World Journal of Engineering and Technology, 2021, 9, 250-267
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Importance of Geotechnical Investigation for Design and Construction of Shafts over 1000 m Deep

Dragana Savić[1], Milan Tumara[2], Milutin Petrović[3]

[1]Geoing Group, Belgrade, Serbia
[2]Energoprojekt-Hidroinženjering, Belgrade, Serbia
[3]Hidroenergo Petrović, Belgrade, Serbia
Email: d.savic@geoing.rs, milan.tumara@gmail.com, petrovic.m.milutin@gmail.com

How to cite this paper: Savić, D., Tumara, M. and Petrović, M. (2021) Importance of Geotechnical Investigation for Design and Construction of Shafts over 1000 m Deep. *World Journal of Engineering and Technology*, **9**, 250-267.
https://doi.org/10.4236/wjet.2021.92018

Received: December 23, 2020
Accepted: April 6, 2021
Published: April 9, 2021

Abstract

In most cases, copper ore deposits occur at great depths, so the optimization of excavation costs is of utmost importance to identify the most cost effective and productive mining methods, such as block caving or similar methods specifically developed for these deposits. To be able to apply such methods, it is necessary to have a detailed knowledge of the rock mass in terms of its geo-mechanical, engineering geological and hydrogeological characteristics. This research aims to reduce geological and geotechnical unknowns, analyze in detail the geological environment, and predict geotechnical conditions for the construction of the shaft. This paper uses the example of Borska Reka Copper Deposit, located in Serbia to illustrate the importance of geotechnical investigation to enable best practice in design and construction of shafts that are over 1000 m deep.

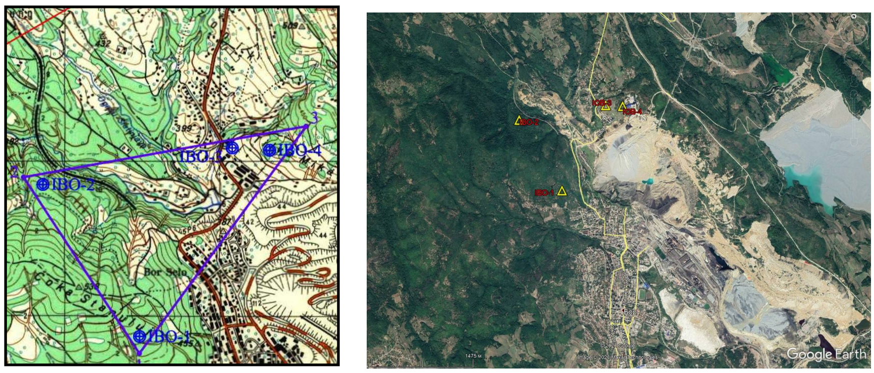
Keywords

Geotechnical Investigation, Mining, Deep Shafts, Geotechnical Environment, Geotechnical Conditions, Rock Mass Primary Stress, Primary Support System

1. Introduction

The research area covers the central part of the Timok Magmatic Complex, located in the Eastern part of Serbia, and belongs to the Bor District (**Figure 1**). The Bor District territory covers an area of 3.507 km^2, of which 33% belongs to the valley type terrain and 67% belongs to the hilly-mountainous type terrain. The copper deposit is located about 2 - 2.5 km northeast of the Bor central region (**Figure 2**).

Figure 1. Map of Serbia with the location of the city of Bor.



(a) (b)

Figure 2. Position of the investigation area and borehole locations (a), Positions of four vertical shafts (source: Google Earth) (b).

The investigation area is defined by the triangular shape (**Figure 2**).

For a better knowledge of the geological composition and geotechnical characteristics, as a first step, it was necessary to make a Program of detailed geotechnical research of four vertical shafts [1].

In the investigation process, the basic questions relate to obtaining the data necessary to determine the geological and geotechnical engineering conditions for shaft design and construction. All the relevant documents are required and prescribed by the currently applicable Legislation.

In the course of research it was necessary to collect data on the following: lithological composition, rock structure and rock mass development, as well as, condition of rock masses (discontinuities, faults, broken zones, joint orientation, alterations, roughness, crack fill, groundwater conditions, etc.) [2].

Firstly, it was required to determine the physical and mechanical properties of the represented rock masses including the xchanges that occur with depth. Besides, in order to estimate the water inflow, it was vital to establish the hydrogeological properties of the rock masses, water permeability and hydrogeological functions of individual zones of the terrain. Finally, to select properly the primary support system it was necessary to determine the primary stress state of the rock mass [3].

All the previous activities aim to contribute, from a geotechnical point of view to the development of the Mining Project, that will help identify and design optimal technical solutions for the excavation and permanent support of new mining shafts: return air shafts (Shaft IBO-1N and Shaft IBO-2), inlet air shaft (Shaft IBO-3) and deputy shaft (Shaft IBO-4).

According to the Geotechnical Investigation Program [1], each borehole is located at the center of one future mining shaft. A special Geotechnical Study was prepared for each shaft separately [4] [5] [6] [7].

2. Materials and Methods

2.1. The Geological Composition of the Investigation Area

The Borska Reka Deposit and the Bor Ore Field are, as a whole, in a spatial and genetic connection with the Upper Cretaceous igneous complexes known as the Timok Magmatic Complex (TMK).

The rocks of the intrusive phase are extremely saturated with silica and belong to the group of rocks poor in potassium. The textures are medium to fine-grained, and the structures are porphyrin based. The mineral composition of these rocks is plagioclase (35% - 45% An), hornblende, biotite, quartz, and probably augite. The products of transformation are sericite, albite, epidote, and accessory minerals are apatite and magnetite. The position and representation of the rocks can be seen on geological profiles. These magmatic processes were accompanied by hydrothermal solutions, which made various changes in volcanic intrusions, partly in the rocks of the sedimentary series, thus creating a large hydrothermal altered zone, within which copper mineralization was formed in suitable conditions and environment, **Figure 3** [8].

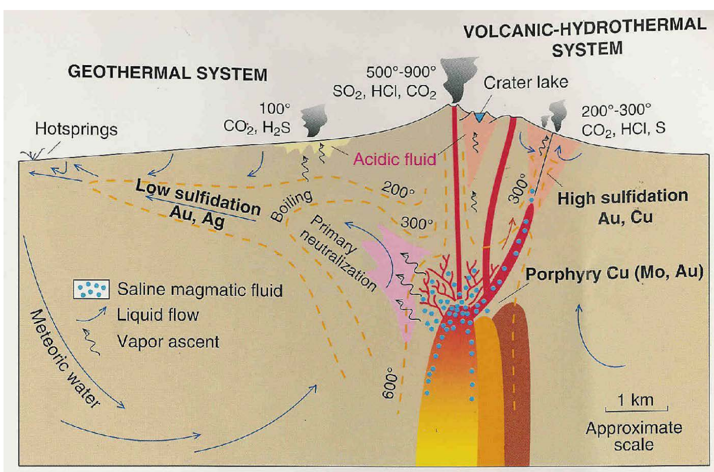


Figure 3. Volcanic-hydrothermal and geothermal systems for high and low sulfide systems of epithermal gold deposits [8].

The youngest formations in this area are Neogene and Quaternary sediments. Neogene sediments lie transgressively over the rocks of the andesite basaltic association. They include loosely bound conglomerates, gravels, sands, and sand clays of the Slatina Basin. Quaternary formations are represented by alluvial deposits of the Borska River composed of gravel, sand, and limestone pebbles. The presence of artificial creations, which are represented by mining and flotation tailings and molten slag, is also impressive.

The Borska Reka Deposit is the largest and deepest deposit within the Bor Ore Field, built mostly of hydrothermally altered and mineralized volcanic rocks. At the bottom of the deposit there is a thick series of Bor conglomerates and sandstones and in the cover, a series of Bor pelites, volcanic agglomerates, and breccias of hornblende biotite andesites and dacites. A several-stage research was carried out to determine the hydrogeological parameters and characteristics of the reservoir. These included mapping of hydrogeological phenomena on the terrain surface, mapping of exploratory holes during reservoir exploration, structural-geological and hydrogeological research at the level of the horizon XVII.

In the course of the mining activities developed in the area of Bor, the relief has changed significantly due to ore tailings disposal. In the deeper parts of the terrain, joints are usually compressed, closed or with smaller openings and a larger number of joints and cracks are filled with calcite, zeolite or decomposition products which reduce their water permeability.

Jointed and cracked volcanic rocks, up to an approximate depth of 400 m represent well-permeable rocks with a crack-type porosity. An aquifer was formed within numerous systems of joints, cracks, and fissures. The stated depth of about 400 m is approximate and it can be smaller or larger depending on the morphology of the terrain, the petrological composition of the rocks and the existence and proximity of larger tectonic faults such as the Bor Fault (red line in **Figure 4**).

The conglomerates that are of different composition have similar hydrogeological properties. The agglomerates and breccias that make up the series are rather cracked rocks with a large number of open joints and cracks and therefore have a high porosity. Tufts and pelites within the Bor Pelites series are rocks with poorly developed crack porosity where open cracks are rare and filled cracks predominate due to the higher content of clay.

Hydrothermally altered volcanic rocks, intensively kaolinized and chlorinated are poorly permeable rocks with clay-like properties. Joints and cracks in these rocks are regularly filled and compressed. In contact with water, these rocks have the property of swelling, whereby their water permeability is further reduced. Intensively silicified, pyrite and sulfated rocks have hydrogeological properties similar to cracked unaltered andesites. Exploratory drilling confirmed the absence of open joints and cracks in the deeper parts of these rocks, where there are mostly cracks filled with calcite, zeolite, anhydrite, kaolin and sulfide minerals - mainly pyrite.

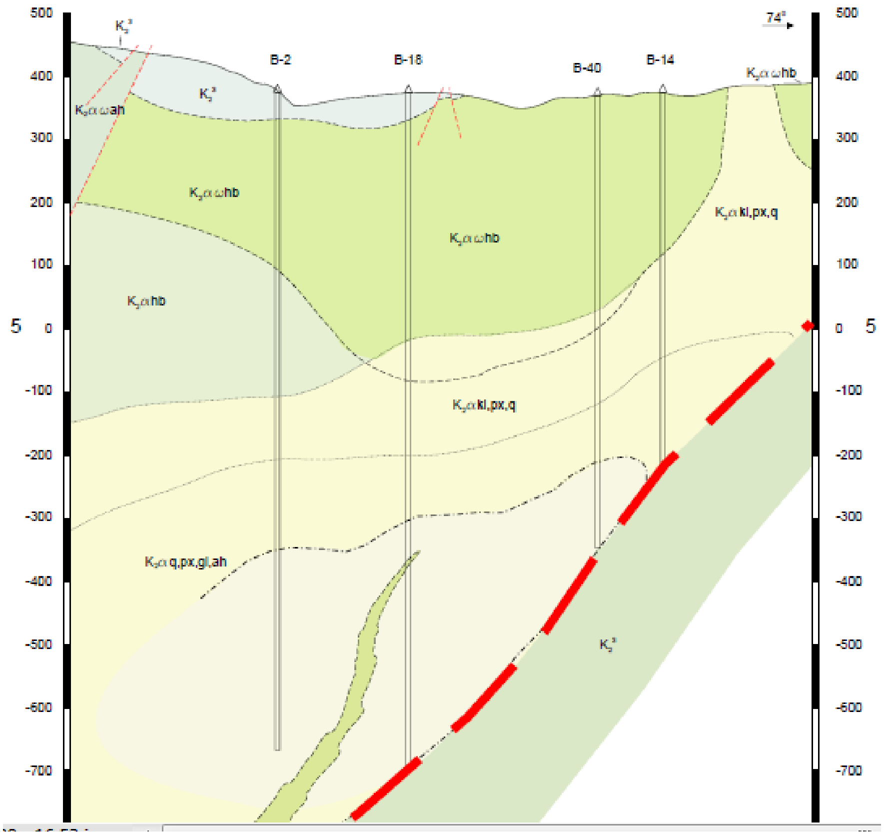


Figure 4. Geological profile of the borska reka deposit - transverse profile 5 - 5' [9].

The ore body is built of hydrothermally altered volcanics and volcanoclastites. The engineering geological characteristics of the ore body depend on the lithological-petrological characteristics and tectonic relations within the deposit and close environment. Hornblende pyroxene andesites (younger rocks that are quite fresh) are represented, as petrological members, in the roof of the deposit, while the ore body is located in hydrothermally altered andesites.

Post-ore tectonic movements and accompanying processes influenced the final state of the rock mass in the engineering-geological sense. Pre-ore, intra-ore, and post-ore tectonics have caused the appearance of various systems of joints and faults.

Roofing hornblende-pyroxene andesites, since they are quite fresh and tectonically less disturbed, from an engineering-geological point of view represents a favorable working environment. On the other hand, kaolinized and more strongly chloritic andesite, tectonic clays, and tectonic breccias, represent an unfavorable working environment. Silicified and sulfated andesite, which also participates in the structure of the deposit, represents a favorable working environment, except in the case when it is tectonically disturbed.

In the field of the deposit, the terrain was covered, so it was not possible to measure the strike/dip elements of the present discontinuities. In this case, discontinuity data can only be provided based on borehole core mapping.

Fault zones were detected at the borehole core mainly as broken and highly fragmented rocks. The existence of fault zones has further intensified the process of degradation of the bedrock. Plastic clays with swelling potential are present in some fault zones or fault infill is often washed away.

Fault and joint systems were the main channels used by hydrothermal solutions and are one of the main factors in the formation of mineralization. Detailed engineering geological and geotechnical core mapping identified numerous faults and fractured zones in the zones of future mining shafts (**Table 1**).

Figure 5 presents the lithological content and the contacts of different lithological members that were registered in each hole.

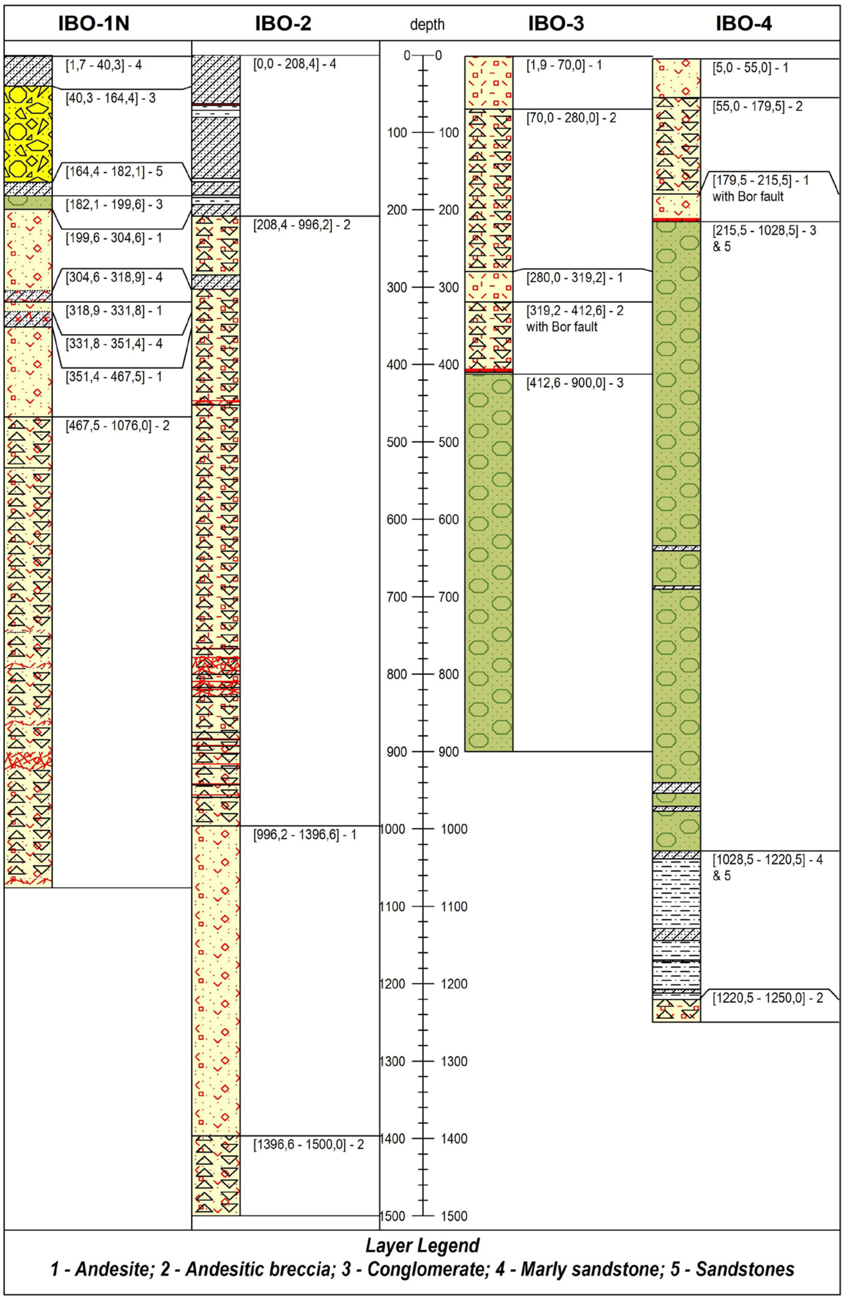


Figure 5. Lithological members in holes with main fault zones.

Table 1. Faults and broken zone in investigation boreholes.

Shaft/hole	Deep (m)	Faults (nb.)	Broken zone (nb.)
IBO-1N	1076	46	58
IBO-2	1500	30	57
IBO-3	900	11	37
IBO-4	1250	11	43

2.2. Rock Mass Classification

Although the techniques for testing rocks and rock masses have reached an enviable level, there are still many problems in applying theoretical knowledge to solving practical engineering problems. In such circumstances, classifications emerged as a compromise between the use of theoretical solutions and a complete lack of information on rock mass properties. All classifications include several key rock mass parameters and assign a single parameter to one of the predefined classes. Each of the classes is assigned a corresponding numeric value. By summing the associated numerical values for each of the rock mass parameters, a final numerical value is obtained that marks the behavior of the analyzed rock mass.

The goals of engineering classifications are:

- Identify the most significant parameters that affect the behavior of rock mass;
- Division of rock mass into structural regions in which rock mass has similar behavior;
- Provide a basis for understanding the characteristics of each of the classes;
- Compare the experience with the properties of rock mass in one location with the properties in another location;
- Describe the behavior of the rock mass by numerical values, so that analyses can be performed;
- Provide a foundation to enable communication between geologists and engineers.

Identification and classification of rock masses is the first step in the process of defining their behavior. In [10], a distinction was made between these terms as follows: classification is defined as the process of grouping objects based on their mutual relations. Identification means classifying unidentified objects in the appropriate class previously established by the classification.

The classification can be based on only one property and is then called univariate [10]. If the classification is based on two or more properties, then it is called bivariate or multivariate [10]. The more parameters considered, the better the picture of the studied objects [10].

Classifications of the rock massif represent an integral part of the empirical approach, as one of the three methods presently adopted to solve geotechnical problems, *i.e.* the design of geotechnical objects in the rock massif. As the empirical approach is based on observation, experience, laboratory test results, and engineering assessment, it sets the empirical basis of quantitative characteristics of the rock mass, taking into account not only the diversity of rock material properties in geological and geotechnical terms but also the purpose for which classification is performed.

Although many geotechnical classifications are already traditionally related to tunnel construction, their application has spread to many areas in which rock mass is explored for engineering purposes, in particular when assessing the possibility of making and ways of supporting chambers, corridors, when assessing the load-bearing capacity, stability of rock slopes, when choosing mechanization and methods of excavation in mining.

Due to the complex nature of the rock massif, which, as already mentioned, is usually cracked, heterogeneous, anisotropic and naturally stressed, there is no single, universal engineering geological classification that would be acceptable for all works in rock masses.

We apply empirical methods in an attempt to overcome the problems of the complex nature of rocks and the difficulties in defining their behavior. There are several types of classification systems used for the construction of underground facilities: RMR, MRMR, Q system, GSI and others.

They differ from each other, among other things, in the number of parameters that are taken into account in the classification of rock masses [11] (**Table 2**).

To apply the rock mass classification in mining, Laubscher [12], and then Jakubec and Laubscher modified the RMR classification called MRMR classification [13] [14]. In the 2000 s, this classification by Laubscher and Jakubec [12], in addition to open discontinuities, also included the influence of filled cracks.

In technical terms, many authors of classifications recommend that, especially for major projects, a minimum of two classifications must be used for comparison purposes. Therefore, for the sake of a more detailed analysis of the shaft in

Table 2. Parameters applicable to different rock mass classifications [11].

Classification	RMR89	MRMR	Q	GSI
Parameters	Uniaxial compressive strength (UCS)	UCS		State of discontinuities
	RQD	RQD	RQD	Structure/connection of well block
	Joint distance	Joint distance	Joint roughness Jr	
	State of the joints	State of the joints	Joint alteration Ja	
	Groundwater state	Groundwater state	Groundwater reduction factor Jw	
			Stress reduction factor (SRF)	
Correction factor	Joint orientation	Joint orientation, blasting and alteration		

this project, the results of the classifications RMR (Bieniawski, [10]) and MRMR (Laubscher, [12]) are presented below.

Based on a comparison of the results obtained in two mines in Chile, Laubscher [15] proposed the following correlations with the Bieniawski RMR and Barton's Q index:

$$RMR = 1.1 \times RMR_{LB} - 2\left(25 \le RMR \le 75\right) \tag{1}$$

$$Q = 10_{0.067} \times RMR_{LB} - 2.962\left(25 \le RMR \le 70\right) \tag{2}$$

Although an empirical connection has been conditionally established between these classifications, the same connection is based on a small amount of data, so the author himself called for caution when using it. However, for this paper, no empirical link was used, but the RMR and MRMR classifications were made independently, to compare the results of the classifications.

Also, for the purpose of these classifications, geotechnical laboratory tests were done on borehole core samples from all types of rocks, which will not be shown in this article due to the large volume of data.

The following are the results of the classifications.

3. Results

The research aims to reduce geological and geotechnical unknowns, analyze in detail the geotechnical environment, predict geotechnical conditions for the construction of the shaft, and present all of that in the Geotechnical Study.

The issues that were resolved referred to the acquisition of data necessary for the determination of engineering geological and geotechnical conditions for designing and construction of the shaft. These conditions are required and prescribed by relevant legislation.

The purpose of these investigations was defined in the Terms of Reference. The research was necessary to collect data on the following:

- terrain structure (composition, structure and geological development);
- condition of rock masses (discontinuities, faults, broken zones, crack orientation, alternation roughness, crack fillings, groundwater condition, etc.);
- physical-mechanical properties (characteristics) of the represented rock masses for all characteristic members and its changes with depth;
- hydrogeological properties of rock masses (water permeability, hydrogeological functions of individual zones of the terrain, hydrogeological conditions, and assessment of water inflow);
- rock mass primary stress state to select properly the primary support system.

After *in situ* work and laboratory tests, Cabinet work included the following:

- collection and study of available documentation on previous research in the wider research area (analysis of all available geological, geotechnical and hydrogeological documentation);
- selection and elaboration of appropriate classification methods required for preparing the Research Project;
- preparation of the Project of investigation works with technical specifica-

tions;
- analysis of research and laboratory test results;
- classification of rock mass following the adopted methods and research results;
- stress analysis of rock mass along the future mining shaft.

As a result of the application of the scoring system according to the Bieniawski RMR classification, the categories of rock mass are defined and shown in the following **Table 3**.

The adopted methodology includes the assignment of *in situ* rock mass estimates based on measurable geological parameters.

Each geological parameter is evaluated according to its importance and the maximum value is assigned in such a way that the total number of all parameters is up to 100. The range of points from 0 to 100 covers all variations of rock massifs, from very poor to very good qualities.

Estimates represent the relative strengths of rock massive and the accuracy of the classification depends on the sampling area being investigated.

Assessing how the massif will behave in the development of the mining pit, the values of the rock massive (RMR_{LB}) are adjusted taking into account weathering, induced mineral stresses, crack orientation and explosive effects. The customs classification is called MRMR or Mining Rock Mass Rating.

The geological parameters that must be assessed are the following: resistance (strength) of intact rock (IRS); discontinuity spacing; a state of discontinuity and the presence of water [15]. The classification is divided into five classes (categories) with 20 points per class and with subclasses called A and B, **Table 4**.

The map uses a range of colors to indicate classes in the plan and the profile: class 1, blue; class 2, green; class 3, yellow; class 4, brown and class 5, red.

The classification of rock mass was also performed according to Laubscher's MRMR classification for depths of mining works that range from 0.00 m to the final hole depth. The parameters Cw, Co, Cs, and Cb were adopted following the

Table 3. Categories of rock mass according to RMR [10].

Rock class	V	IV	III	II	I
	Very poor	Poor	Fair	Good	Very good
Rock class raiting	<21	40 - 21	60 - 41	80 - 61	100 - 81

Table 4. Rock mass categories according to MRMR.

	Rock class raiting									
Rock class	5		4		3		2		1	
Rock subclass	B	A	B	A	B	A	B	A	B	A
R m raiting	0 - 10	11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	61 - 70	71 - 80	81 - 90	91 - 100
Description	Very poor		Poor		Fair		Good		Very good	
Color	Red		Brown		Yellow		Green		Blue	

mapping results and the given object, a vertical mining shaft with the assumption of the application of controlled blasting.

Results of Rock Mass Classifications at the Location of Deep Shafts

1) Results of rock mass classifications at the location of the shaft IBO-1N [4]:

- The Bieniawski RMR classification was performed at 3.10 m - 1076.00 m. Was drilled through the dusty clay, and by 11.60 m the weathering rock and rock blocks;
- According to this classification, the rock mass at the location of the future shaft ranges from very poor rock (V cat.) to fair rock (III category);
- The rock mass rating was also performed, according to Laubscher's MRMR classification for mining works from 3.10 m to 1076.00 m. The parameters Cw, Co, Cs, and Cb were assumed following the mapping results and the given object, a vertical mining shaft with the assumption of the application of controlled blasting;
- Zones of approx. 3.10 - 30.40 m; 252.40 - 302.40 m; 341.0 - 410.20 m; 425.10 - 434.30 m; 473.40 - 478.50 m; 785.40 - 792.60 m; 821.40 - 836.40 m; 896.20 - 923.20 m, 1024.50 - 1033.70 m, and 1063.60 - 1072.90 m indicate very poor rock mass at larger intervals, which suggests that at these intervals, the conditions for shaft construction will be especially difficult;
- The rock mass at the location of the future shaft ranges from very poor rock (5A class) to fair rock (3B class).

2) Results of rock mass classifications at the location of the shaft IBO-2 [5]:

- The Bieniawski RMR classification was applied from 0.00 m to 1500.00 m. The first 3.8 m are in weathered and fractured rock;
- According to this classification, the rock mass at the location of the future shaft ranges from very poor rock (V category) to fair rock (III category). RMRcorr correction factors were adopted based on geotechnical core mapping;
- Zones of approx. 281.00 - 322.00 m, then 767.00 m to about 917.00 m and approx. 1424.00 to 1500.00 m indicate very poor rock mass at larger intervals, which implies that at these intervals, the conditions for shaft construction will be especially difficult;
- The rock mass at the location of the future shaft ranges from very poor rock (5A class) to fair rock (3A class).

3) Results of rock mass classifications at the location of the shaft IBO-3 [6]:

- The Bieniawski RMR classification was performed from 2.4 m to 900 m. The first 1.9 m is in clay soil and crumbling rock;
- According to this classification, the rock mass at the location of the future shaft ranges from very weak rock (V cat.) to good rock (II-floor), with the largest part of the shaft ranging from weak (IV cat.) to favorable rock;
- The classification of rock mass was also performed, according to Laubscher's MRMR classification for mining works. The parameters C0, Cs, and Cb were assumed following the mapping results and the given object, a vertical min-

ing shaft with the assumption of the application of controlled blasting;

- The results of scoring according to this classification indicate that the shaft will be made in environments from category 5A to category 3A, *i.e.* in the rock that is of very poor to medium quality, and for the most part it will be made in the poor rock mass, *i.e.* categories 4B and 4A.

4) Results of rock mass classifications at the location of the shaft IBO-4 [7]:

- The Bieniawski RMR classification was performed from 0.00 m to 1250.00 m. The first 5.00 m are in clayey diluvium and weathered rock;
- According to this classification, the rock mass at the location of the future shaft ranges from very poor rock (V category) to good rock quality (II category). The dominant zones of weak to very weak rock masses are in the intervals from 5.00 to 42.80 m and 92.10 to 161.30 m. Other sporadic intervals of weak rock masses are much shorter in length;
- The results of scoring according to this classification indicate that the shaft will be made in environments from category 5A to category 3A, *i.e.* in the rock of very poor to medium quality, and for the most part it will be made in the poor rock mass, *i.e.* categories 4B and 4A. The results of MRMR classification indicate particularly weak zones of rock mass at intervals from approximately 5.00 to 43.00 m and from 92.00 to 161.00 m. Other weak zones are of the shorter intervals.

4. Discussion

The values obtained by the RMR and MRMR classifications can be correlated quite well. Comparing the results of these two classifications, it can be concluded that the MRMR classification gave more conservative results, *i.e.* on the safety side, which is somewhat logical since this classification also takes into account the impact of blasting.

According to RMR classification, the rock masses at the location of the future shaft:

- IBO-1N are in the largest part of the shaft in the range of the Poor rock (IV category), **Figure 6(a)**;
- IBO-2 are in the largest part of the shaft in the range of the Fair rock (III category), **Figure 6(b)**;
- IBO-3 are in the largest part of the shaft in the range of the Fair rock (III category), **Figure 6(c)**;
- IBO-4 are in the largest part of the shaft in the range of the Fair rock (III category), **Figure 6(d)**.

The RMR rock mass classification system is often used to design the support system for underground openings. For an underground opening excavated in the same quality rock mass at different depths, the system proposes the same support system. Since the classifications of RMR and MRMR are based on examples of rock masses at shallower depths, and according to the issues concerning deep shaft excavation, it is necessary to consider the influence of depth on

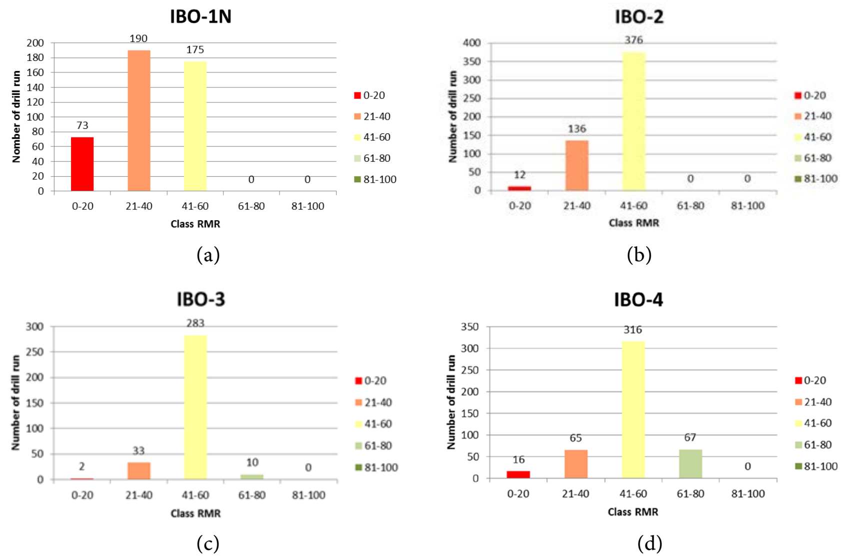


Figure 6. Histograms of the obtained RMR classes per shafts.

the primary support system. In this case, the available literature considerations on this issue were used [4].

An empirical equation and graph were produced showing the relationship between RMR, depth and the support pressure ratio, obtained by dividing necessary support pressure by RMR proposed support pressure [4].

Figure 7 shows the graph illustrating the relationship between the depth and the support pressure required to maintain the strain below 2% for the rock masses of different qualities [4]. As the quality of rock mass increases, the required support pressure decreases. For the same rock mass quality, as the depth increases the required support pressure also increases. The increment rate changes depending on the quality of the rock mass.

Stress-strain analysis was performed to provide numerical control and appropriate recommendations. Also, for the purposes of stress analysis, it was necessary to evaluate the deformability parameters of the rock mass for analytical modeling.

In keeping with the general practice that defines space as the working environment in which an underground facility will be constructed, the shaft sections were separated according to the expected similar physical and mechanical properties and other geological characteristics.

Also, for the construction of all the shafts, it is vital to consider the hydrogeological conditions that are determined based on data from exploration works (exploratory drilling, mapping of the drilled core, geophysical logging tests, performed Lugeon test and water pamping step-tests).

Giving valid estimates of inflows into mining shafts is a challenging activity, and a precise approach requires more accurate and diverse parameters, especially for increased shaft depths.

The final values of the estimate of inflow and filtration parameter for the mining shafts are given in **Table 5**.

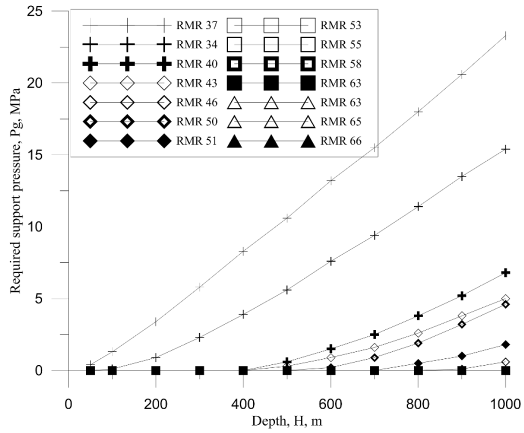


Figure 7. Support pressure necessary to keep the stability of the opening excavated in different quality rock masses and depths [4].

Table 5. Estimate of the filtration parameter and water inflow in the mining shafts.

Hole	Parameters	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10
IBO-1N	Depth (m)	0.0 - 40.3	40.0 - 164.4	164.4 - 182.1	182.1 - 199.6	199.6 - 467.5	467.5 - 1076.0				
	Kf (m/s)	9.4E−7	5.2E−7	9.4E−7	5.2E−7	9.5E−7	5.0E−7				
	q (l/min/m')	46.8	26.05	46.08	26.05	47.5	25.0				
	inflow (l/s)	3.12	1.74	3.12	1.74	3.17	1.67				
IBO-2	Depth (m)	0 - 26.4	26.4 - 44.4	44.4 - 53.4	53.4 - 180.7	180.7 - 208.4	208.4 - 996.2	996.2 - 1396.6	1396.6 - 1500.0		
	Kf (m/s)	2.6E−7	5.5E−7	2.6E−7	5.5E−7	2.6E−7	2.3E−7	1.3E−6	2.3E−7		
	q (l/min/m')	13.0	27.3	13.0	27.3	13.0	11.36	66.49	11.36		
	inflow (l/s)	0.87	1.82	0.87	1.82	0.87	0.76	4.4	0.76		
IBO-3	Depth (m)	0.0 - 70.0	70.0 - 280.0	280.0 - 319.0	319.0 - 413.0	413.0 - 900.0					
	Kf (m/s)	5.0E−7	3.2E−7	3.2E−7	3.2E−7	1.0.5E−6					
	q (l/min/m')	25.0	16.0	16.0	16.0	49.40					
	inflow (l/s)	1.7	1.1	1.1	1.1	3.3					
IBO-4	Depth (m)	0.0 - 11.6	11.6 - 54.1	54.1 - 191.3	191.3 - 215.5	215.5 - 633.9	633.9 - 640.5	640.5 - 686.0	686.0 - 1037.3	1037.3 - 1220.5	1220.5 - 1250.0
	Kf (m/s)		1.3E−6	2.3E−7	1.3E−6	2.3E−7	5.5E−7	2.3E−7	2.3E−7	2.6E−7	2.3E−7
	q (l/min/m')	0	66.5	11.4	66.5	11.7	27.3	11.7	11.7	13	11.4
	inflow (l/s)	0	4.4	0.76	4.4	0.78	1.8	0.78	0.78	0.87	0.76

Geotechnical domains were defined based on similar geotechnical conditions that can be expected. The geotechnical domains were divided in conformity with the results of the rock mass classifications according to Bieniawski and Laubscher, RMR and MRMR, **Figure 8** [4].

The following different geotechnical rock mass types have been singled out:

GT1 - Solid rock mass, sandstones, marls, andesites, breccias, cracks rare and mostly single, without filling or with solid filling, unaltered, rocks of low deformability, mainly crack type of porosity.

GT2 - Solid rock mass, sandstones, marls, conglomerates, andesites, breccias, cracked rock mass, slightly altered, small joint aperture, without filling, rocks of low deformability, crack type of porosity, possible formation of individual wedges in the rock mass.

GT3 - The rock mass consists of fractured and weakened (broken in places) zones. There may be cracks in some places within the set of smaller distances (high frequency), formation of wedges, but also the appearance of cracks with falling angles unfavorable for the stability of the excavation.

GT4 - Broken rock mass, zones of intensively fractured rock mass with more sets of cracks and possible to very probable higher inflows of water along cracks or faults.

GT5 - Broken rock mass, with inflow of mineralized water potentially aggressive to steel and cement based materials (reinforced concrete, etc.)

Based on the results of stress-strain analyses of the characteristic transverse profiles of the unsupported shaft, 5 types of primary support are proposed:

Type 1 - microfiber MB30 shotcrete 3 cm thick and wiremesh Q196 (5 mm, 100 × 100), anchors l = 2.4 m sporadically as needed;

Interval	From	To	Type of geotechnical section	Support type		Tickness of plastification zone	PROPOSED TYPE OF PRIMARY SUPPORT
	[m]	[m]		According to Bieniavsk	According to Laubscher	[m]	
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
140	329.00	331.70	GT-5	V-very poor	5A		
141	331.70	334.80	GT-3	IV-poor	4B	3,70	
142	334.80	337.90		III-fair	4A	3,70	type 3
143	337.90	341.00		IV-poor			
144	341.00	344.10			4B		
145	344.10	345.60	GT-5	V-very poor	5A		type 5
146	345.60	347.30					
147	347.30	349.50		IV-poor			
148	349.50	350.40		V-very poor			
149	350.40	352.90		IV-poor			
150	352.90	354.10		V-very poor			
151	354.10	356.30					
152	356.30	357.60					
153	357.60	358.60					
154	358.60	360.40					
155	360.40	362.10		IV-poor			
156	362.10	364.10					
157	364.10	365.50		V-very poor			
158	365.50	367.40					
159	367.40	370.10					
160	370.10	371.30					

Figure 8. Proposed support types for interval 329.00 - 371.30 m, Shaft IBO-1N [4].

Table 6. Support types in shafts.

Shaft/hole	No of intervals	T1 nb/%	T2	T3	T4	T4	Σ T4 + T5
IBO-1N	429	95/22.14	77/17.95	154/35.90	35/8.16	68/15.85	24.01%
IBO-2	524	162/30.92	86/16.41	127/24.24	149/28.43	-	28.43%
IBO-3	325	80/24.61	165/50.77	48/14.77	32/9.85	-	9.85%
IBO-4	464	108/23.29	172/37.07	131/28.23	153/3.23	38/8.19	11.42%

Type 2 - microfiber MB30 shotcrete 5 cm thick and wire mesh Q196 (5 mm, 100 × 100), anchors filled with two-component resin L = 2.4 m/2.5 × 2.5 m;

Type 3 - microfiber shotcrete MB30 in 3 layers, each 5 cm thick with two Q196 reinforcing meshs, anchors filled with a two-component mass of l = 2.4 m/2.0 × 2.0 m;

Type 4 - microfiber MB30 shotcrete 20 cm thick (3 layers: 4 + 8 + 8 cm), with 2 reinforcing wiremeshs Q196 (5 mm, 100 × 100), anchors filled with two-component resin mass l = 3 m/1.2 × 1.2 m, lattice girders at 0.75 m as needed, after systematic pre-injection of the shaft section using cement mixtures to stabilize the rock mass (consolidation type of injection) by reaching uniaxial rock strength of at least 30 MPa. It is primarily applied to fault and broken zones (GT4 and GT5);

Type 5 - shotcrete microfiber MB30 in thickness of 15 cm, with reinforcing mesh Q196 (2 meshs 5 mm, 100 × 100), anchors filled with two-component mass l = 3 m/1.2 × 1.2 m, lattice girders at a distance of 0.75 m as needed, after systematic pre-injection of the section with mixtures for the stabilization of the working environment (consolidation injection by reaching uniaxial rock strength of at least 30 MPa). It is applied primarily for fault and broken zones (GT4 and GT5).

The following **Figure 8** shows the proposed types of support according to:

- Bieniawski, Laubscher, geotechnical domains, the thickness of the plasticization zone around the opening based on stress-strain analysis, rock mass zoning and the proposed type of primary support per different rock mass zones.

By observing the total number of analyzed intervals, in which the primary support system per each shaft/hole was determined, it was possible to conclude that the most unfavorable conditions for construction are found in the IBO-1N shaft and IBO-2 shaft (24.01% - 28.43% of total depth) **Table 6**.

5. Conclusions

Due to the complex geological and geotechnical environment, designing underground mining openings, such as vertical shafts, is always considered as difficult. For many years, empirical methods have provided a practical solution to these problems and they have been used widely for the assessment of support requirements to ensure stability [3].

Conserning the significance and magnitude of shaft construction, it may be noted that, at shaft locations, geotechnical research is currently at a very modest level. Only one exploration borehole with a small number of hydrogeological tests cannot represent the scope of research that is required for a shaft with a diameter between 6.50 - 7.00 m and a depth between 900 - 1500 m.

At the same time, 2/3 or all of the boreholes length was deprived of geophysical logging tests. However, even this small volume of geophysical logging measurements was of great help since it was not possible to perform more hydrogeological packer tests or step water pumping tests.

Properly performed geotechnical mapping of the borehole core, in accordance with ISRM standards, enabled the collection of the maximum number of data, all of which were very useful for rock mass classifications and for defining geotechnical conditions.

The paper presents a detailed mapping of fault and fractured zones in the boreholes, the presence of poor rock and fair rock masses noted in the borehole log that directly correspond to proposed rock types and selected primary support.

The Terms of Reference does not anticipate the rock excavation technology, nor the technology of permanent (secondary) shaft support. Therefore, the types of primary support were given for any type of shaft excavation and support technologies.

Due to different circumstances, the time interval between primary and permanent support emplacement can be several weeks, and therefore the proposed primary support should enable the stability of the excavation walls during all possible downtimes and temporary delay of the permanent supporting.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Savić, D. and Petrović, M. (2020) Projekat detaljnih geotehničkih istraživanja za potrebe izgradnje novih rudarskih objekata 4 vertikalna okna na lokaciji kompleksa rudnika ZIJIN Bor, projektant GEOING GROUP.

[2] Lokin, P. (2002) Metode inženjerskogeoloških istraživanja, Rudarsko-geološki fakultet, Beograd.

[3] Karakaplan, E., Basarir, H. and Wesseloo, J. (2016) Theoretical Investigation of the Effect of Stress on the Performance of Support Systems Based on Rock Mass Rating (RMR) Support Recommendation*. Groud Support,* Lulea, Sweden.

[4] Petrović, M., Tumara, M. and Savić, D. (2020) Elaborat o geotehničkim uslovima za potrebe izvođenja rudarskog okna IBO-1N, lokacija "Kormaros" projektant HIDROENERGO PETROVIĆ.

[5] Petrović, M., Tumara, M. and Savić, D. (2021) Elaborat o geotehničkim uslovima za potrebe izvođenja rudarskog okna IBO-2 lokacija "Brezonik" projektant HIDROENERGO PETROVIĆ.

[6] Petrović, M., Tumara, M. and Savić, D. (2020) Elaborat o geotehničkim uslovima za potrebe izvođenja rudarskog okna IBO-3, lokacija "Zmajevo" projektant HIDROENERGO PETROVIĆ.

[7] Petrović, M., Tumara, M. and Savić, D. (2021) Elaborat o geotehničkim uslovima za potrebe izvođenja rudarskog okna IBO-4, lokacija "Brezanik" projektant HIDROENERGO PETROVIĆ.

[8] Hedenquist, J.W., Antonio, A.R. and Gonzalez-Urien, E. (2020) Exploration for Epithermal Gold Deposits, Gold in 2020, Society of Economic Geologists, Vol. 13. https://doi.org/10.5382/Rev.13

[9] Simić, D. and Mihajlović, B. (2006) Study on Reserves of Copper and Accompanying Elements in the Borska Reka Deposit, projektant JANTAR GRUPA.

[10] Bieniawski, Z.T. (1989) Engineering Rock Mass Classification. John Wiley & Sons, New York, 251 p.

[11] Zhang, L. (2010) Estimating the Strength of Jointed Rock Masses'. *Rock Mechanics and Rock Engineering*, **43**, 391-402. https://doi.org/10.1007/s00603-009-0065-x

[12] Laubscher, D.H. (2000) Block Caving Manual, Prepared for International Caving Study, JKMRC and Itasca Consulting Group, Inc., Brisbane.

[13] Laubscher, D.H. and Jakubec, J. (2001) The MRMR Rock Mass Classification for Jointed Rock Masses. In: Hustrulid, W.A. and Bullock, R.L., Eds., *Underground Mining Methods*: *Engineering Fundamentals and International Case Histories*, SME, Littleton, Colorado, 455-463.

[14] Laubscher, Dr.D.H. and Jakubec, J. (2000) The MRMR Rock Mass Rating Classification System in Mining Practice.

[15] Laubscher, D.H. (1990) A Geomechanics Classification System for the Rating of Rock Mass in Mine Design. *J.S.Afr.Inst.MinMetall.*, **90**, 257-273.