers to diluvial sediments and rock that is totally weathered and fissured on the surface up to level of diluvial debris. The values of the second zone are between 1580 and 1850m/s and it is a zone that corresponds to a fissured rock mass mainly represented by phyllites. The third zone has the highest values of the elastic waves ranging from 3520 and 3960m/s. This zone corresponds to a relatively less fissured rock mass and is defined as a zone of rock mass of best quality. These investigations did not result in spreading velocity values higher than 4000m/s. This indicates that generally the entire rock mass is significantly fissured.

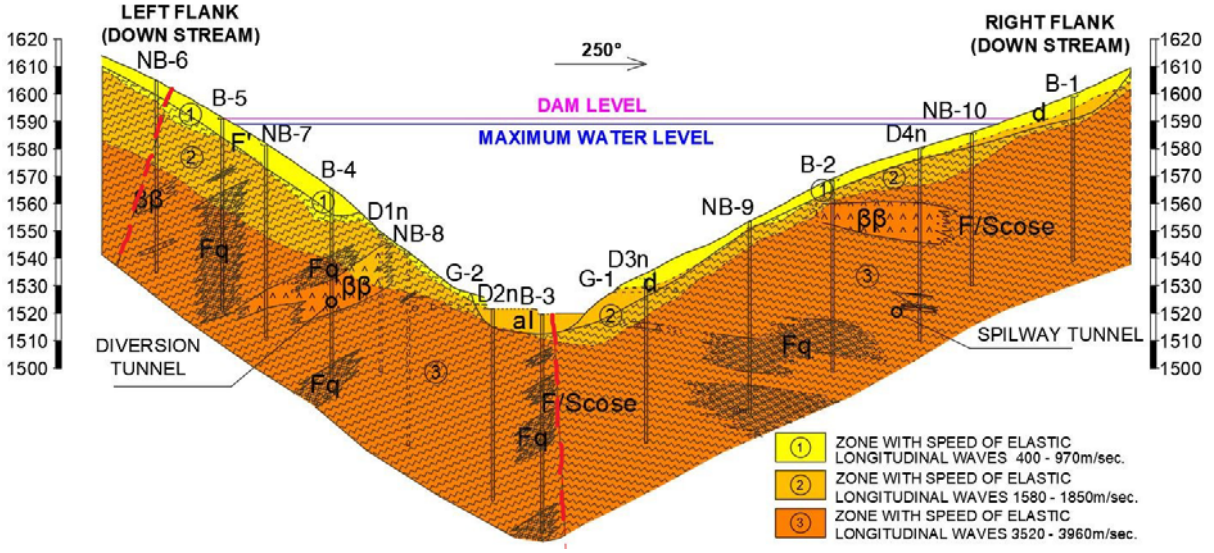


Fig. 7 Engineering-geological model by parameter of seismic waves along dam axis.

Legend:**al**- alluvium, **d** - diluvium, **F'**- phyllites, **F/Scose** - complex of phylitic and chlorite-sericitic schists, **ββ** - meta-diabase, **Fq** - silicified phyllites (quartz phylites), B-1 - borehole, _ _ _ _- fault (presumed)

Water permeability test was performed in 13 boreholes. In 9 boreholes the water permeability test was performed by applying both, the complete and brief Lugeon's method of injecting water under pressure of 0-2-4-6-8-10-8-6-4-2-0 Bar. In 4 boreholes (NB-6, NB-7, NB-8 и NB-9) water permeability was performed by applying the Le Franc method.Highest values (2.84 l/sec.) are registered in borehole NB-9.

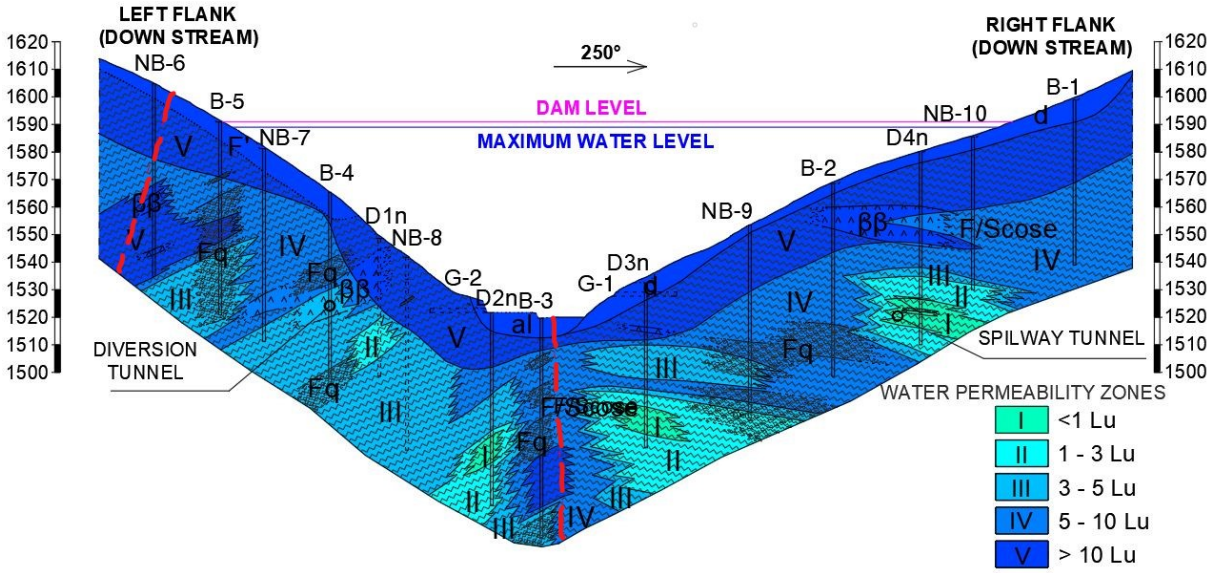


Fig. 8 Engineering-geological model by parameter of water permeability along dam axis.

Legend:**al**- alluvium, **d** - diluvium, **F'**- phyllites, **F/Scose** - complex of phylitic and chlorite-sericitic schists, **ββ** - meta-diabase, **Fq** - silicified phyllites (quartz phylites), B-1 - borehole, _ _ _ _- fault (presumed)

Based on the analyses of the water permeability, it is obvious that in the surface zones with rather degraded rocks and wide joints, there is a high degree of permeability. An interesting data is the water permeability tested in areas of meta-diabases, where there were zones to which it was impossible to reach the designed flow so that it was calculated by the analytic extrapolation per Lugeon, the method of quasi-Lugeon. The reason for occurrence of such high degree of permeability (> 50 Lü at D1n, &> 80 Lü in D2n) is the stiff structure of the meta-diabases i.e. their joints are stiff, hard without filler compared to the phyllitic schists where the joints are filled with clay and silt.

The highest values for water permeability of the rock massif in depth were determined in borehole B-3, which is located in the lowest part of the terrain. This indicates presence of a fault which is positioned along the axial plane of fold.

4 Conclusion

Based on the previously noted data from the field and laboratory research, it can be concluded that the location where the Lukovo Pole dam is designed, represents a complex geological environment with a variable geotechnical parameter of the rock mass.

By analysing the structural data from geological mapping and the water permeability of the rock mass, it can be concluded that the dam is situated on an eroded anticlinal structure along whose axialplane fault structure was formed thru which the erosion process took place. The presence of this fault was indirectly confirmed by water permeability test in B-1 where big values (>5Lu) were detected all the way up to 70m depth. The anticlinal form was established by analyzing the dip amount of foliation planes from both sides of the dam site where approximately symmetrical but opposite dip of the foliation planes was detected.

Special attention is drawn to the occurrence of meta-diabases, where the highest values of water permeability of the rocks have been determined. This situation is a result of the wide openings and unfilled cracks in this type of rock. On the other hand, quartz-phyllites, which also have increased hardness and are even somewhat more fractured than diabases, have significantly lower water permeability values. This stems precisely from the fact that the presence of fine grained (clay/silty) filling in the cracks was determined in borehole core. This is most likely a result of the relatively young age and disorder of the basalt intrusions, as well as the mineralogical-petrographic composition itself, which, in comparison with phyllites, is not of clay origin. What is also characteristic is the planar distribution of water permeability, which, with the exception of the fault zone, is mainly directed along the foliation planes.

Considering the fact that the analyzed structure represents an eroded anticline, it can be concluded that it represents a medium with drainage character. Unfavorable strike and dip direction of the foliation planes on both flanks have crucial role in this case. This actually represents the essential connection between the structural geological form and the geotechnical properties of the rock mass. Relatively younger meta-diabase and quartz intrusions play significant role in formation of more compact and solid sections inside the medium, but also more water permeable. By resolving the structural geological properties of the rock mass in this case, we provided a proper way to direct the geotechnical investigations and have better understanding of the physical-mechanical characteristics of the rock.

Generally speaking, it can be concluded that this is a rather complex geological environment with a specific structural property in which, despite the high level of exploration, it is difficult to precisely distinguish quasi-homogeneous zones with similar geotechnical properties.

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