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MODELING OF ROCK MASSIF IN THE JAMA BOR WITH SPECIAL FOCUS ON THE PREVIOUS EXPLORATIONS OF THE ORE BODY »BORSKA REKA«[***]

Abstract

Research the stability of underground structures that are almost done, can be divided into the frameworks of theoretical processing, basic laboratory analyses and information on previous experiences in the exploitation of deep deposits and, as such, they can serve as a reference for more detailed research. In this paper, the example of the ore body "Borska Reka" in the underground mine Jama Bor, shows one of the ways to get the reliable data on the working environment that can be used to model the rock mass. Therefore, the results will provide a realistic assessment the stability of the analyzed structures.

Keywords: *rock mass modeling, stability of underground structures, triaxial tests*

INTRODUCTION

Modeling of the rock mass is done for the needs of research the stability of underground structures. It starts from defining the geometry of underground structure that may lead to an increase or decrease of its stability. It is recommended that any change in the geometry follows the correct sequence. This sequence is defined by: the location of structure, its orientation, the characteristics of surrounding rocks, size and other factors.

Selection of an adequate cross-section depends on several factors, such as: the characteristics of work environment, stress state, and dimensions or purpose of underground structure.

Underground structures (mining activities) often have significantly expressed one dimension compared to the other two, so the problem in most cases can be considered as two-dimensional. From this point of view, the order of required analyses is determined and may be as follows:

- Determining the technical requirements: shape and size of the room, depth;
- Determining the characteristics of the work environment - Modeling of the rock mass:
  - Depending on the level of exploration the work environment, the volume of tests also depends;
  - Determine the engineering-technical and other parameters using the appropriate test;

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- Determine the massif quality using the geomechanical classifications.
- Defining the stress of rock mass;
- Determining the stress on the contour of underground structure and/or in the massif;
- Determining the stress concentration coefficient and assessment the stability degree.

If further stability analysis is required, the size of unstable zone around underground structure is determined. Analysis is continued both by changing the structure geometry or entering the appropriate parameters of support system.

For the appropriate cross and longitudinal sections of underground structure with defining a discontinuity and boundary conditions, a view of stress-strain state in the area of observed structure is obtained.

For consideration and prediction the behavior of the system rock mass - support system at all stages of construction, it is necessary to conduct the appropriate stress-deformation analyses for the proposed types of support systems.

The objective is to determine the way in which the shape and size of disrupted (unstable) zone around the structure changes (zone exposed to tensile and/or shear). At the same time, the stability of constructed structures is estimated as well as the mining operations that are planned by the mining projects for development.

MODELING OF ROCK MASS

Properties of the work environment

In order to determine the characteristics of the work environment, the current technical documentation of geological, petrological-mineralogical, structural and physical-mechanical tests was reviewed, which were conducted for the ore body "Borska reka" in the Jama Bor. Based on this, it can be generally concluded that much was done and a lot of work and effort were invested.

Here, it will only be mentioned the year when the subject research was carried out starting from 1997 [1], 1999 [2] and 2007 [3], and in the phase of preparation, also the most recent Elaborate on engineering-geological (geotechnical), geomechanical explorations and laboratory testing of the ore and rock mass at the copper deposit "Borska reka", carried out by the Mining and Metallurgy Institute Bor.

However, since the research was carried out over a period of nearly 20 years, there are discrepancies in the interpretation of results due to the application of different measuring methods. As the laboratory tests were mainly carried out on samples taken from drill holes, the research was used that was conducted on the samples of rock masses from underground works in the same reporting period of time. [4]

Thus, for further analysis in this paper, a part of the results of geotechnical testing is shown that will be able to be compared with the aspects of modeling the rock mass. This research, carried out in 1999, will be compared with the results of recent research, carried out during 2014.

Research conducted on samples taken from the core of the exploration drill holes

Data are drawn from the Elaborate from 1999 on parameters that are needed to define the work environment in terms of strength calculation and stability analysis. [2]

Since data are presented per each drill hole separately, in order to have an idea of the mean value of data at the level closest to the XVII horizon, i.e., K-155, it was necessary to systematize data and they are shown in Table 1. Table 1 shows the values for the first sampling interval from each drill hole, and statistical indicators are given at the end of column for corresponding parameter, while below row shows statistical indicators for complete results from each interval in the corresponding drill hole.

In addition to these physical and mechanical tests, it should be noted that based on the structural characteristics of rock mass, obtained by mapping the core of exploratory drill holes as well as mapping the drifts at the XVII horizon, the quality of the rock mass could be assessed.

Table 1 *Data from Elaborate from 1999*

Drill hole	X_b [m]	Y_b [m]	Z_b [m]	γ [KN/m^3]	σ_c [MPa]	σ_i [MPa]	φ [°]	C [MPa]	E [MPa]	G [MPa]	ν	RQD
Mean values of the first interval				**27.66**	**79.4**	**6.5**	**58**	**11.3**	**32363**	**13108**	**0.24**	**78**
Standard deviation				0.85	19.76	1.78	2.43	2.92	8552.10	3619.87	0.06	12.02
Coefficient of variation				3.07%	24.88%	27.44%	4.19%	25.87%	26.43%	27.62%	25.33%	15.45%
P a r a m e t r e s				γ	σ_c	σ_i	φ	**C**	**E**	**G**	ν	**RQD**
Mean values of complete results				**27.96**	**73.6**	**7.3**	**56**	**11.0**	**32626**	**13021**	**0.26**	**72**
Standard deviation				0.95	18.96	1.74	2.65	2.83	6482.10	2730.48	0.07	16.48
Coefficient of variation				3.40%	25.75%	23.95%	4.71%	25.81%	19.87%	20.97%	26.43%	22.84%

In addition to data in the table below, it is only noted that testewd specific gravity (γs) ranges from 27.62÷30.30 KN/m^3, humidity (W) of 0.34÷1.51%, and porosity (n) of 1.31÷7.80%.

Since the data of triaxial tests are not systematized in the aforementioned Elaborate, the values obtained for the angle of internal friction (φ) are in the range of 39°÷46° and cohesion (C) of 16÷23 MPa. These values are certainly different from those shown in the Table above, due to the primary reason that there are those parameters obtained by transfer through the laboratory values of compressive strength and tensile.

Research conducted on samples taken from constructed rooms

The required research was carried out on samples taken from the ore body "Borska reka" from the XVII horizon. [4]

In testing the physical properties, the bulk density of taken samples was determined, while the uniaxial compressive strength, tensile strength and triaxial strength were tested in mechanical strength testing. In addition to these values, the deformation parameters were determined.

Selection of sampling place was carried out in the pit with the help of drift plan at the XVII horizon. In this way, the selected samples are the starting material for production and preparation of test bodies, which were tested in the laboratory by appropriate methods. For those reasons, the rock mass samples had smaller dimensions. They were appropriately selected and taken from the main mass and they are a part of this mass from the given place from which the adequate sample was taken.

Sampling was done at five places from which the test bodies were obtained (marked as S-1, U-2, U-3, U-4 and U-5).

In this way, all parameters, obtained from the corresponding tests, relate to the physic-mechanical parameters of mineralized massif [4].

Here, only detailed tests of triaxial strength and deformability will be displayed.

Test of triaxial strength and the obtained values of main stresses in triaxial tests are shown in Table 2 [6].

Table 2 *Values of the principal stresses in triaxial tests*

Designation of series (samples) with values of the principal stresses at fracture									
U – 1		U – 2		U – 3		U – 4		U – 5	
σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]
0	76	0	71	0	83.2	0	86	0	88
10	107	8	98.6	5	111.8	10	145.6	5	118.1
15	143	16	150	10	132	15	185	10	145
20	168	24	195	15	176	20	230.2	15	205
25	190	32	204	20	195	30	242	25	227.4
30	203								
40	230								

The Hoek-Brown constant (m_i) is determined by triaxial testing and data processing for intact (undisturbed) rock, which takes that the second constant is s = 1.

In the case of methods of determining the elastic deformability of rock materials, it should be noted that the tests are mostly confined to determining the elasticity modulus, deformation modulus and the Poisson ratio, noting that deformation modulus is always smaller than elasticity modulus.

In testing the elasticity modulus, the unit deformation in direction of forces can be registered, the unit deformation can be determined perpendicular to the effect of force, which is defined by the Poisson ratio.

A number of different methods and procedures are applied which differ among themselves only through the use of a large number of meters for registration of deformations and forces, or stresses. In this case, testing the deformation characteristics was carried out with a triaxial cell under the influence of pressure [7].

The Phillips measuring bridge with direct reading in μmm/mm. was used for deformation registration on strain gauges, induced by load. To prevent measurement due to high sensitivity of this measuring system and minimum temperature changes, a test body was made which is connected with the measuring bridge, and on which the identical strain gauges are affixed, which are used as the temperature compensation. The strain gauge with the following characteristics was selected for strain gauges that can register the deformations of test body:

Manufacturer: Tokyo Sokki Kenkyujo Co., Ltd

- Type PL-20-11
- Gauge length 20 mm
- Gauge resistance 120±0.3 Ω
- Gauge Factor 2.10

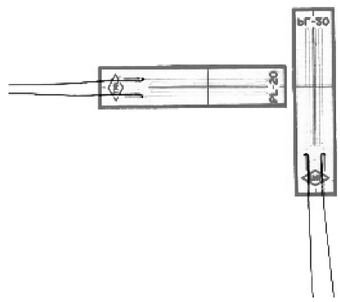


Figure 1 *Appearance and position of strain gauges on test body*

Tests were performed with lateral pressure of 16 MPa. Each table is followed by σ - ε diagram, from which the backward deformations of test body can be read in order to determine the elasticity modulus and hysteresis curve shape.

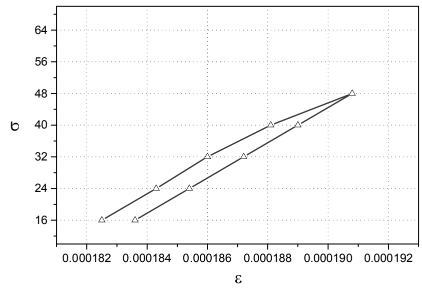
To simulate the stress state of the rock mass at greater depths, it is necessary to test for the appropriate depth of works (γH). Thus, for example, the lateral pressure of 16 MPa for depth of 550÷580 m, 24 MPa for 880 ÷ 900 m, etc.

In deformation testing, the elastic-plastic behavior of the rock mass was determined, which is reflected in the residual plastic deformations. Due to this reason, the parameters of plasticity need to be included in the model parameters [8].

Table 3 *An example of measuring results on one of the test bodies with constant lateral pressure of 16 MPa*

σ_1	Reading [μ mm/mm]						Deformations		Koef. Poissona	Note:
	Horizontal			Vertical			ε_h	ε_v		
[MPa]	1	2	sredina	1	2	sredina	[mm]	[mm]	ν	
16	15400	15750	15575	13900	13910	13905	0.0000414	0.0001825	0.227	Dimensions of test body are
24	15330	15700	15515	14005	14080	14043	0.0000413	0.0001843	0.224	
32	15300	15665	15483	14095	14256	14176	0.0000412	0.0001860	0.221	h = 76.20 mm
40	15270	15635	15453	14220	14440	14330	0.0000411	0.0001881	0.219	d = 38.10 mm
48	15160	15570	15365	14490	14590	14540	0.0000409	0.0001908	0.214	
40	15230	15615	15423	14280	14520	14400	0.0000410	0.0001890	0.217	Volume
32	15260	15640	15450	14200	14330	14265	0.0000411	0.0001872	0.219	O=dπ
24	15310	15690	15500	14040	14220	14130	0.0000412	0.0001854	0.222	O = 119.647
16	15400	15755	15578	13930	14055	13993	0.0000414	0.0001836	0.226	mm

Based on investigations of deformability for the initial lateral pressure of 16 Mpa, the parameters of elasticity were obtained, as follows:
ν = 0.221
E = 44120 MPa
E_d = 34076 MPa



Based on selected lateral pressure for this test, the mean value of data for E and ν, Table 4, will be used in modeling the rock mass and development the numerical model.

Table 4 *Table of test results the deformation characteristics*

Ordinal number of the test body	E [MPa]	E_d [MPa]	ν -
Mean value	40490	33255	0.216
Standard deviation	2629	1066	0.004
Coefficient of variation	6.49%	3.20%	1.72%

Assessment the quality of rock massif

Assessment the quality of rock massif is carried out using the geological strength index - GSI. In this case, for the XVII horizon of the ore body "Borska reka", based on the physical appearance of taken undisturbed samples, recorded structure and condition of the surfaces "in situ", the GSI assessment for this area is in the range of 65÷75.

However, RMR classification can be used for GSI determination.

In previous research for the ore body "Borska reka, the RQD value was stated of 72%÷92% for all exploratory drill holes that were drilled to test the deeper parts of the ore body. For the mean RQD value in the first interval of sampling from the core of exploratory drill holes, which are the closest to the horizon XVII, the value of 78% was statistically determined.

In considering and determining the RMR classification, the value of RQD = 78% and σ_{ci} = 72 MPa is taken, which was obtained by triaxial tests in exploration the rock massif at the XVII horizon. Considering the information on structural characteristics from previous research, and using the classification of Bieniawski from 1989, the value for description of rock mass at the XVII horizon of the ore body "Borska reka" is obtained and it is 73 points. For getting GSI over RMR the classification of Bieniawski, $GSI=RMR_{89}-5$, i.e. GSI = 68, is taken.

Comparing the values obtained from the RMR classification and physical appearance of the cores from taken samples, it can be concluded that it would be acceptable if the value GSI is 70. Here, it must be carefully because the factor of damage the structure must be included in development from which the samples were taken (the impact of blasting) as well as the time after development (movement along the contour).

The research results of rock massif

Based on laboratory tests of mechanical strength, deformation characteristics and assessment the massif quality, the laboratory values of rock massif parameters at the XVII horizon of the ore body, "Borska reka", Table 5 [5], are obtained.

Thus defined parameters were used in modeling the rock massif and analysis the stability of structures at the XVII horizon of the ore body "Borska reka" to the aim of proving the possibility of using the methodology that uses the Hoek-Brown failure criterion.

Table 5 *Physico-mechanical parameters obtained by laboratory tests on samples of rock mass from the XVII horizon of the ore body "Borska reka"*

Working environment (XVII horizon)	γ [kN/m^3]	σ_c [MPa]	σ_i [MPa]	E [MPa]	E_d [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
K-155 silicified andesite	28,2	63,39	6,71	40490	33255	0,216	41.6	15,09	18.9	73	70

Determining the relevant physic-mechanical parameters of rock massif

To determine the physic-mechanical parameters of rock massif to be used for further numerical analysis and calculations, it is necessary to compare the results of laboratory tests, the existing correlations between the physic-mechanical, structural properties and the results of categorizing the rock masses, as well as defining the strength of rock massif by the Hoek-Brown failure criterion, based on previous research. On that basis, carefully evaluate and determine the parameters that will be relevant or authoritative to characterize the state of rock mass, and thus enter into the modeling of rock massif.

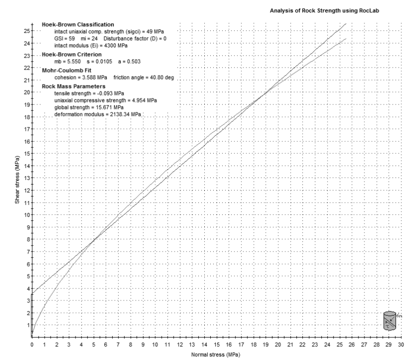
Until now, according to the preliminary analyses, carried out within the framework of the latest research, there are data that show a partial lower values that describe the physic-mechanical properties of the rock material, Table 6 and Figure 2.

Table 6 *Physico-mechanical parameters obtained by laboratory tests on samples taken from drill holes within the recent geomechanical explorations the rock mass of the ore body "Borska reka"*

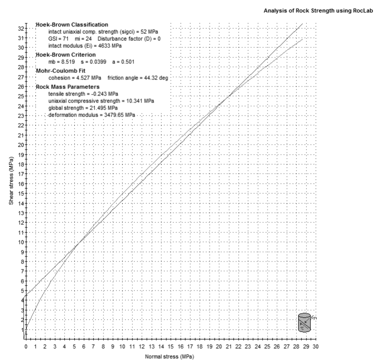
Geotechnical environment	γ [kN/m^3]	σ_c [MPa]	σ_i [MPa]	E_t [MPa]	E_s [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
Bor·s pelytes	25.4	49	4.95	5600	3730	0.34	36.0	24	12.13	54	
Andesites	25.9	52	5.37	6927	4633	0.31	36.8	26	12.90	66	
Kaolinizated andesites	27.0	25	3.04	5490	3672	0.37	30.4	20	7.53	34	
Silicified andesites	27.7	67	7.57	10790	7127	0.32	37.4	28	16.70	51	

It is therefore necessary, when the results are final and the Elaborate is complete, to perform a comparative analysis of data for modeling the rock massif and make appropriate conclusions regarding the relevant data to continue going in the calculation the stability and defining the ways and methods of exploitation the copper ore from the ore body Borska reka in the Jama Bor.

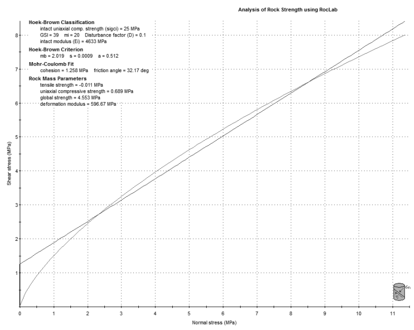
Since these are great depths, where safety is a priority, the geomechanical research has a great importance, and also the responsibility in precise defining of parameters. Sometimes the exaggeration in providing the satisfactory safety factor, in the case of the ore body Borska reka, may deter from further investment due to the economic reasons. Therefore, the responsibility for defining these parameters becomes even greater.



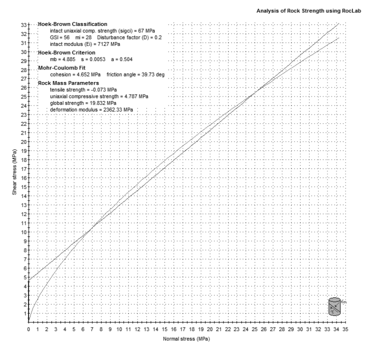
Bor's pelytes



Andesites



Kaolinized andesites



Silicified andesites

Figure 2 *Strength parameters of the rock mass for all isolated environment*

CONCLUSION

Based on the previous results of conducted laboratory tests on samples of rock massif and core from exploration drill holes, with taking into account the state of rock massif, degree of representativeness of samples, effect of size and others, a selection of parameters of physico-mechanical properties of rock masses was done that are applicable to the modeling of rock massif.

By development of software packages that deal with the preparation and analysis of numerical models, the application the Hoek-Brown failure criterion has also experienced a particular progress. This fracture criterion is one of the most widely used and generally accepted criteria for modeling of rock massif.

Therefore, this work contains, in addition to a part on the results of physico-mechanical research the ore body "Borska reka", a precisely determining the triaxial strength and deformability of rock massif. Such contribution to modeling of rock massif, with knowledge on direction and intensity of stresses in the massif and applying the appropriate mathematical model, leads to optimal solutions in sizing the underground structures as a function of depth and required safety factor.

Generally speaking, development of modern underground mining is followed by more complex mining-geological conditions. Therefore, the problems in the underground construction are related to the solutions that must be based on a good knowledge the rules of development the mechanical processes in the rock mass. Physical-structural and mechanical properties of rock massif, technological specifities of exploitation system and preparation method of block caving also predetermine the mechanical state of these complex systems.

All of this requires a different approach, type and scope of geotechnical research, especially if the use of numerical models is planned. They require a selection of forms of underground structures, modeling of rock massif and failure criterion parameters based on a detailed study of rock massif through the appropriate laboratory and field tests. That makes it even greater justification for a more detailed introduction to the new techniques, already applied, in the world, so there is no reason that such a program is not applied to our deposits.

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MODELIRANJE STENSKOG MASIVA U JAMI BOR SA POSEBNIM OSVRTOM NA DOSADAŠNJA ISTRAŽIVANJA RUDNOG TELA »BORSKA REKA«***

Izvod

Istraživanje stabilnosti podzemnih objekata koja su do skoro kod nas rađena, mogu se svrstati u okvire teoretske obrade, osnovnih laboratorijskih analiza i informacija o dosadašnjim iskustvima na eksploataciji dubokih ležišta i kao takva mogu da služe kao orijentacija za detaljnija istraživanja. U ovom radu se, na primeru rudnog tela »Borska Reka« u Jami Bor, prikazuje jedan od načina kako doći do pouzdanih podataka o radnoj sredini koje možemo koristiti za modeliranje stenskog masiva. Samim tim i rezultati će omogućiti realnu procenu stabilnosti analiziranih objekata.
Ključne reči: *modeliranje stenskog masiva, stabilnost podzemnih objekata, triaksijalna ispitivanja*

UVOD

Modeliranje stenskog masiva radi se za potrebe istraživanja stabilnosti podzemnih objekata. Započinje od definisanja same geometrije podzemnog objekata koja može da dovede do povećanja ili smanjenja njegove stabilnosti. Preporučuje se da svaka promena geometrije prati odgovarajući redosled. Taj redosled je definisan: lokacijom objekta, njegovom orijentacijom, osobinama okolnih stena, veličinom i drugim činiocima.

Na izbor adekvatnog poprečnog preseka utiče nekoliko činilaca, kao što su: svojstva radne sredine, naponsko stanje i dimenzije odnosno namena podzemnog objekta.

Podzemni objekti (rudarski radovi) najčešće imaju znatno izraženu jednu dimenziju u odnosu na druge dve, pa se problem u većini slučaja može smatrati dvodimenzionalnim. Sa tog aspekta se i utvrđuje redosled potrebnih analiza i on može biti sledeći:

- Utvrđivanje tehničkih uslova: oblik i veličina prostorije, dubina;
- Utvrđivanje osobina radne sredine - Modeliranje stenskog masiva:
  - U zavisnosti od stepena istraženosti radne sredine zavisi i obim ispitivanja;
  - Odgovarajućim ispitivanjima utvrditi inženjersko - tehničke i druge parametre;
  - Primenom geomehaničkih klasifikacija odrediti kvalitet masiva.
- Definisanje napona stenskog masiva;

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*** *Ovaj rad je proistekao kao rezultat projekta TR 33021 "Istraživanje i praćenje promena naponsko deformacijskog stanja u stenskom masivu "in-situ" oko podzemnih prostorija sa izradom modela sa posebnim osvrtom na tunel Kriveljske reke i Jame Bor", koga finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije*

- Određivanje napona na konturi podzemnog objektai/ili u masivu;
- Određivanje koeficijenta koncentracije napona i ocena stepena stabilnosti.

Ukoliko je potrebna dalja analiza stabilnosti, određuje se veličina nestabilne zone oko podzemnog objekta. Analiza se nastavlja ili promenom geometrije objekta ili unošenjem parametara odgovarajućeg podgradnog sistema.

Za odgovarajuće poprečne i uzdužne preseke podzemnog objekta uz definisanje diskontinuiteta i graničnih uslova dobija se slika naponsko-deformacijskog stanja u zoni posmatranog objekta.

Radi sagledavanja i predviđanja ponašanja sistema stenski masiv - podgradni sistem, u svim fazama izgradnje objekta, neophodno je sprovoditi odgovarajuće naponsko-deformacijske analize za predložene tipove podgradnih sistema.

Cilj je da se utvrdi način na koji se oblik i veličina poremećene (nestabilne) zone oko objekta menja (zone izložene dejstvu zatezanja i/ili smicanja). Ujedno, procenjuje se stabilnost izrađenih objekata kao i rudarskih radova koji su rudarskim projektom predviđeni za izradu.

MODELIRANJE STENSKOG MASIVA

Osobine radne sredine

U cilju utvrđivanja osobina radne sredine, pregledana je dosadašnja tehnička dokumentacija o geološkim, petrološko-mineraloškim, strukturnim kao i fizičko-mehaničkim ispitivanjima, koja su rađena za rudno telo "Borska reka" u Jami Bor. Na osnovu toga se može generalno izvući zaključak da je dosta toga urađeno i da je uložen veliki rad i trud.

Ovde će se samo navesti godine kada su vršena predmetna istraživanja i to počev od 1997 [1], 1999 [2] i 2007 [3], a u fazi izrade je i najnoviji Elaborat o inženjersko-geološkim (geotehničkim), geomehaničkim istraživanjima i laboratorijskim ispitivanjima rude i stenskog masiva na ležištu bakra „Borska Reka", koga radi Institut za rudarstvo i metalurgiju Bor.

Međutim, obzirom da su istraživanja rađena u periodu od skoro 20 godina, postoje odstupanja kod interpretacije rezultata iz razloga primene različitih metoda merenja. Kako su laboratorijska ispitivanja rađena uglavnom na uzorcima uzetih iz bušotina, korišćena su i istraživanja koja su rađena na uzorcima stenske mase iz samih podzemnih radova u istom posmatranom periodu vremena. [4]

Stoga se za dalju analizu, u ovom radu, prikazuje deo rezultata geomehaničkih ispitivanja koji će moći da se komparativno uporede sa aspekta modeliranja stenskog masiva. To su istraživanja urađena tokom 1999. godine koja će biti uporediva sa rezultatima najnovijih istraživanja koja su rađena tokom 2014. godine.

Istraživanja urađena na uzorcima uzetim iz jezgra istražnih bušotina

Iz Elaborata iz 1999 godine su izvučeni podaci o parametrima koji su potrebni za definisanje radne sredine sa aspekta proračuna čvrstoće i analize stabilnosti [2].

Obzirom da su podaci prikazani po svakoj bušotini pojedinačno, da bi imali predstavu o srednjoj vrednosti podataka na nivou najbližem XVII horizontu tj. K-155, bilo je potrebno da se sistematizuju podaci i oni su prikazani u tabeli 1. U tabeli su prikazane vrednosti za prvi interval uzorkovanja iz svake bušotine, na kraju kolone dati su statistički pokazatelji za odgovarajući parametar, dok su u redu ispod prikazani statistički pokazatelji za kompletne rezultate sa svakog intervala iz odgovarajuće bušotine.

Pored ovih fizičko-mehaničkih ispitivanja, potrebno je pomenuti da se na osnovu strukturnih karakteristika stenskog masiva koji su dobijeni kartiranjem jezgra istražnih bušotina kao i kartiranjem hodnika na nivou XVII horizonta, mogao proceniti kvalitet stenske mase.

Tabela1. *Podaci iz Elaborata iz 1999. godine*

Bušotina	X_b [m]	Y_b [m]	Z_b [m]	γ [KN/m^3]	σ_c [MPa]	σ_i [MPa]	φ [°]	C [MPa]	E [MPa]	G [MPa]	ν	RQD
Srednje vrednosti prvog intervala				**27.66**	**79.4**	**6.5**	**58**	**11.3**	**32363**	**13108**	**0.24**	**78**
Standardno odstupanje				0.85	19.76	1.78	2.43	2.92	8552.10	3619.87	0.06	12.02
Koeficijent varijacije				3.07%	24.88%	27.44%	4.19%	25.87%	26.43%	27.62%	25.33%	15.45%
P a r a m e t r i				**γ**	**σ_c**	**σ_i**	**φ**	**C**	**E**	**G**	**ν**	**RQD**
Srednje vrenosti kompletnih rezultata				**27.96**	**73.6**	**7.3**	**56**	**11.0**	**32626**	**13021**	**0.26**	**72**
Standardno odstupanje				0.95	18.96	1.74	2.65	2.83	6482.10	2730.48	0.07	16.48
Koeficijent varijacije				3.40%	25.75%	23.95%	4.71%	25.81%	19.87%	20.97%	26.43%	22.84%

Pored podataka koji su u tabeli prikazani, samo se napominje da se ispitivana specifična težina (γs) kreće u granicama od 27,62÷30,30 KN/m^3, vlažnost (W) od 0,34÷1,51 % i poroznost (n) od 1,31÷7,80 %.

Obzirom da podaci triaksijalnih ispitivanja nisu sistematizovani u pomenutom Elaboratu, dobijene vrednosti za ugao unutrašnjeg trenja (φ) su u granicama od 39°÷46° i kohezije (C) od 16÷23 MPa. Ove vrednosti se naravno razlikuju od onih koje su prikazane u gornjoj tabeli, iz osnovnog razloga jer su tamo ti parametri dobijeni prevođenjem preko laboratorijskih vrednosti čvrstoće na pritisak i zatezanje.

ISTRAŽIVANJA URAĐENA NA UZORCIMA UZETIM IZ IZGRAĐENIH PROSTORIJA

Urađena su potrebna istraživanja na uzorcima uzetim iz rudnog tela "Borska reka" sa XVII horizonta. [4]

Kod ispitivanja fizičkih osobina utvrđivana je zapreminska težina uzetih uzoraka, dok je kod ispitivanja mehaničkih čvrstoća, ispitivana jednoaksijalna čvrstoća na pritisak, čvrstoća na zatezanje i triaksijalna čvrstoća. Pored ovih veličina utvrđivani su i parametri deformabilnosti.

Izbor mesta uzimanja uzoraka vršen je u jami uz pomoć plana hodnika na XVII horizontu. Na ovaj način izabrani uzorci su početni materijal za izradu i pripremu probnih tela, koja su ispitivana u laboratoriji odgovarajućim metodama. Iz tih razloga su uzorci iz stenske mase bili manjih dimenzija. Oni su na odgovarajući način odabrani i uzimani iz osnovne mase i predstavljaju deo te mase sa datog mesta sa koga je uzet odgovarajući uzorak.

Uzimanje uzorka je urađeno na pet mesta iz kojih su dobijena probna tela (označeni su sa U–1, U–2, U–3, U–4 i U-5).

Na taj način se i svi parametri, koji su se dobili iz odgovarajućih ispitivanja, odnose na fizičko-mehaničke parametre orudnjenog masiva. [4]

Ovde će se samo detaljnije prikazati ispitivanje triaksijalne čvrstoće i ispitivanje deformabilnosti.

Ispitivanje triaksijalne čvrstoća i dobijene vrednosti glavnih napona kod triaksijalnog ispitivanja prikazani su u tabeli 2.[6]

Tabela 2. *Vrednosti glavnih napona kod triaksijalnog ispitivanja*

Oznaka serije (uzorka) sa vrednostima glavnih napona pri lomu									
U – 1		U – 2		U – 3		U – 4		U – 5	
σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]	σ_3 [MPa]	σ_1 [MPa]
0	76	0	71	0	83.2	0	86	0	88
10	107	8	98.6	5	111.8	10	145.6	5	118.1
15	143	16	150	10	132	15	185	10	145
20	168	24	195	15	176	20	230.2	15	205
25	190	32	204	20	195	30	242	25	227.4
30	203								
40	230								

Triaksijalnim ispitivanjem i obradom podataka određuje se i Hoek-Brown konstanta (m_i) za intaktnu (neporemećenu) stenu, pri čemu se uzima da je druga konstanta s=1.

Kada se radi o metodama određivanja deformabilnosti elastičnih stenskih materijala, treba ukazati da se ispitivanja uglavnom svode na određivanje modula elastičnosti, modula deformacije i Poissonovog koeficijenta, uz napomenu da je modul deformacije uvek manji od modula elastičnosti.

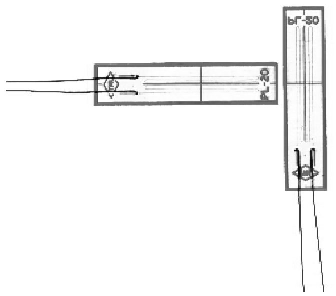
Prilikom ispitivanja modula elastičnosti moguće je pored registrovanja jedinične deformacije, u pravcu dejstva sile, utvrditi i jediničnu deformaciju upravno na dejstvo sile, čiji je odnos definisan Poissonovim koeficijentom.

U primeni je veliki broj različitih metoda i postupaka koji se između sebe razlikuju jedino kroz primenu velikog broja merača za registrovanje deformacija i sila, odnosno napona. U ovom slučaju, ispitivanje deformacionih karakteristika je vršeno sa triaksijalnom ćelijom pod uticajem svestranog pritiska. [7]

Za registrovanje deformacija na mernim trakama, izazvanim opterećenjem, korišćen je Philips-ov merni most sa očitavanjem direktno u µmm/mm. Da bi se zbog velike osetljivosti ovog mernog sistema i na minimalne promene temperature, predupredile greške pri merenju, izrađeno je probno telo koje je povezano sa mernim mostom, a na kome su zalepljene identične merne trake koje služe kao temperaturna kompenzacija. Za merne trake koje mogu da registruje deformaciju na probnom telu, izabrana je merna traka, sledećih karakteristika:

Proizvođač: Tokyo Sokki Kenkyujo Co., Ltd

- Tip (Type) PL-20-11
- Dužina trake (Gauge length) 20 mm
- Otpor trake (Gauge Resist) 120±0.3 Ω
- Faktor trake (Gauge Factor) 2.10



Sl. 1. *Izgled i položaj mernih traka na probnom telu*

Ispitivanja su rađena sa bočnim pritiskom od 16 MPa. Svaku tabelu prati i σ - ε dijagram, sa koga se očitava zaostala deformacija probnog tela u cilju utvrđivanja modula elastičnosti i oblika histerezisne krive.

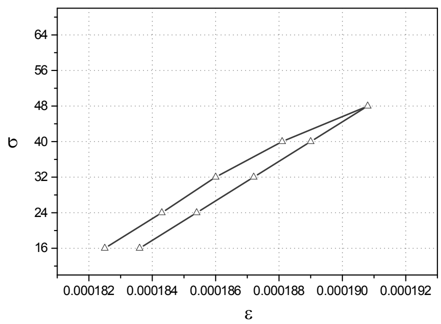
- Za simulaciju naponskog stanja stenskog masiva na većim dubinama potrebno je izvršiti ispitivanja za odgovarajuću dubinu izvođenja radova (γH). Tako je npr. bočni pritisak 16 MPa za dubinu 550÷580 m, 24 MPa za 880÷900 m itd.
- Prilikom ispitivanja deformabilnosti utvrđeno je elasto-plastično ponašanje stenske mase, koje se ogleda u zaostalim plastičnim deformacijama. Iz tog razloga u parametre modela je potrebno uključiti i parametre plastičnosti. [8]

Tabela 3. *Primer rezultata merenja deformacija na jednom od probnih tela sa konstantnim bočnim pritiskom od 16 MPa*

σ_1	Očitavanje[μ mm/mm]						Deformacije		Koef. Poissona	Napomena:
	horizontalno			vertikalno			ε_h	ε_v		
[MPa]	1	2	sredina	1	2	sredina	[mm]	[mm]	ν	
16	15400	15750	15575	13900	13910	13905	0.0000414	0.0001825	0.227	Dimenzije probnog tela su:
24	15330	15700	15515	14005	14080	14043	0.0000413	0.0001843	0.224	
32	15300	15665	15483	14095	14256	14176	0.0000412	0.0001860	0.221	
40	15270	15635	15453	14220	14440	14330	0.0000411	0.0001881	0.219	h = 76.20 mm
48	15160	15570	15365	14490	14590	14540	0.0000409	0.0001908	0.214	d = 38.10 mm
40	15230	15615	15423	14280	14520	14400	0.0000410	0.0001890	0.217	
32	15260	15640	15450	14200	14330	14265	0.0000411	0.0001872	0.219	Obim
24	15310	15690	15500	14040	14220	14130	0.0000412	0.0001854	0.222	O=dπ
16	15400	15755	15578	13930	14055	13993	0.0000414	0.0001836	0.226	O = 119.647 mm

Na osnovu ispitivanja deformabilnosti za početni bočni pritisak od 16 MPa dobijeni su parametri elastičnosti, i to:

ν = 0.221
E = 44120 MPa
E_d = 34076 MPa



Na osnovu izabranog bočnog pritiska za ovo ispitivanje, kod modeliranja stenskog masiva i izrade numeričkog modela koristiće se srednja vrednost podataka za E i ν, tabela 4.

Tabela 4. *Tabela rezultata ispitivanja deformacionih karakteristika*

Redni broj probnog tela	E [MPa]	E_d [MPa]	ν -
Srednja vrednost	40490	33255	0.216
Standardno odstupanje	2629	1066	0.004
Koeficijent varijacije	6.49%	3.20%	1.72%

Procena kvaliteta stenskog masiva

Procena kvaliteta stenskog masiva se vrši geološkim indeksom čvrstoće – GSI. U konkretnom slučaju, za XVII horizont u rudnom telu "Borska reka", na osnovu fizičkog izgleda uzetih neporemećenih uzoraka, snimljene strukture i stanje površina "in situ", procena GSI za ovakvu sredinu kreće se u granicama od 65÷75.

Međutim, za određivanje GSI moguće je koristiti i RMR klasifikaciju.

U dosadašnjim istraživanjima za rudno telo "Borska reka" konstatovana je vrednost RQD od 72% ÷ 92%, za sve istražne bušotine koje su bušene u cilju ispitivanja dubljih delova rudnog tela. Za srednju vrednost RQD na prvom intervalu uzorkovanja iz jezgra istražnih bušotina, koji su najbliži XVII horizontu, statistički je određena vrednost od 78%.

Kod razmatranja i utvrđivanja RMR klasifikacije, uzima se vrednost RQD = 78%

i σ_{ci} = 72 MPa koja je dobijena triaksijalnim ispitivanjima u istraživanju stenskog masiva na XVII horizontu. Uzimajući podatke o strukturnim karakteristikama, iz dosadašnjih istraživanja, a koristeći klasifikacija Bieniawskog iz 1989, dolazimo do vrednosti za opis stenske mase na XVII horizontu rudnog tela "Borska reka" i ona iznosi 73 poena. Za dobijanje GSI preko RMR klasifikacije Bieniawskog, uzima se GSI=RMR_{89} –5, tj. GSI = 68.

Upoređivanjem vrednosti dobijenih na osnovu RMR klasifikacije i fizičkog izgleda jezgra iz uzetih uzoraka, možemo konstatovati da bi bilo prihvatljivo da vrednost GSI iznosi 70. Ovde se mora biti oprezan, jer se mora uključiti i faktor oštećenja prostorije prilikom izrade iz kojih su uzeti uzorci (uticaj miniranja) kao i u vremenu posle izrade (pomeranja po konturi).

Rezultati istraživanja stenskog masiva

Na osnovu laboratorijskih ispitivanja mehaničkih čvrstoća, deformacionih karakteristika i procene kvaliteta masiva dolazimo do laboratorijskih vrednosti parametara stenskog masiva na XVII horizontu u rudnom telu "Borska Reka", tabela 5.[5]

Ovako definisani parametri su korišćeni kod modeliranja stenskog masiva i analizu stabilnosti objekata na nivou XVII horizonta u rudnom telu "Borska reka" u cilju dokazivanja mogućnosti korišćenja metodologije koja koristi Hoek-Brown-ovom kriterijumu loma.

Tabela 5. *Fizičko-mehanički parametri dobijeni laboratorijskim ispitivanjima na uzorcima stenskog masiva sa XVII horizonta rudnog tela "Borska reka"*

Radna sredina (XVII horizont)	γ [kN/m^3]	σ_c [MPa]	σ_i [MPa]	E [MPa]	E_d [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
K-155 Silifikovan andezit	28,2	63,39	6,71	40490	33255	0,216	41.6	15,09	18.9	73	70

Određivanje relevantnih fizičko-mehaničkih parametara stenskog masiva

Da bi se odredili fizičko-mehanički parametri stenskog masiva koji bi se koristili za dalju numeričku analizu i proračune, potrebno je uporediti rezultate laboratorijskih ispitivanja, postojećih korelacionih veza između fizičko-mehaničkih, strukturnih svojstava i rezultata kategorizacije stenskih masa, kao i definisanje čvrstoće stenskog masiva po Hoek-Brown-ovom kriterijumu loma, na osnovu dosadašnjih istraživanja. Na osnovu toga pažljivo proceniti i odrediti parametre koji će biti relevantni tj. merodavni da karakterišu stanje stenske mase, a samim tim i ući u modeliranje stenskog masiva.

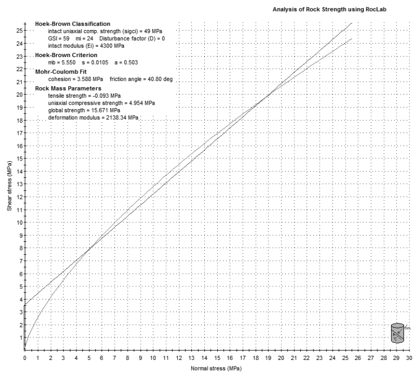
Do sada, prema prvim analizama koja su urađena u okviru najnovijih istraživanja, došlo se do podataka koji pokazuju delimično niže vrednosti koji opisuju fizičko-mehanička svojstva stenskog materijala, tabela 6 i slika 2.

Tabela 6. *Fizičko-mehanički parametri dobijeni laboratorijskim ispitivanjima na uzorcima uzetih iz bušotina u okiru najnovijih geomehaničkih istraživanja stenskog masiva iz rudnog tela "Borska reka"*

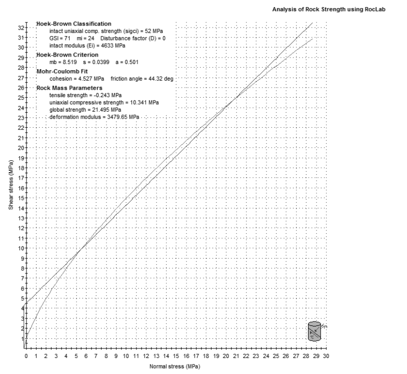
Geotehnička sredina	γ [kN/m^3]	σ_c [MPa]	σ_i [MPa]	E_t [MPa]	E_s [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
Borski peliti	25,4	49	4,95	5600	3730	0,34	36,0	24	12,13	54	
Andeziti	25,9	52	5,37	6927	4633	0,31	36,8	26	12,90	66	
Andeziti kaolinisani	27,0	25	3,04	5490	3672	0,37	30,4	20	7,53	34	
Andeziti silifikovani	27,7	67	7,57	10790	7127	0,32	37,4	28	16,70	51	

Upravo zbog toga je potrebno, kada rezultati budu konačni i Elaborat završen, izvršiti komparativnu analizu podataka za modeliranje stenskog masiva i doneti odgovarajuće zaključke u vezi relevantnih podataka sa kojima će se dalje ići u proračune stabilnosti i definisanja načina i metode eksploatacije rude bakra iz rudnog tela Borska reka u Jami Bor.

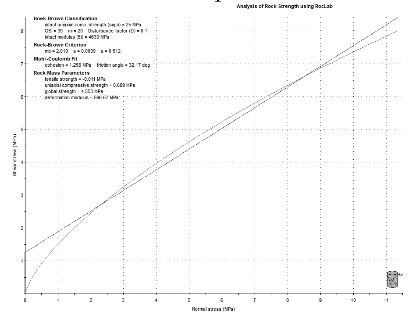
Kako se radi o velikim dubinama, gde je bezbednost na prvom mestu, geomehanička istraživanja dobijaju veliki značaj, ali i odgovornost kod preciznog definisanja parametara. Nekad i preterivanje u obezbeđivanju zadovoljavajućeg faktora sigurnosti, u slučaju rudnog tela Borska reka, može da odvrati od daljeg investiranja iz ekonomskih razloga. Samim tim, odgovornost kod definisanja ovih parametara postaje još veća.



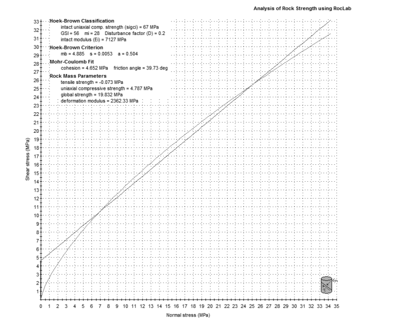
Borski peliti



Andeziti



Andeziti kaolinisani



Andeziti silifikovani

Sl. 2. *Parametri čvrstoće stenske mase za sve izdvojene sredine*

ZAKLJUČAK

Na osnovu rezultata do sada obavljenih laboratorijskih ispitivanja na uzorcima stenskog masiva i jezgra istražnih bušotina uz uvažavanje stanja stenskog masiva, stepena reprezentativnosti uzoraka, efekta razmere i dr., izvršen je izbor parametara fizičko-mehaničkih svojstava stenske mase koji su merodavni za modeliranje stenskog masiva.

Razvojem programskih paketa koji se bave pripremom i analizom numeričkih modela i primena Hoek-Brown kriterijuma loma doživela je poseban napredak. Ovaj kriterijum loma je jedan od opšte prihvaćenih i najkorišćenijih kriterijuma za modeliranje stenskog masiva.

Samim tim, ovaj rad sadrži, pored dela o rezultatima fizičko-mehaničkih ispitivanja rudnog tela "Borska reka" upravo i određivanje triaksijalne čvrstoće i deformabilnosti stenskog masiva. Takav doprinos modeliranju stenskog masiva, uz poznavanje pravca i inteziteta napona u masivu i primenom adekvatnog matematičkog modela, dolazi do optimalnih rešenja kod dimenzionisanja podzemnih objekata u funkciji dubine i potrebnog faktora sigurnosti.

Uopšteno govoreći, razvoj savremene podzemne eksploatacije prate sve složeniji rudarsko - geološki uslovi. Zato su i problemi u podzemnoj gradnji vezani za rešenja koja se moraju bazirati na dobrom poznavanju zakonitosti razvoja mehaničkih procesa u stenskom masivu. Fizičko - strukturne i mehaničke osobine stenskog masiva, tehnološke specifičnosti sistema eksploatacije i način pripreme otkopnih blokova predodređuju i mehaničko stanje tih složenih sistema.

Sve ovo traži drugačiji pristup, vrstu i obim geomehaničkih istraživanja, naročito ako se planira upotreba numeričkih modela. Oni zahtevaju izbor oblika podzemnih objekata, modeliranje stenskog masiva i parametara kriterijuma loma na osnovu detaljnog izučavanja stenskog masiva kroz odgovarajuća laboratorijska i terenska ispitivanja. To čini još većom opravdanost za detaljnijim upoznavanjem sa novim tehnikama koje se u svetu već uveliko primenjuju, pa nema razloga da se takav program ne primeni i na naša ležišta.

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