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INFLUENCE OF STRUCTURAL-GEOLOGICAL PROPERTIES IN DETERMINATION OF ENGINEERING-GEOLOGICAL QUASI-HOMOGENEOUS ZONES WITHIN A MONOLITHOLOGICAL ENVIRONMENT AT THE "OTINJA" DAM SITE

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A b s t r a c t: This study presents the results from research of influence of structural-geological properties for defining engineering-geological quasi-homogeneous zones within the monolithological granite environment of the Otinja dam site. For this purpose, a series of field investigations and tests were carried out, which consisted of detailed geological mapping of the foundation pits and core from exploratory boreholes, as well as sclerometer tests of the rock. In addition, cadastres of discontinuities and sclerometer tests were formed. Based on a detailed analysis of obtained data, four quasi-homogeneous zones were distinguished within the granite massif. In addition, the excavation conditions for each of these quasi-homogeneous zones were defined. By preparing engineering-geological maps and profiles, their representation on the surface and in depth was defined. By analyzing fracturing contour diagrams, the influence of dominant fracture systems in different parts of the terrain was determined. It has been concluded that the greatest influence on the fracturing degree is exerted by the faults on the right flank of the dam site, where five different fracturing systems are present. It has also been determined that the degree of fracturing in zones with leucocratic granites is significantly lower.

Key words: mapping; discontinuities; cadaster; classification; sclerometer; excavation

INTRODUCTION

On 7 July 2021, began the "Otinja" Dam project. According to the previously performed detailed geological explorations for design level (Jovanovski, 2018), relevant data was obtained based on which the excavation and foundation elevations for this object were defined. However, in practice, for structural-geological properties of the terrain there are almost always certain deviations in terms of design and data obtained during excavation of foundation pits (Aswar et al., 2022). Often this occurs in mono-lithological environments, such as the granite massif in the zone of the "Otinja" dam site. This primarily refers to the occurrence of certain fault structures and joint sets that are difficult to detect due to high degree of surface rock weathering, or sediment coverage. In such cases, the exploration level of the terrain obtained by vertical surveying using structural boreholes, or geophysical surveys, does not represent a linear value, i.e., there is no proportional dependence between the level of exploration and the level of awareness (Best, 1984). This situation results in a certain deviation from the initially determined structural-geologic data, quantities of rock mass by excavation categories, and due to this, a certain change of foundation elevations for the structure (Stapeldon, 1976). Therefore, during the excavation phase, it is very important to make detail analysis of the structural-geological properties, and assess the condition of the rock mass in "one to one scale" (Paige, 1950).

In the R.N.Macedonia, according to the technical norms for excavation of rock mass in civil engineering, the so called GN200 Brauns-Stini norm is used (Jovanovski et al., 2012). In accordance to this norm, the entire rock mass is divided into 7 categories through which the method of excavation is determined, and due to this the cost of excavation. This situation results in need for determination of quasi-homogeneous zones within the granite massif, which would be based on fracturing level and physical condition of the rock mass (Jiongchao et al., 2020). For this purpose, in order to have better engineering-geological overview of the terrain, several rock mass classifications and categorizations were applied.

METHODOLOGY AND USED EQUIPMENT

According to standard practice in geotechnical engineering, during excavations for foundation of the dam (Figure 1), a detailed geological mapping of construction pits was carried out. By this, all structural geological characteristics that define the division of quasi-homogeneous zones within the rock massif had been determined. In addition to determination of all registered discontinuities (faults and fracturing sets), using sclerometer (i.e., Schmidt hammer), surface examination for establishing physical-mechanical condition of the rock was also performed (Aydin and Basu, 2005). With combination of these two methods, precise data was obtained by which quasi-homogeneous zones were defined. To that aim, cadasters of discontinuities, and sclerometer rebound values were created.

Fig. 1. Geological mapping of foundation pit at the Otinja dam

During the geological mapping of the construction pits (Figure 1), special emphasis was given to joint sets because they represent a basic structural element for determining the fracturing level of the rock mass (Palmstrom, 2001). Also, joint length, visibility, mutual distance, opening width, type of infill, surface roughness, and water presence where noted for each discontinuity (Ulusay et al., 2007). These data were also used for calculating slope stability in some excavation zones. For this process, as a special zone of interest are considered the fault locations because often, they can represent the border between the quasi-homogeneous zones (Xiao et al, 2016). As elementary tool for this purpose a "Brunton" type of geological compass was used.

Essential parameters for defining the fracturing level of the rock mass are determination of the rock quality designation (RQD) and fracture spacing (Ls) parameters (Zhang, 2016). RQD was established along the axis of the foundation pits simultaneously having in consideration the vertical impact on both sides of the pit. "Ls" was determined side wise. RQD was also defined for the borehole core.

Important segment of geological mapping for this purpose is also macroscopic determination of mineralogical-petrologic properties of the rock mass. The overall strength of the rock depends on the proportion within the rock mass (Keikha and Keykha, 2013). Also, the degree of mineralogical decomposition of individual minerals can have a major impact on the physical-mechanical condition of the rock. As special zone of interest is considered quartz streaks and zones of silicification, since they usually increase the mechanical strength of the rock.

Sclerometer tests were performed on average for every 10 – 15 m distance along the foundation pits (Figure 2). The procedure was applied by min. 20 strikes for each measurement point, out of which average arithmetic value was established (Aydin, 2009). Also, for each measurement, testing angle is recorded as it has essential impact to the results. For this purpose, L-type PCE-HT 75 sclerometer model was used, which has 0.735 Nm impact energy (Lozano, 2025).

Fig. 2. Sclerometer test point in leucocratic granite

Approximate value of uniaxial compressive strength (UCS) of the rock mass was obtained by the correlation chart between UCS and Schmidt hammer rebound value (SHRV) (Figure 3). For this purpose, also rock density input data was used. Rock density was determined according to B.B8.032 [MKS] standard. Then the joint compressive strength (JCS) of the rock mass for every measurement point was determined. This was provided by using standard empirical formula (Barton et al., 1977):

$$\log_{10}(\mathrm{JCS}) = 0.00088\gamma R + 1.01$$

where

JCS = joint wall compressive strength (MN/m^2 or MPa)

γ = dry density of the rock (kN/m^3)

R = Schmidt hammer rebound value

Detail information for structural-geological properties (joint sets and faulting) was provided by joint stereonet analysis. This was performed by using DIPS v5.0 software.

By providing analytical data for the discontinuities of the rock mass, as well as the values for the UCS and JCS, basic hardness parameters for excavation conditions were established.

Based on the overall terrain investigation, detailed engineering geological maps and profiles in scale 1:100 and 1:200 were produced. This way, detailed divisions of quasi-homogeneous zones within the rock massif were provided.

RESULTS AND DISCUSSION

Based on geological mapping of the terrain, several types of sedimentary and two varieties of granite rock were determined (Dumurdžanov and Petrov, 2005). The sediments are represented by proluvial granite debris and clayish layers with small thickness on the flanks, and alluvial gravel sediments within the river bed. Granite rocks mainly appear with fine-grained texture and in gray color, and less often as leucocratic with a porphyritic texture. Detail overview of the rock mass in general was established while performing the foundation pits for the dam, spillway and drainage pipeline. The excavation was performed predominantly in monolithological granite rock by using excavator, hydraulic hammer and partially with blasting. From beginning this gave a clear picture of the physical-mechanical condition of the rock mass, which basically depends on the degree of fracturing and the strength properties of the rock and rock discontinuities.

In addition, zones with different degrees of fracturing and joint orientation sets were distinguished (Dumurdžanov, 1999), as well as zones with different petrological composition of the rock mass. As most representative zone in terms of structural and physical-mechanical variability is considered to be the axis along the drainage pipeline. In this zone the biggest variation for SHRV values and fracturing sets is registered (Table 1).

T a b l e 1

Sclerometer test results along drainage pipeline foundation pit

No.	Station	Type of rock	Hammer orientation	SHRV (average)	γ (kN/m³)	JCS (Mpa)	UCS (≈Mpa)
1	0+10m	granite	↙	18	26,20	25,55	38
2	0+22m	granite	←	34	26,20	53,96	62
3	0+22m	granite	↙	19	26,20	25,82	37
4	0+30m	granite	←	39	26,20	66,34	83
5	0+30m	granite	↙	25	26,20	33,90	50
6	0+36m	granite	↖	33	26,40	52,03	70
7	0+44m	granite	←	37	26,40	60,88	71
8	0+53m	granite	←	40	26,40	70,61	87
9	0+58m	granite	↙	41	26,40	76,70	96
10	0+71m	granite	↙	39	26,40	66,97	93
11	0+78m	granite	←	39	26,40	69,46	89
12	0+94m	granite	←	36	26,40	59,36	55
13	0+100m	granite	↙	33	26,40	51,35	72
14	0+112m	granite	←	39	26,40	68,78	88
15	0+115m	granite	←	45	26,40	92,72	112
16	0+120m	granite	↙	58	26,70	177,11	220
17	0+133m	granite	↙	52	26,70	132,89	153
18	0+155m	granite	↙	57	26,70	166,71	185

Obtained results for approximate values of uniaxial compressive strength (UCS) of the rock mass is presented on the following UCS / SHRV correlation chart (Figure 3).

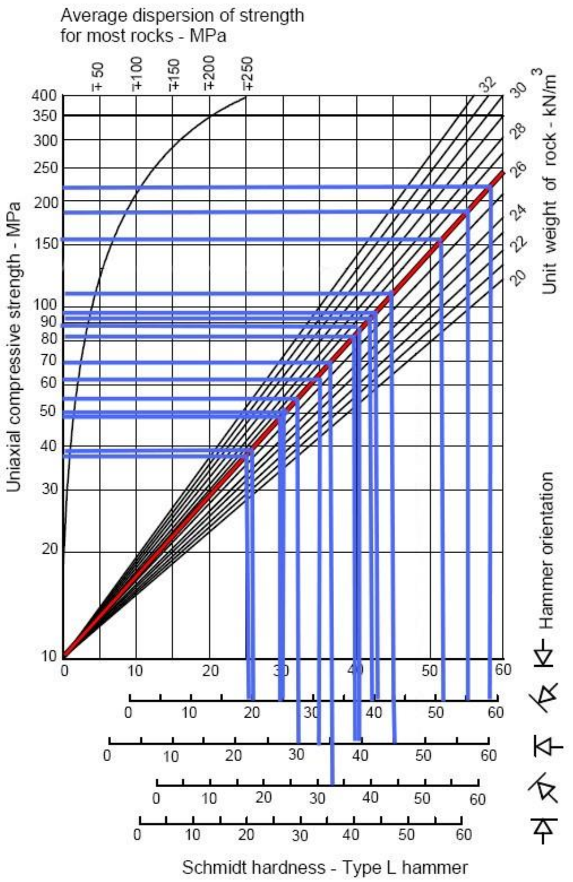

Fig. 3. Correlation chart between UCS and Schmidt hammer rebound value (SHRV)

By combining the obtained data from sclerometer tests (UCS & JCS) and fracturing level of the rock mass (RQD), four quasi-homogeneous zones were defined:

γ Low fissured and very little altered granite rock with occurrence of 1 or 2 joint sets and big joint spacing. Value of JCS is generally >100 MPa.

γ′ – Medium fissured and locally altered granite rock with occurrence of several (2 to 4) joint sets and medium joint spacing. Value of JCS is in range 50 to 100 MPa.

γ″ – Highly fissured and altered granite rock with occurrence of 4 or more joint sets and very close joint spacing. Value of JCS is in range 25 to 50 MPa.

γ‴ – Totally fissured and completely altered granite rock. Value of JCS is generally <25 MPa.

As usual, obtained UCS values in this case are higher than those for JCS (Engin, 2026). Characteristic for these results is the small variation between the values of UCS and JCS. For low fissured granite (γ) UCS value is on average 19% higher, for medium fissured granite (γ’) is 22%, and for highly fissured granite it is 32%. This makes approximate variation of around 13% between low and high fissured granite zones. The reason for relatively small deviations in ratios between low and highly fissured granites is considered to be the roughness of the joint surfaces, which in this case is smooth and almost uniform. As main cause for difference in UCS/JCS values can be considered to be the degree of fracturing of the rock mass and the uniform dip angle of the joint sets, which in this case is quite steep. However, for totally fissured and completely altered granite rock (γ’’’), no such correlation can be provided because in most cases no measurement data can be obtained. The rock is usually so soft that no rebound value on the Schmidt hammer is registered.

For better overview of the quasi-homogeneous zones, several types of rock classifications have been used.

Geological strength index (GSI) is one of most used classification (Hoek, 1994). Since there are several ways to calculate GSI (Vasarhelyi et al., 2016), in order to establish the connection between RMR and GSI, in this case as most suitable was chosen the one that takes in consideration rock quality designation (RQD) and joint wall conditions ($J_{cond\text{-}89}$) (Hoek et al., 2013):

$$GSI = 1.5\ J_{cond89} + 0.5\ RQD$$

According to this formula, following results were obtained (Table 2):

T a b l e 2

Result for GSI calculation

Q.H.Z.	RQD	J_{cond89}	GSI
γ	17	25	40 – 55
γ’	13	20	30 – 40
γ’’	8	10	15 – 25
γ’’’	3	0	0 – 10

Obtained results from GSI calculation are graphically shown on the following chart (Figure 4).

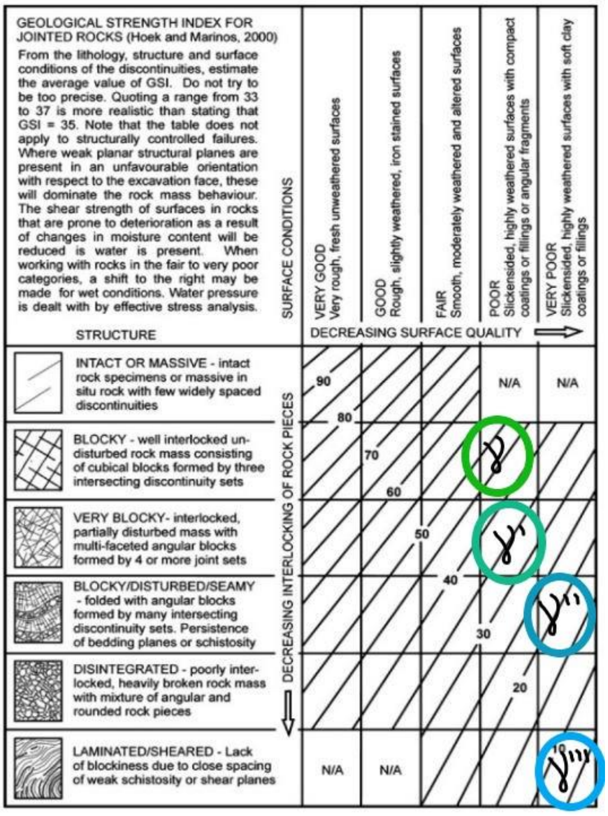

Fig. 4. GSI chart for obtained results
(Chart according Marinos and Hoek, 2000.)

As more important in this case are considered classifications for the rock masses with reference to excavatability. For this purpose, two-parameter classification charts have been used in which one of parameter is density spacing (Ls), and the other is uniaxial compressive strength (UCS) and bulk density (Figures 5 and 6).

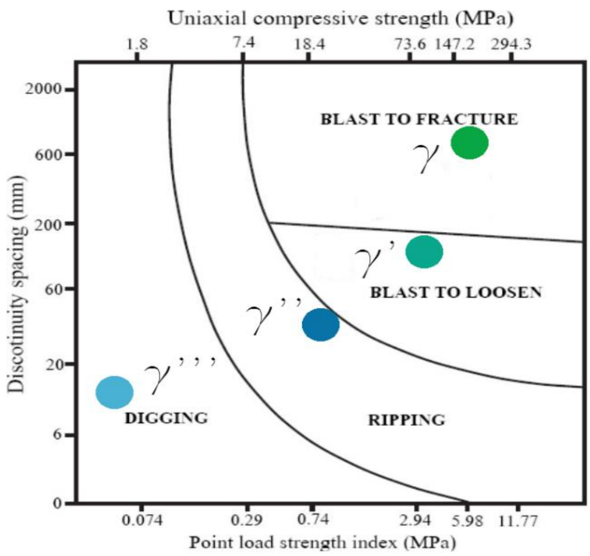

Fig. 5. Assessment of rock masses with reference to excavatability classification system (Franklin et al., 1971)

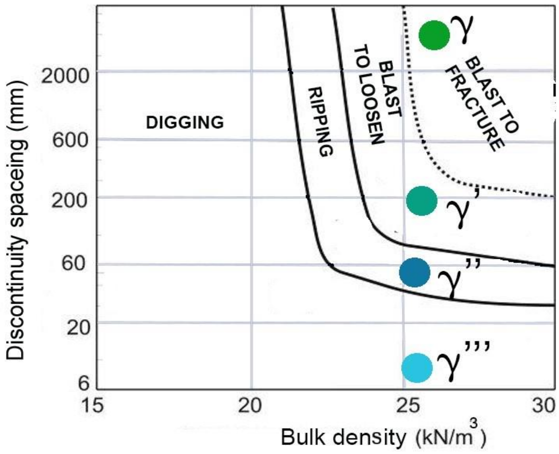

Fig. 6. Assessment of rock masses with reference to excavatability classification system (Jovanovski, 2018)

By comparing the result from the charts (Figures 5 & 6), it is obvious that all four types of granite that represent the quasi-homogeneous zones are clearly distinguishable by reference to excavatability. However, in most cases the border between the zones represents gradual transition. By this, it is important to note that the border between γ & γ'' and γ''' & γ''' is more clearly visible than the one between γ' & γ''. The easiest to distinguish are the zones with the occurrence of leucocratic granites where the demarcation between the zones is most clearly visible (Figure 7).

Fig. 7. Border between γ'' gray granites
and γ' leucocratic granites

Also, in some cases a fault structure is noticed to represent the border between the zones. This case is generally dominate on the right flank of dam site and is mostly noticeable within the dam foundation pit (Figure 8). As previously noted, the mineralogical and petrographic properties of the granite rock mass also have significant impact. Besides occurrence of leucocratic type of granite, frequently small enclaves (2 – 3 m in size) of gneiss appear in the main granite mass.

Fig. 8. Tectonic border between γ'' highly fissured and γ' medium fissured gray granites

They are result of assimilation of an older neighboring metamorphic rock complex during the process of granite plutonism. These gneiss enclaves generally have lower physical properties compared to surrounding rock, and are very distinguishable.

The process of silification and mineralization also have significant impact to structural properties of the granite rock mass. This process is registered predominantly on the right flank of the dam site, during excavation of the foundation pits and by core drilling. It is manifested by long thin quartz and pyrite streaks, and silification of surrounding host rock. In these zones joint surfaces are predominately covered with dark and yellowish oxidation layer which gives negative physical impact to the rock.

For detail structural-geological analysis stereonet for discontinuities of the granite massif, was created (Dumurdžanov, 1999). This way, detail overview for total amount of joint sets and dominant discontinuities was created (Figures 9, 10, 11).

By analyzing the joints stereonet, it was determined that in the middle (bottom) part of the dam there are three dominant joint sets (DA: 57/58°, 297/82°, 234/71°). The analysis was performed on 53 measurement points, and it was concluded that the most dominant is the one with DA 57/58°..

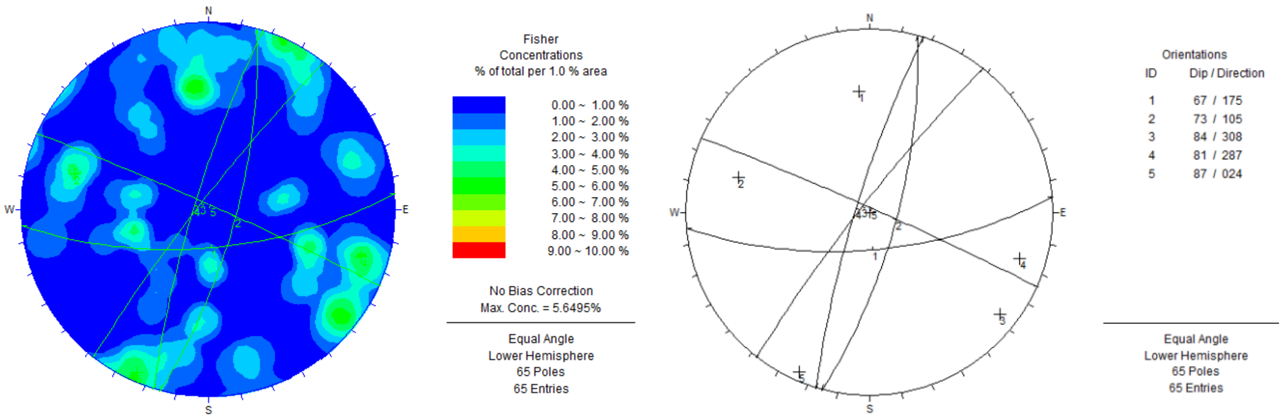

Fig. 9. Joint stereonet analysis for left flank of the dam (DIPS v5.0.)

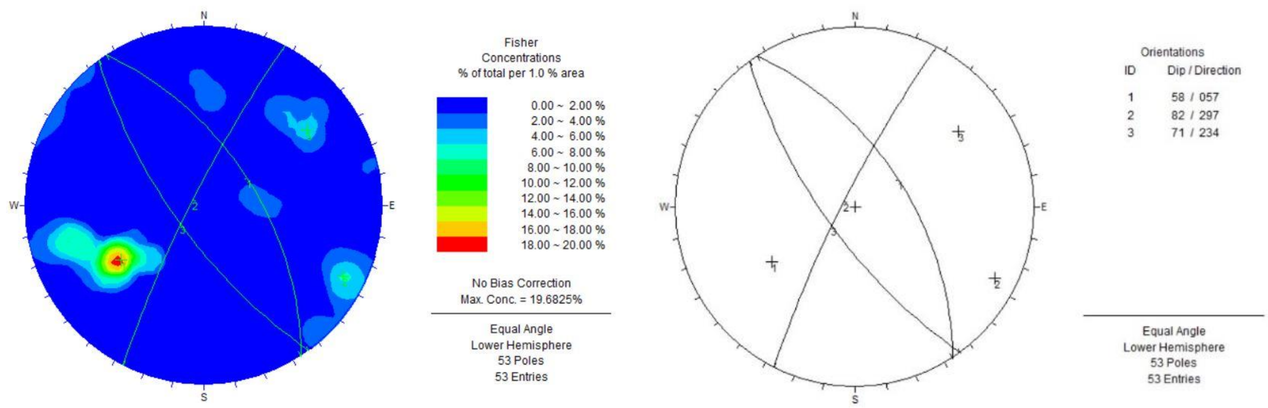

Fig. 10. Joint stereonet analysis for middle (bottom) part of the dam (DIPS v5.0.)

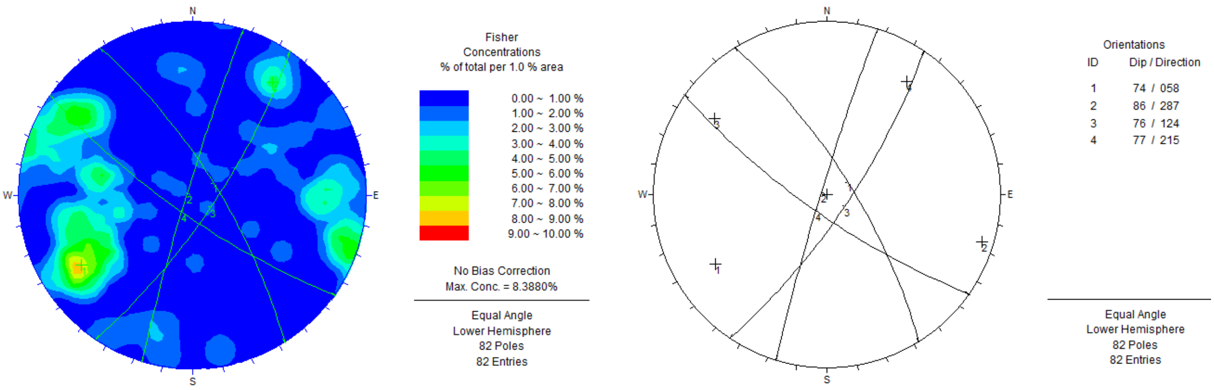

Fig. 11. Joint stereonet analysis for right flank of the dam (DIPS v5.0.)

On the left flank, the analysis was performed on 65 measurement points, and 5 joint sets were determined (DA: 175/67°, 105/73°, 308/84°, 287/81°, 24/87°) which are in general evenly distributed. Such systematic joint characterization consists of established engineering-geological practices for dam site investigations, ensuring reliable input for stability assessment and engineering-geological zoning.

On the right flank, the analysis was performed at 82 measurement points, where 4 joint sets were determined (DA: 58/74°, 287/86°, 124/76°, 215/77°). Similar to the left flank, a uniform distribution of joint systems was also concluded.

Regarding faulting, at the bottom (middle) section of the dam site four major faults were registered with following dip direction/angle DA 225/60°, DA 218/60°, DA 147/75°, and DA 60/58°. As most important is considered the last one: (DA 60/58°) since it has the greatest impact to the fracturing set occurrence.

On the left flank also four major faults were registered with following dip direction/angle DA 350/80°, DA 282/76°, DA 220/78°, DA 258/78°.

In this section almost all noted faults have equal impact to the fracturing sets.

The right flank of the dam site is considered as most fissured. Here also four major faults are registered: DA 218/80°, DA 82/46°, DA 120/80°, DA 224/88°. As most influential is considered the one with dip direction/angle DA 82/46°.

Based on previously noted geological research and examinations, an engineering geological map for the Otinja dam site was created (Figure 12).

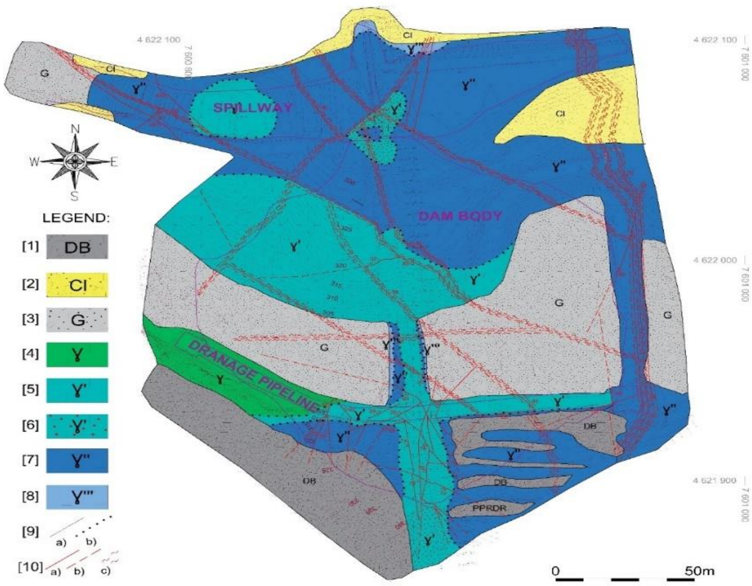

Fig. 12. Engineering geological map of the "Otinja" dam site.
Legend: [1] sandy to dusty debris, [2] sandy to dusty clay with debris, [3] sandy gravel, [4] low fractured granite, [5] medium fractured granite, [6] medium fractured leucocratic granite, [7] highly fractured granite, [8] totally fractured and altered granite, [9] lithological border: a) normal b) gradual transition, [10] fault: a) established, b) approximated, c) fault zone

As previously noted, definition of quasi-homogeneous zones in depth was carried out using core data from structural boreholes. Fracturing level was determinate by using RQD parameter on one meter interval. This was performed on 21 vertical and inclined boreholes. This way fault spreading in depth was also detected (Figure 13).

Fig. 13. Core from ID 25 vvborehole

Sharp increase of fracturing level and appearance of oxidation minerals and stretch marks on joint surfaces clearly indicated the fault presence in depth (En-Chao et al., 2007).

For detail overview of the rock mass, engineering geological profile along the dam axis was created. By this, detail information for quazi-homogeneous zone spreading in depth was determinate (Figure 14).

It has been determined that the rock mass on the right flank is significantly more fissured in depth compared to the rest of the granite massif. Almost in every borehole there are traces of secondary minerals on the joint surfaces (Staněk and Géraud, 2019; Ait Baha et al., 2025).

At the lowest elevations of the terrain, in the foothills of the right flank, the lowest fracturing has been determined. This was established by borehole I37 which is located between two larger faults (DA 147/75° and DA 60/58°) (Fig. 14). Registered RQD value ranges from 40% to 95% which most importantly is almost evenly distributed in depth. This makes this zone to be defined as relatively isolated block in the granite massif.

Opposite to previously noted, the higher levels of the right flank are intensively fissured. This was determinate by several boreholes (I45, K2, K3, DK14, I57 & K4). RQD in this zone is predominantly 0% or frequently up to 25% (Figure 15).

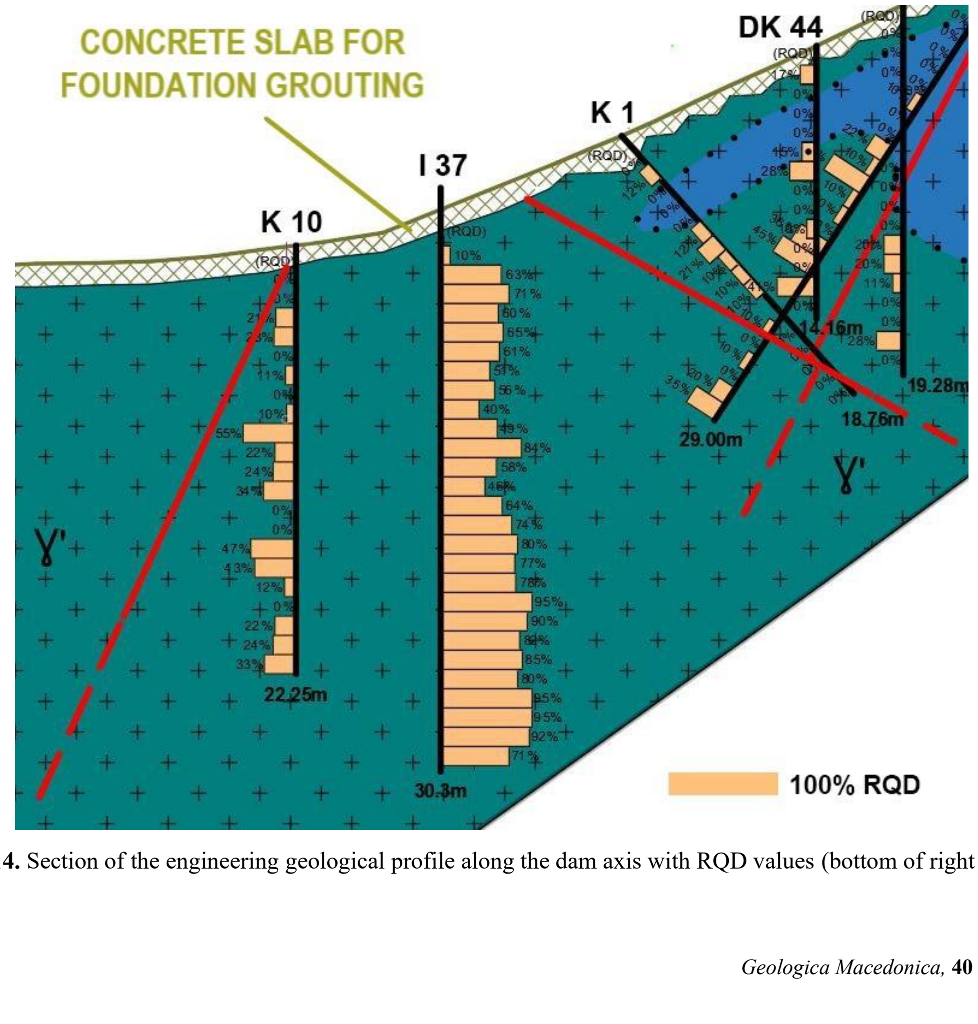

Fig. 14. Section of the engineering geological profile along the dam axis with RQD values (bottom of right flank)

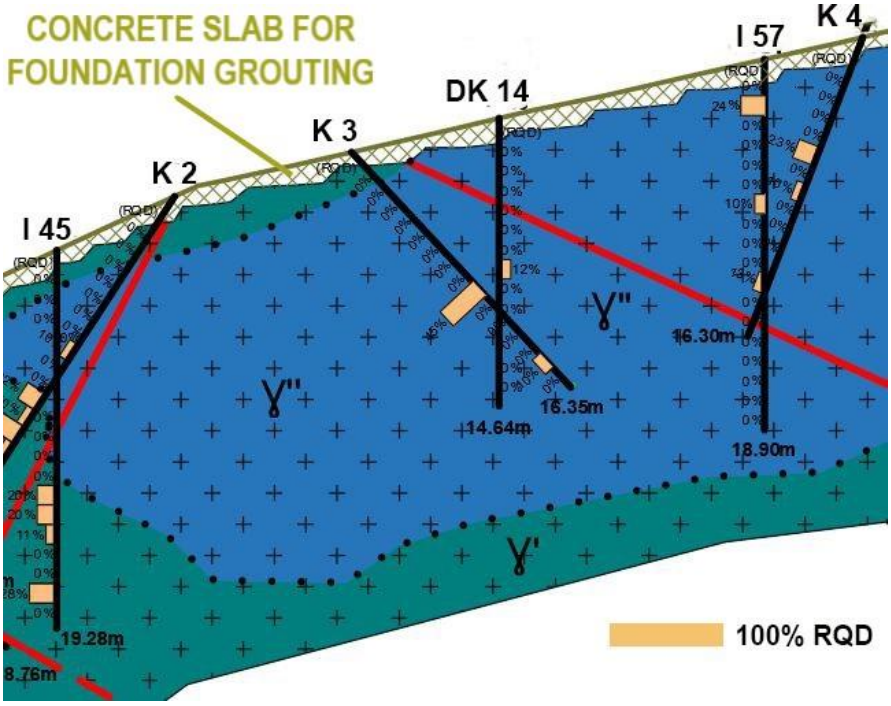

Fig. 15. Section of the engineering geological profile along the dam axis with RQD values (middle of right flank)

The left flank is considered as relatively less fissured compared to the right flank. This was concluded according to data from boreholes (I17, I5 & K7) (Figure 16). Although numerous faults have been identified here also, the rock mass is still more compact and solid compared to the right flank.

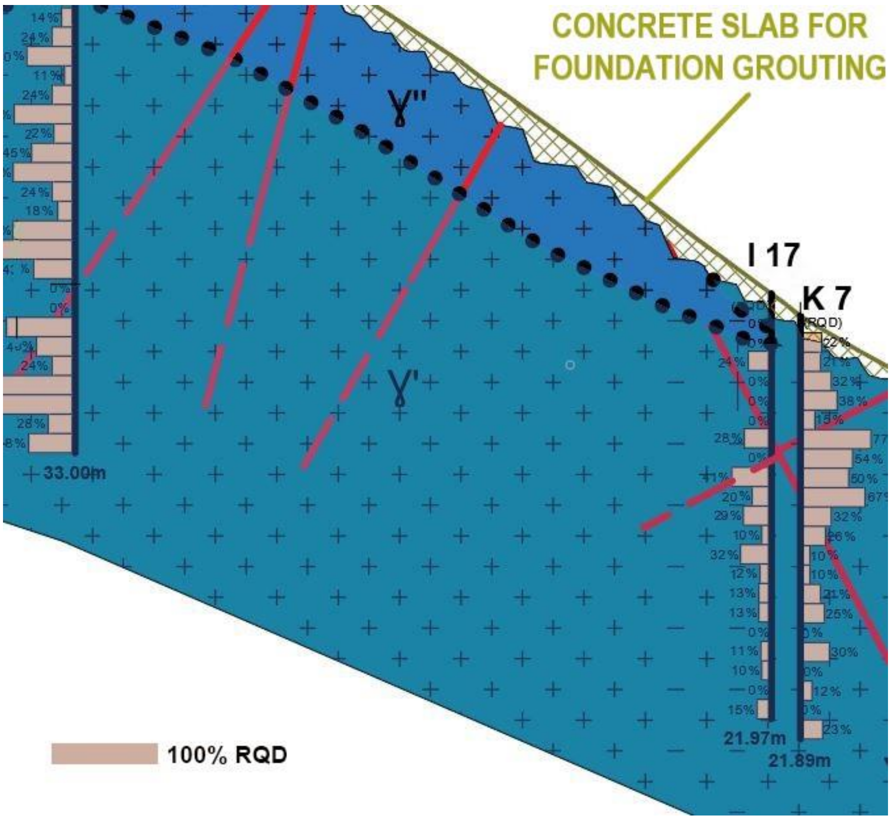

Fig. 16. Section of the engineering geological profile along the dam axis with RQD values (middle of left flank)

CONCLUSION

Based on comprehensive and detailed geological research, it has been determined that the terrain on which “Otinja” dam was designed represents a monolithological granite environment with complex structural properties. This terrain is dominated by major faults with a northwest-southeast trending direction, which are typical discontinuities in the Vardar geotectonic province. In addition, several lower-rank faults with various deepening elements also have been identified. This situation is result of influence of regional tectonics due to relative proximity of this granite massif (as part of the Vardar geotectonic province), to the Serbian-Macedonian geotectonic province to the east. According to structural-geologic data 12 major joint sets with variable level of fracturing have been registered. Most fissured is considered the right flank of the dam site where dominant faults appear. Although numerous faults have been registered on the left flank also, the rock mass is still more compact and solid compared to the right flank. As least fissured is considered to be the bottom (central) part of the dam site.

Also, it was noted that significant impact to structural properties have the mineralogical-petrologic composition of the granite massive. Leucocratic granites were determined within the dominant gray granite massif, as well as occurrence of quartz veins and silicification zones. At these sections the rock mass usually has better physical properties. Opposite to this, at several locations predominately on the right flank, small gneiss enclaves appear which have lower physical properties than the surrounding granite rock.

According to data form detailed geological mapping, and examinations with sclerometer, four quasi-homogeneous zones were determinate: low fissured – γ', medium fissured – γ', highly fissured – γ'', and totally fissured granite rock – γ'''. These quasi-homogeneous zones in general have clearly distinguishing structural and physical properties which are manifested during excavation. Due to this, excavation assessment was made, by which different types of excavation methods were applied: blast to loosen – γ, blast to fracture – γ', ripping – γ'', and digging – γ'''. Regarding the fact that in Republic of North Macedonia, GN200 ease of excavation categorization norm is still in use, excavation methods had to be accommodated to it. By this, the quasi-homogeneous zones were determinate as followed: γ' – VI cat., γ' – V cat., γ'' and γ''' – IV cat. It is important to note that within the separate zones, locally structural and physical propertiecs can vary greatly. The boundary between these zones is usually a gradual transition, except in cases where faults represent the dividing line. Also, it is important to note that inside these quasi-homogeneous zones some small variations of higher or lower category of rock mass appear. This situation is result of frequent appearance of gneiss enclaves or silification zones which were previously noted.

According to stereonet data, it was determined that in the middle (bottom) part of the dam there are three dominant joint sets (DA: 57/58°, 297/82°, 234/71°), on the left flank five (DA: 175/67°, 105/73°, 308/84°, 287/81°, 24/87°), and on the right flank four dominant joint sets (DA: 58/74°, 287/86°, 124/76°, 215/77°).

Regarding faulting, major occurrences are registered predominantly on the right flank (DA 218/80°, DA 82/46°, DA 120/80°, DA 224/88°) and at the middle (bottom) section (DA 225/60°, DA 218/60°, DA 147/75°, and DA 60/58°).

By data provided from borehole core, it was established that on the right flank highly fissured granite γ'' is present up to 20 m in depth. For comparison, on the left flank this zone is shallow (3 – 5 m). This situation is due to the fact that the right flank of the granite massif represents the contact zone with the older surrounding gneisses. At the central (bottom) part of the dam, relatively low fissured granite block between two major faults is registered. This appearance is most likely result of fracturing isolation by these two older faults through which the tectonic movement was absorbed.

According to all previously presented data, it can be concluded that structural - geological properties have great and complex impact to engineering-geological determination of quasi-homogeneous zones in the granite massive. This situation is result of combination between complex tectonic and petrological properties of the rock mass..

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ВЛИЈАНИЕТО НА СТРУКТУРНО -ГЕОЛОШКИТЕ СВОЈСТВА ПРИ ДЕФИНИРАЊЕ НА ИНЖЕНЕРСКО-ГЕОЛОШКИ КВАЗИ-ХОМОГЕНИ ЗОНИ ВО МОНОЛИТОЛОШКА СРЕДИНА НА ПРЕГРАДНОТО МЕСТО НА БРАНАТА „ОТИЊА“

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Клучни зборови: картирање; дисконтинуитети; катастар; класификација; склерометар; ископ

Во овој труд се прикажани резултатите од истражувањата за влијанието на структурно-геолошките карактеристики на карпите при дефинирање на инженерско-геолошки квази-хомогени зони во монолитолошката гранитна средина на преградното место на браната Отиња. За таа цел се извршени низа теренски истражувања и испитувања кои се состоеја од детаљно геолошко картирање на темелните јами и јадрото од истражните дупнатини, како и испитувања на карпите со склерометар. Формирани се катастри на дисконтинуитетите и испитувањата со склерометар. Врз основа на детална анализа на добиените податоци издвоени се четири квази-хомогени зони во рамките на гранитниот масив. На тој начин се дефинирани услови за ископ за секоја од овие квази хомогени зони. Со изработка на инженерско-геолошки карти и профили е дефинирана нивната застапеност на површината и во длабочината. Со анализа на контурни дијаграми на пукнатини е утврдено влијанието на доминантните пукнатински системи во различни делови од теренот. Утврдено е дека најголемо влијание врз степенот на испканоста имаат раседите на десниот брег од преградното место кадешто се застапени 5 различни системи на пукнатини. Исто така, е утврдено и дека степенот на испуканоста во зоните со леукократни гранити и силификација е значително помалку изразен.