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FORECAST THE BEHAVIOUR OF ROCK MASS BEFORE TAKING UP THE EXCAVATION AT DEEPER LAYERS OF THE ORE BODY BORSKA REKA^{****}

Abstract

This paper presents one possible approach for resolving some important issues related to the stability of underground rock structures at higher depths. The analysis is focused on forecast the behavior of rock mass before performing the mining excavation at deeper levels of the ore body "Borska Reka".

Regardless of extensive previous research of the ore body "Borska reka" and necessary parameters obtained for modeling of stress and strain that occur under the influence of mining excavation, additionally the estimation state of stress in the rock massif is also done. The stability analysis is shown for the roadway at the level XVII and forecast their stability for deeper level. As the result, it is expected that the level of uncertainty and risk associated with many identified geomechanical risks with management of rock massif will be reduced.

Keywords: forecast, behaviour of rock mass, roadway stability, ore body Borska reka

INTRODUCTION

The mining works and roadways construction in deep mines causes instability which may occur as the result of roof falls, wall failures or combination of both. Thus, in order to safety come first when performing the mining operations, the stability of such roadways is very important. The prime concern in excavations is the control of displacements in the rock surrounding the excavation. In each excavation, the design objective is to ensure that displacements of

the rock do not interfere with the specified engineering activities.

Computer modeling for strata control in rock mechanics has significantly developed in recent years. There are various numerical methods and codes available for stability analysis of underground openings. Despite the significant advances that have been made, it must be recognized that the successful application of numerical methods in rock engineering design analyses depends to a

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great extent on geomechanical models and boundary conditions developed from the site characterization data. Due to a difficulty in defining some of the input data, the deterministically, probabilistic or stochastic methods are often used to represent mechanical properties of rocks and rock masses, and in the analyses themselves.

Underground mine design requires an iterative process which is often approached in different ways. Initially, the possible mining methods are selected, likely production capacities determined and indicative cut-offs derived. Preferred mining methods are selected followed by more refined ore definition. The primary infrastructure options are then established and the analysis taken through to the global extraction sequencing. Much evaluation has to be done before design commences.

When the primary infrastructures - roadways have to be designed, one of the first questions often put to the rock mechanic & mining engineers is "What is the maximum stable opening?" However, it is often too early and there is rarely anything like enough data available on which to base an informed decision.

Serious consideration of geomechanics problems, associated with deep and high stress mining, began before the advent of modern high-speed digital computers and numerical modelling methods.

In this computer era, a wide range of computer software has been used in numerical analyses of the rock mass behavior. They include the range of displacement discontinuity and related programs, as well as **FEM*** (**Phase2**), **BEM**[†], **FDM**[‡] and **DEM**[§] codes. [1]

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* *Finite Element (FEM) and related methods* (Beck et al., 2009, 2010; Goodman et al., 1968; Wittke, 1977, 1990; Zienkiewicz, 1977)

† *Boundary Element Methods (BEM)* (Beer and Watson, 1992; Brady, 1979, 1987; Crouch and Starfield, 1983)

‡ *Finite Difference Methods (FDM)* (Hart et al., 2008; Itasca, 2011; Sainsbury et al., 2011)

Despite the availability of computer techniques and software and applicable engineering procedures, the geomechanical analysis is even more of an art than real modelling of rock mass.

Obviously, it will never be possible to do enough geomechanical exploration to enable geomechanics risks of this wide range of types to be fully accounted in the planning stages of mining project. However, as the project proceeds through the various stages from concept to detailed design and implementation, the level of uncertainty and risk associated with many sources of geomechanics risk identified previously can be expected to be reduced.

Applicability of standard strength criteria

Most of numerical analyses, currently used for evaluation the stability of underground excavations, are based on the linear Mohr-Coulomb strength criterion. However, the experimental data and experience of the field engineering showed that the strength of nearly all types of rock mass is followed by the non-linear Hoek-Brown strength criterion. The Hoek-Brown strength criterion for rock mass is widely accepted and applied in a large number of engineering in the world.

The classic Mohr-Coulomb strength criterion consisting of two independent cohesive and frictional components does not provide a realistic representation of progressive fracture and breakdown of rock under stress. The Hoek-Brown criterion is widely applied to jointed rock masses, but may also be applied to intact rock. In fact, much more data

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§ *Discrete Element Methods (DEM)* (Jing and Stephansson, 2007)

for intact rock than for rock masses were used in its original development by Hoek and Brown (1980) and later. [2]

CASE STUDY OF ORE DEPOSIT “BORSKA REKA”

For purposes of this paper, this analysis will be mainly focused on forecast the behaviour of rock mass in particular case of ore deposit (body) “Borska Reka” in the underground mine “Jama” in Bor.

This deposit has a length of about 1,000 m and a thickness about 500 m, dipping to the west at an angle of 45° to 55°, according with dipping of Bor conglomerates and sandstones, and it is separated by the Bor fault from hydrothermal zone. Exploration works on the ore body “Borska Reka” deposit have been carrying out in the period from 1976 until these days with a large volume of research works. Detailed exploration works were carried out to the level -155 m and it is assumed that the deposit is dipping to elevate at the level of -800 m and even deeper. Part of the deposit above the XIX level K-235, is opened by the transport system for the ore bodies “Tilva Roš” and “P2A”.

Mining operations are carried out on the basis of mining project for exploitation of copper ore above the XIX level (K-235). After many years of determination the mineral reserves in the ore body “Borska Reka”, additional explorations and prepared documentations, this ore body is still waiting for exploitation. There are plans to increase the mine production using mining excavation methods with preserving the surface and all constructed facilities, infrastructures and mining works above the ore deposit “Borska Reka”, starting with excavation from the

level XIX. The deeper layers will be considered for exploitation in the further steps.

This is certainly a serious challenge in managing the rock massif and geomechanical risks. Therefore, the results of this analysis, on one hand, referred to the need for forecasts the behavior of rock mass before taking up the excavation at deeper layer, and on the other hand, the excavation of deeper layer of the ore body “Borska Reka” requests to carry out all necessary geomechanical testings in order to obtain reliable information as a basis for decision-making.

PREVIOUS EXPLORATIONS AND MODELING OF STRESS-STRAIN STATE

Previous explorations

In order to determine the geomechanical characteristics of working environment, the current technical documentations of geological, geotechnical and hydrogeological investigations and design analysis were reviewed concerning the ore body “Borska Reka” in the underground mine “Jama” Bor. Based on this, it can be generally concluded that much was done and a lot of work and effort and money were invested.

Here, some of the years will only be mentioned when the subject explorations were carried out starting from 1997, 1999, 2007 and 2014 by the Mining and Metallurgy Institute Bor. [3]

So far, according to the carried out analyses within the latest explorations, it was found out that the data show partially lower values of physical and mechanical properties of rock in relation to the previous explorations, Table 1.

Table 1 Physical-mechanical parameters obtained by laboratory tests on samples of rock mass from 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
Pelytes *2014	25.4	49	4.95	5600	3730	0.34	36.0	24	12.13	54	
Andesites *2014	25.9	52	5.37	6927	4633	0.31	36.8	26	12.90	66	
Kaolinized Andesites *2014	27.0	25	3.04	5490	3672	0.37	30.4	20	7.53	34	
Silicified Andesites *2014	27.7	67	7.57	10790	7127	0.32	37.4	28	16.70	51	
(level XVII) K-155	γ [kN/m ³]	σ_c [MPa]	σ_i [MPa]	E [MPa]	E_d [MPa]	ν -	ϕ [°]	m_i -	C [MPa]	RMR ₈₉	GSI
Silicified Andesites *1999	28.2	63.39	6.71	40490	33255	0.216	41.6	15.09	18.9	73	65

Modeling of stress-strain state

Apart from the standard laboratory tests and “in situ” observations and measurements, the laboratory test procedures were carried out for testing the strength parameters and deformable characteristics of working environment using the triaxial compression. Triaxial experiment is aimed to simulate the conditions that may occur in the rocks surrounding the underground infrastructures – roadways and facilities and these openings could be exposed to the limit pressure and shearing stress. [4]

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 samples size, mechanical strength, deformation characteristics and quality assessment of rock mass, the laboratory values are obtained for parameters of rock mass at the level XVII in the ore body “Borska Reka”. [5]

The rock stability analysis was carried out on a standard cross-section of roadway which is designed and constructed in the underground mine “Jama” Bor (4x3.5m), with a scope of confirmation the relevance of data collected from previous explorations and studies mentioned above.

State of stress in the ore body “Borska Reka” is not measured previously, therefore this data was not available. Due to the lack of knowledge on the stress state of rock massif, the field of stress will be defined through the gravitational component - γH . Stress was measured in the nearest ore body “Tilva Ros” and given the proximity indicating on relations between the principal stresses (Fig. 1). The ratio is between 0.7 ± 0.05 . This assessment could be also accepted for the ore body “Borska Reka” and XVII level (K -155). [6]

It should be noted that the stress measurements were made more than twenty years ago and only on the roadway contour. It can be assumed that the actual values are higher if the stress was measured deeper into the rock massif. That means the shortage of precise stress values for a specific level of depth in the ore body “Borska Reka” indicate the first problem in accuracy of executed certain calculations and conclusions.

Instead of qualitative rock mass stability analysis, the empirical analysis can be performed based on estimations and assumptions in order to meet the required range of values, but it may be wrong in that required range. [7]

Figure 1 Linear function of stress measured variations by depth of principal stresses for the ore body "Tilva Ros" in the underground mine "Jama" Bor

Determined value of stresses taken from the (Fig. 1) for level XVII is for $\sigma_1 = \sigma_v = 14$ MPa, and for $\sigma_3 = 9.5$ MPa.

Model design

Boundary conditions are defined so that the stress on model will be only under the influence of gravitational component, and the model external boundary is fixed so it cannot move in the X and Y axis direction.

The required density of points (nodes) of which depends the number of finite elements density is determined by the model discretization. A density of 75 points (nodes) on contour profile was chosen in this case. This can show what extent the density of finite element affects the accuracy of results and the interpolation accuracy, i.e. drawing the contours of stress and strain. The finite element grid is composed of triangles and

is shown in any figure of result interpretation.

Result interpretation and stability assesment

For designed roadway cross section modeling, the finite element mesh is generated with total of 1404 elements and 729 nodes. Data entry for each case only differs in direction of principal stresses. Interpretation of results and stability assessment is given for both defined cases. Calculation results are interpreted with contour lines of safety factor, total displacement and principal stress. Deformation grid is also presented, deformation on model contour lines with the direction of displacement (which is magnified 100 times) as well as the plasticity zone marked with markers. Markers in the form of crosses (x) mark fracture occur due to shear stress, and in the form of circles (o) mark fracture caused by tension stress. (Fig. 2).

Designed - constructed object (roadway) on the level XVII - 4x3.5 m

in the zone of elastic deformation

in the zone of plastic deformation

Stress field - defined by gravitational component - γH

Figure 2 Stress-strain analyses in case the stress field under the influence of gravitational component - γH

If the rock mass around given premises located in the zone of elastic deformation, so long that zone will be stable to the apportionment factors of safety as it is shown in Fig. 2b. Contour line of the safety factor of 1.3 meets the set criterion of stability. But it is seen that the sides of roadway that line is further from the contours and that consequently this area becomes susceptible to transition from the elastic zones into the zone of plastic deformation. The total displacement along the contour is 1.8 mm (Fig. 2c).

In the parts around the roadway cross-section with plastic deformation (Fig. 2e), the plastic zone due to shear stress (x) will occur in the roadway arch, and the complex plastic zone due to shear and tension stress (x and o) occurs on the sides of roadway.

It can be concluded that in this case the roadway is stable. However, the appearance of plastic deformation, which is manifested as a sporadic rock fragmentation in the form of flaking and falling down of small pieces, could be appropriately protected with the same roof support system to secure the site from future spread of damage. [8]

FORECAST THE BEHAVIOUR OF ROCK MASS

To take an advantage of modeling research which allows forecasting the be-

haviour of rock mass before taking up the excavation at deeper layers, the stability analysis of deeper levels of the level XVII will be used in this section.

Depth selection was taken at the level of XIX (K -235), XXI (K -315), XXIII (K -395) and XXV (K -475) and they represent a depth value of about 630 m, 710 m, 790 m and 870 m under surface.

Based on that, it can be said that the chosen levels for stability analyses, XVII and XIX level are included in the new mine design. It can be useful, because the newly constructed facilities at the levels, with the appropriate observations can be useful to demonstrate the validity of this stability analysis assessment. Other three levels are analyzed in order to predict what can be expected at deeper levels at a later stage and will be the subject of further elaboration. [9]

Interpretation of stability assessment results are done as well as stability analysis for level XVII and it might be easier to compare the results.

The values of the principal stress were obtained on the basis of the gravity component $\sigma_v = \gamma H$, and the ratio of principal stresses σ_1 and σ_3 obtained from the analytical equation from the graph in Figure 1.

Table 2 Prognostic value of the principal stresses for selected depth

Level	Ground level	Depth m	γH MPa	σ_1 MPa	σ_3 MPa	σ_3/σ_1
XVII	-155	550	14	14	9.5	0.70±0.05
XIX	-235	630	17	17	10.5	0.65±0.05
XXI	-315	710	19.2	19.2	11.5	0.60±0.05
XXIII	-395	790	21.3	21.3	12.6	0.55±0.05
XXV	-475	870	23.5	23.5	13.5	0.55±0.05

Figure 3 Stress-strain analyses for deeper levels in case the stress field under the influence of gravitational component - γH

Forecast the stability model at depth below the level XVII

The results of model analysis are made for the stress field determined by the gravitational component - γH . The finite element grid is used for modeling as in the previous analysis.

To define rock mass parameters for the analysis, the fracture criterion and parameters of the rock mass obtained from the parameters at the XVII level were used. It was necessary to simulate those depths for assessment the stability by increase the lateral sample using the triaxial tests, which determined the deformable characteristics of the rock mass at the level XVII. These tests were not carried out and deformable characteristics of the rock mass at the XVII level were used for these analyses.

The stress-strain analysis of rock mass at the levels XIX, XXI, XXII and XXV are shown in Figure 3.

Looking at the results of stability analysis by levels, it can be concluded that the stability of the roadway decreases linearly with increasing depth and it was expected.

Considering that maximum displacements on the model grow with the increase of depth as 2.1 mm, 2.4 mm, 2.76 mm and 3.2 mm, the rock fragmentation and rock deterioration can be expected for deeper levels than the level XXI.

The places with occurrence of plastic deformation, plastic zone on roadway will have such a character that on the roof appear the plastic zone (x), and on the sides appear plastic zone (x and o). This could be applies only for the level XIX while the deeper levels it should be expected plastic zones (x and o) all over the roadway. The size of the plastic zone influence is in the range of 18 cm, 21 cm, 28 cm and 35 cm. In the roof their value is 16 cm, 17 cm, 18 cm and 20 cm, while on the floor only the level XIX deployed in the corners and on the other levels is distributed all over the floor.

In this case of principal stress appointed, contour line of the safety factor on the side of roadway is increasingly moving away from the side. Base on that risk the stability increased due to the stress from the side of the roadway. [10]

It can be estimated that at the level XIX this roadway can stay unsupported, except on places with the plastic zone appearance and the support must be installed in these places. Forecast the stability for the same roadway at the levels XXI, XXIII and XXV indicates that it must have the adequate roof supports in some sections or on the entire length. As the result of increasing, the depth may notice a certain "calming" in plastic zone increasing around the cross-section. That requires redefining the boundary conditions on the model and estimated or measured new value of the principal stresses and their direction.

In the areas of plastic zone, the rock fragmentation is mainly induced by extensive deformation. Deformation starts immediately after excavation, and it is commonly stabilized with reaction of the installed support, reaching the equilibrium of forces, but it could be transformed into deterioration as the result of rheological behaviors of rock mass.

Rock deterioration in proximity of underground openings – roadways might occur for several reasons. The major cause is a stress concentration in immediate roof and floor rocks, as well as in sides. This concentration is generated by the initial equilibrium disturbance following the roadway development, resulting in concentration of vertical stress in sides of the roadway, while the horizontal stress is concentrated in the roof and floor. Deterioration would be manifested as a forming zone of deteriorated rock mass in the roadway roof. This is noted during previous re-

search. In such zones, the rock is very fragmented, and the deterioration zone also continues to expand in the immediate roadway rock mass. [11]

Future research

The future research certainly should include measuring of the stress in the ore body "Borska reka" with determining the direction of principle stresses. In that case, the field of stress would be defined by the stress components σ_1 , σ_3 , σ_v and also taken into consideration possible influence of the Bor fault zone as well as inclination angle of the ore body "Borska reka". That could greatly change the picture of stability.

In opening every another level, the additional geomechanical investigations should be carried out. These investigations will determine the physical and mechanical parameters of the rock mass which would be used for further numerical analysis and calculations and compared with the previous laboratory tests results. Also, they would odemtofy the correlation between the physical-mechanical, structural properties and categorization of rock mass results as well as defining the behavior of rock mass by the Hoek-Brown's strength criterion. Based on this, it can carefully evaluate and determine the parameters relevant to characterize the behavior of rock mass and thereby used for further modeling of the rock mass and a new forecast for deeper levels.

CONCLUSION

This paper presents a case study forecast of behavior the rock mass for deeper levels in the ore body "Borska reka" where the field of stress is defined only by the influence of gravitational component and vertical stress direction. The principal

stresses were defined by the linear function result from stress measurements in the ore body "Tilva Roš".

Based on laboratory tests on the previous results, which include the rock mass at the level XVII (K -155 m) in the ore body "Borska reka" and the accurate research and triaxial tests that were carried out on test samples taken from the rock mass, the results were analyzed by the Hoek-Brown methodology and are directly used as the input parameters for numerical modeling.

There was a limiting factor in defining values for stress, because the stress measurement for given location was not measured. Stress state is determined on the basis of the gravity component, and since the ratio of principal stresses have been evaluated on the basis of stress measurement stress for the ore body "Tilva Roš" even 20 years ago and more.

The numerical model is based on the finite element method (FEM) and the software package PHASE² is used for this purpose. Analysis and interpretation of the results were carried and shown for designed and constructed roadway. The results are contained within in displacement vectors, principal stress distribution and plastic zone around the analyzed object.

Stability analysis was firstly done for the level XVII where the straining criterion and necessary data for analyses are defined for the rock mass. Based on that, the analyses were carried out for deeper layers in the second phase of forecast stability. The included levels are XIX (-235 K), XXI (-315 K), XXIII (-395 K) and XXV (K -475).

Results and forecast stability of the roadway at deeper layers with characteristics of the rock mass and assumed stress, showing that the stability decreases of the roadway on the analyzed model. Model applied in the analysis remains stable up to the level XIX, while at deeper levels have to be safe and secure with the roof support

system or with fully support. This conclusion is based on the parameters at the level XVII which are according to the volume and estimated stress insufficient for qualitative forecasting stability, especially in the deeper levels. Due to these reasons, it is essential that for each new level the additional geomechanical investigations are needed. As the mining operations go deeper, the results of forecast for the same level would be verified or corrected with these new data, and also work out the forecast of behavior the rock mass for the next deeper level.

Certainly that one qualitative analysis such as stability analysis would be fully been worked out with no use of any estimated value as in this case for the stress value and its direction. To this end, the evaluation of stress in the ore body "Borska reka" as well as to define the parameters essential for understanding the behaviour of rock mass is necessary to complement the current geomechanical investigations with appropriate methods for stress measuring.

Synthesis of previous and proposed research would give more complex image of the ore body "Borska reka". Through appropriate models, from that aspect it would be possible to analyze all kinds of mining activities and performed work. Results of these analyzes could be more reliable applied in practice.

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PROGNOZA PONAŠANJA STENSKOG MASIVA PRE OTKOPAVANJA NA DUBLJIM HORIZONTIMA RUDNOG TELA BORSKA REKA****

Izvod

U ovom radu prikazan jedan od načina na koji bi moglo da se pristupi u rešavanju nekih važnih pitanja vezanih za stabilnost podzemnih objekata na većim dubinama. Analiza je fokusirana na predviđanje ponašanja stenskog masiva pre izvođenja rudarskih radova i to u konkretnom slučaju na dubljim nivoima u rudnom telu "Borska reka" u rudniku Jama u Boru.

Pored obimnog dosadašnjeg istraživanja rudog tela "Borska reka" i dobijenih parametara za modeliranje stanja napona i deformacija koji se javljaju pod uticajem rudarskih radova, dodatno je izvršena i procena naponskog stanja u masivu. Prikazana je analiza stabilnosti prostorija na nivou XVII horizonta i izvršena prognoza stabilnosti istih prostorija za dublje nivoe otvaranja. Kao rezultat se očekuje da će nivo neizvesnosti i rizika u vezi sa mnogim identifikovanim geomehničkim rizicima u upravljanju stenskim masivom biti smanjen.

***Ključne reči:** predviđanje, ponašanje stenskog masiva, stabilnost prostorije, rt Borska reka*

UVOD

Rudarski radovi i izrada prostorija u dubokim rudnicima izazivaju nestabilnost u radnoj sredini koja može nastati kao rezultat popuštanja krovine, pukotina i izboja iz bokova ili kombinacije oba. Zbog toga, stavljajući bezbednost na prvom mestu prilikom izvođenja rudarskih radova, stabilnost ovakvih prostorija je veoma važna. Osnovna briga u otkopavanju je kontrola pomeranja u stenskom masivu oko

izgrađene prostorije. Za svaku prostoriju, cilj projektovanja je da osigura da pomeranja oko prostorije nemaju uticaj na određene rudarske aktivnosti.

Modeliranje u kontroli ponašanja nadkopnih stena i slojeva u mehanici stena značajno je razvijan poslednjih decenija. Postoje različite numeričke metode i softveri dostupni za analizu stabilnosti podzemnih otvora. Uprkos značajnom napredku koji je

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napravljen, prepoznaje se da uspešna primena numeričkih metoda u projektovanju i analizi stabilnosti, zavise u velikoj meri od geomehaničkog modela i graničnih uslova razvijenih za podatke sa date lokacije. Zbog teškoća u definisanju nekih od ulaznih podataka, često se koriste stohastičke metode i verovatnoća za predstavljanje mehaničkih osobine stena i stenske mase, kao i u samim analizama.

Projekat za rudnik podzemne eksplo-

utvrđivanje proizvodnih kapaciteta i graničnog sadržaja korisne komponente. Bira se odgovarajuća metoda prateći granice rudnog ležišta. Utvrđuje se plan razvoja osnovne infrastrukture otvaranja i analiza opšteg redosleda otkopavanja. Mnogo procena mora da se uradi pre nego što projekat započne.

Kada se projektuje osnovna infrastruktura otvaranja, jedno od prvih pitanja koja se često postavlja pred mehaniku stena tj. rudarskim inženjerima je "Koliki je maksimalni stabilan profil prostorije?". Međutim, često je prerano i retko da postoji dovoljno dostupnih i sličnih podataka

ve modernih brzih digitalnih računara i numeričkih metoda modeliranja.

U ovoj kompijuterskoj eri, širok spektar računarskog softvera se koristi u numeričkim analizama ponašanja stenske mase. Oni uključuju različita pomeranja po diskontinuitetu i srodne programa, kao što su **FEM**^{*} (**Phase2**), **BEM**[†], **FDM**[‡] i **DEM**[§]. [1]

^{*} *Metode Konačnih Elemenata (FEM) (Beck et al., 2009, 2010; Goodman et al., 1968; Wittke, 1977, 1990; Zienkiewicz, 1977)*

[†] *Metode Graničnih Elemenata (BEM) (Beer and Watson, 1992; Brady, 1979, 1987; Crouch and Starfield, 1983)*

Uprkos dostupnosti računarske tehnike i geomehanička analiza je još uvek više umetnost nego stvarno modeliranje stenske mase.

uraditi dovoljno geomehaničkih istraživanja u fazi planiranja jednog rudarskog projekt

tipova geomehaničkog rizika bude u potpunosti uzet obzir. Međutim, kako se projekat odvija kroz razne faze od ideje do detaljnog dizajna i implementacije, nivo neizvesnosti i rizika u vezi sa mnogim izvorima geomehaničkog rizika koji su prethodno identifikovani može se očekivati da budu smanjeni.

Primena standardnih kriterijuma čvrstoće

nutno koriste za procenu stabilnosti podzemnih prostorija se zasnivaju na linearnom Mohr-Coulomb kriterijumu čvrstoće. Međutim, eksperimentalni podaci i inženjersko iskustvo pokazalo je da čvrstoća za skoro sve vrste stenske mase prati ne-linearan Hoek-Braun kriterijum čvrstoće. Hoek-Braun kriterijum čvrstoće za stenske mase

čajeve u svetu.

Klasični Mohr-Coulomb kriterijum čvrstoće sastoji se od dve nezavisne komponente kohezije i ugla unutrašnjeg trenja i ne daje realnu sliku o progresivnom lomu i raspadu stene pod pritiskom. Kriterijum Hoek-Braun je široko zastupljeniji za ispucalu radnu sredinu, ali takođe može da se primeni i na

[‡] *Konačne Diferencijalne Metode (FDM) (Hart et al., 2008; Itasca, 2011; Sainsbury et al., 2011)*

[§] *Metode Diskretnih Elemenata (DEM) (Jing and Stephansson, 2007)*

neporemećeni stenski masiv. U stvari, mno-

inom razvoju Hoek i
Brown modela od (1980), a i kasnije. [2]

ANALIZA SLUČAJA NA PRIMERU RUDNOG TELA "BORSKA REKA"

Za svrhu ovog rada, analiza se uglavnom bazira na ponašanju stenske mase na konkretnom primeru, ležištu – rudnom telu "Borska reka" u rudniku Jama u Boru.

Ovo ležište po pružanju ima dužinu od oko 1.000 metara i moćnost oko 500 m, zaleže ka zapadu pod uglom od 45° do 55°, u skladu sa zaleganjem borskih konglomerata i peščara, a od hidrotermalne zone odvojen je borskim rasedom. Istražni radovi na rudnom telu "Borska reka" su započela u periodu od 1976. do ovih dana i to sa velikim obimom istraživačkih radova. Detaljni istražni radovi su izvedeni na nivou K-155 m, a pretpostavlja se da rudno telo zaleže do nivoa K-800 m, pa čak i dublje. Deo ležišta iznad nivoa K-235, otvoren je transportnim sistemom za rudna tela "Tilva Roš" i "P2A".

Rudarski radovi se obavljaju na osnovu rudarskog projekta eksploatacije rude bakra iznad nivoa (K-235). Nakon više godina od utvrđivanja rezervi mineralnih sirovina u rudnom telu "Borska reka", dodatnih istraži-

vanja sa očuvanjem površine terena i svih izgrađenih objekata, infrastrukture i rudarskih radova iznad ležišta "Borska reka", počevši sa otkopavanjem od nivoa XIX

za eksploataciju u sledećoj fazi.

Ovo je svakako i ozbiljan izazov u upravljanju stenskim masivom i geomehaničkim rizicima. Dakle, rezultati ove analize, s jedne strane, odnose se na potrebu za prognozu ponašanja stenske mase pre nego što otkopavanje počne na dubljim nivoima rudnog tela "Borska reka", i sa druge strane, zahtev da se izvrše sva potrebna geomehanička ispitivanja u cilju dobijanja pouzdanih informacija kao osnova za dalje donošenje odluka.

PRETHODNA ISTRAŽIVANJA I MODELIRANJE NAPONSKO- DEFORMACIJSKOG STANJA

Prethodna istraživanja

U cilju utvrđivanja geomehaničkih karakteristika radne sredine, pregledana je sadašnja tehnička dokumentacija geoloških, geotehničkih i hidrogeoloških ispitivanja i analiza koja se odnose za rudno telo "Borska reka" u rudniku Jama Bor. Na osnovu toga, može se generalno zaključiti da je mnogo toga urađeno i da je mnogo rada, truda i novca uloženo.

Ovde će se samo pomenuti neke od godina kada su predmetna istraživanja rađena, počevši od 1997, 1999, 2007 i 2014 godine od strane Instituta za rudarstvo i metalurgiju iz Bora. [3]

Do sada, prema analizama koja su urađena u okviru najnovijih istraživanja, došlo se do podataka koji pokazuju delimično niže vrednosti koji opisuju fizičko-mehanička svojstva stenskog materijala u odnosu na prethodna istraživanja, tabela 1.

Tabela 1. Fizičko-mehanički parametri dobijeni laboratorijskim ispitivanjima na uzorcima uzetih iz stenskog masiva 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 *2014	25,4	49	4,95	5600	3730	0,34	36,0	24	12,13	54	
Andeziti *2014	25,9	52	5,37	6927	4633	0,31	36,8	26	12,90	66	
Andeziti kaolinisani *2014	27,0	25	3,04	5490	3672	0,37	30,4	20	7,53	34	
Andeziti silifikovani *2014	27,7	67	7,57	10790	7127	0,32	37,4	28	16,70	51	
(XVII level) K-155	γ [kN/m ³]	σ_c [MPa]	σ_i [MPa]	E [MPa]	Ed [MPa]	ν -	ϕ [°]	m_i -	C [MPa]	RMR ₈₉	GSI
Andeziti silifikovani *1999	28,2	63,39	6,71	40490	33255	0,216	41,6	15,09	18,9	73	65

Modeliranje naponsko-deformacijskog stanja

Pored standardnih laboratorijskih testova i "in situ" opažanja i merenja, izvršeni su postupci laboratorijskih ispitivanja za testi-

jalne kompresije. Triaksijalni eksperiment ima za cilj da simulira uslove koji se mogu pojaviti u okolnim stenama podzemne infrastrukture - hodnika i objekata i ove prostorije mogu biti izložene graničnom pritisku i naponu smicanja. [4]

Na osnovu prethodnih rezultata laboratorijskih testova sprovedenih na uzorcima stena iz masiva i jezgra istražnih bušotina, uz uzimanje u obzir stanje stenskog masiva, stepena

, deformacionih karakteristika i kvaliteta procene stenske mase, laboratorijske vrednosti su dobijene za parametre stenske mase na nivou XVII horizonta u rudnom telu "Borska reka". [5]

Analiza stabilnosti stena je izvedena na standardnom poprečnom preseku prostorije koja je projektovana i izrađena u Jami Bor (4x3,5m), sa potvrdom relevantnosti obima podataka prikupljenih iz prethodnog istraživanja i gore pomenutih istraživanja.

Stanje napona u rudnom telu "Borska reka" ranije nije mereno, zato ovi podaci nisu dostupni. Zbog nedostatka poznavanja naponskog stanja u stenskom masivu, napo-

ciono komponente - γH . Napon je meren u najbližem

u vidu blizinu, ukazuje na odnose između glavnih napona. Odnos je između $0,7 \pm 0,05$. (Slika 1.) Ova procena će se prihvatiti i za rudno telo "Borska reka" za nivo XVII horizonta (K -155). [6]

Ovde treba napomenuti da su merenja napona urađena pre više od dvadeset godina i samo na konturi prostorije. Može se prët-

je napon meren dublje u stenskom masivu. To znači da nedostatak preciznih vrednosti napona za određeni nivo dubine u rudnom telu "Borska reka" ukazuje na prvi problem u tačnost izvršenih određenih proračuna i zaključaka.

Umesto kvalitativne analize stabilnosti stenske mase, empirijska analiza može da se vrši na osnovu procene i pretpostavke sa namerom da se nađemo u traženom opsegu vrednosti, ali možemo i da pogrešimo. [7]

Sl. 1. Linearna funkcija odnosa promene izmerenih glavnih napona sa dubinom za rudno telo "Tilva Ros" u rudniku Jama Bor

Utvrđena vrednost napona uzeta je sa slike 1. Za nivo XVII horizonta je za $\sigma_1 = \sigma_v = 14$ MPa, i za $\sigma_3 = 9,5$ MPa.

Izrada Modela

Konturni uslovi su odabrani tako da je opterećenje na modelu samo pod uticajem gravitacijske komponente, tako da je model fiksiran i da nema pomeranja u pravcu X i Y ose.

Diskretizacijom modela se određuje potrebna gustina tačaka (čvorova) na konturi profila od koje zavisi broj konačnih elemenata sa kojima će se ući u proračun. U ovom slučaju izabrana je gustina od 75 tačaka (čvorova) po konturi profila. Sa ovim se pokazuje da li i u kojoj meri gustina mreže konačnih elemenata utiče na tačnost rezultata i preciznost kod interpolacije tj. iscrtaavanja izolinija napona i deformacija. Mreža konačnih elemenata je sastavljena od tro-

uglova i prikazana je na svakoj slici kod interpretacije rezultata.

Interpretacija rezultata i ocena stabilnosti

Za modeliranje projektovanog profila prostorije generisana je mreža konačnih elemenata sa ukupno 1.404 elementa i 729 čvorova. Unos podataka se vrši za svaki model posebno, s'time što se razlikuju u pravcima delovanja glavnih napona. Interpretacija rezultata i ocena stabilnosti se prikazuje za sva oba urađena slučaja. Rezultati proračuna su interpretirani izolinijama faktora sigurnosti, totalnih pomeranja i glavnih napona. Takođe je dat prikaz deformacije mreže, deformacija konture sa smerom delovanja pomeranja (koja je uvećana 100 puta) kao i zone plastičnosti obeležene markerima. Marker u obliku krstića (x) obeležavaju da do loma dolazi usled uticaja napona smicanja, a kružići (o) obeležavaju da do loma dolazi usled napona na zatezanje (Slika 2).

Projektovani-izvedeni objekat (prostorija) na XVII horizontu - 4x3,5 m

u zoni elastičnih deformacija

u zoni plastičnih deformacija

Naponsko polje – definisano gravitacionom komponentom - γH

Sl. 2. Naponsko-deformacijska analiza - u slučaju kada je polje napona pod uticajem gravitacione komponente - γH

Ukoliko se stenski masiv oko date prostorije nalazi u zoni elastičnih deformacija, dotle će zona oko prostorije biti stabilna sa raspodelom faktora sigurnosti kako je to na slici 2b prikazano. Ako projektante konturna linija faktora sigurnosti od 1,3 zadovoljava postavljeni kriterijum stabilnosti, vidimo da je u bokovima prostorije ta linija udaljenija od konture i da samim tim ta oblast postaje podložna prelasku iz zone elastičnih u zonu plastičnih deformacija. Maksimalna pomeranja po konturi su 1,8 mm, slika 2c. Na slici su vrednosti totalnih pomeranja date u metrima.

Na mestima na kojima se pojave plastične deformacije, slika 2e, plastifikacija po konturi imaće takav karakter da se po svođenom delu javljaju plastične zone (x), a na bokovima se javljaju plastične zone (x i o).

Može se zaključiti da je ova prostorija stabilna, s tim da je pojava plastičnih deformacija koje se manifestuju u vidu ljuštenja i otpadanja manjih komada iz bokova i stropa sporadična i da se na tim mestima može na odgovarajući način poduhvatiti i zaštititi prostoriju od daljeg širenja oštećenja. [8]

PROGNOZA PONAŠANJA STENSKOG MASIVA

Da bi se iskoristila prednost modelskih istraživanja koja nam omogućavaju da

prognoziramo ponašanje stenskog masiva i na dubinama koje još nisu obuhvaćene rudarskim radovima, u ovom delu će se u analizama stabilnosti koristiti veće dubine od nivoa XVII horizonta.

Za izbor dubina uzeti su nivoi XIX (K -235), XXI (K -315), XXIII (K -395) i XXV (K -475) horizonta i predstavljaju vrednosti od oko 630 m, 710 m, 790 m i 870 m dubine.

Na osnovu toga se može reći da od izabranih horizonata za procenu stabilnosti, XVII i XIX horizont su obuhvaćeni u projektovanju, što može biti od koristi, jer izgrađeni objekti na ovim horizontima, uz odgovarajuća snimanja, mogu u startu da prikažu valjanost procene ovih analiza. Ostala tri horizonta se analiziraju da bi se predvidelo šta se može očekivati na dubljim nivoima u nekoj kasnijoj fazi i sigurno će biti predmet dalje razrade. [9]

Interpretacija rezultata i ocena stabilnosti su urađeni na način kao i analiza stabilnosti na XVII horizontu da bi se moglo lakše izvršiti upoređivanje rezultata.

Vrednosti primarnih napona su dobijane na osnovu gravitacijske komponente $\sigma_v = \gamma H$, a odnos glavnih napona σ_1 i σ_3 je dobijen iz analitičkog izraza sa grafika na slici 1.

Tabela 2. Prognozne vrednosti primarnih napona

Horizont	Kota	okvirna dubina m	γH MPa	σ_1 MPa	σ_3 MPa	σ_3/σ_1
XVII	-155	550	14	14	9,5	0,70±0,05
XIX	-235	630	17	17	10,5	0,65±0,05
XXI	-315	710	19,2	19,2	11,5	0,60±0,05
XXIII	-395	790	21,3	21,3	12,6	0,55±0,05
XXV	-475	870	23,5	23,5	13,5	0,55±0,05

Sl. 3. *Naponsko-deformacijska analiza u slučaju kada je naponsko polje pod uticajem gravitacione komponente - γH*

Prognoza stabilnosti modela po dubini ispod nivoa XVII horizonta

Rezultati analize modela su dobijeni za naponsko polje koje je određeno gravitacionom komponentom - γH . Za modeliranje profila je korišćena mreža konačnih elemenata kao i kod predhodnog ispitivanja.

Za definisanje parametara radne sredine u analizama je korišćen kriterijum loma i parametri stenskog masiva dobijeni na osnovu parametara za XVII horizont. Triaksialnim ispitivanjima, kojima su određivane deformabilne karakteristike stenskog masiva na XVII horizontu, bilo je potrebno, povećanjem bočnog pritiska simulirati i one dubine za koje želimo uraditi procenu stabilnosti. Ova ispitivanja nisu rađena pa su u ovim analizama korišćene deformabilne karakteristike stenskog masiva na XVII horizontu.

Na slici 3, prikazane su naponsko-deformacijske analize stenskog masiva na XIX, XXI, XXIII i XXV horizontu.

Posmatrajući rezultate analize stabilnosti po dubini, može se zaključiti da stabilnost prostorije linearno opada sa povećanjem dubine, što je i bilo očekivano.

Obzirom da su maksimalna pomeranja po konturi u porastu sa povećanjem dubine i to 2,1 mm; 2,4 mm; 2,76 mm i 3,2 mm, a za dublje nivoe od XXI horizonta mogu se očekivati pojačana deformacija i otpadanja komada stenskog materijala iz bokova i stropa prostorije, ukoliko se prostorija ostavi nepodgrađena.

Mesta na kojima se pojavljuju plastične deformacije, plastifikacija po konturi imaće takav karakter da se po svodnom delu javljaju plastične zone (x), a na bokovima se javljaju plastične zone (x i o). Ovo važi samo na XIX horizontu dok se na dubljim horizontoma očekuju plastične zone (x i o) po celoj konturi. Veličine zone plastičnog delovanja se kreću u bokovima 18 cm, 21 cm, 28 cm i 35 cm. U stropu im je vrednost 16 cm, 17 cm, 18 cm i 20 cm, dok je u podu samo na XIX horizontu raspore-

đen po uglovima, a na ostalim horizontima raspoređen je po celom podu.

Ono što može narušiti stabilnost konture profila su naponi iz boka prostorije, pri ovako usvojenom odnosu glavnih napona, jer se konturna linija faktora sigurnosti u boku sve više udaljava od samog profila. [10]

Može se proceniti da na nivou XIX horizonta ta prostorija može ostati nepodgrađena osim na mestima gde se pojave plastične zone i gde se ta mesta moraju osigurati. Prognoza stabilnosti za istu prostoriju na XXI, XXIII i XXV horizontu upućuje da mora imati odgovarajuću podgradu na nekim deonicama ili celom dužinom. Kao posledica povećanja dubine može se primetiti određeno "smirivanje" u povećanju plastične zone oko konture profila što nas navodi da je potrebno redefinisati konturne uslove opterećenja na modelu sa pretpostavljenim ili izmerenim novim vrednostima glavnih napona kao i njihovim pravcem delovanja.

U prostoru plastične zone rastresanje stena uglavnom je izazvana visokom deformacijom. Deformacija počinje odmah nakon iskopa i obično se stabilizuje sa ugradnjom podgrade kada dolazi do ravnoteža sila ali se može doći do pogoršanja i propadanja krovine kao rezultat reoloških ponašanja stenske mase.

Pogoršanje i propadanje krovinskih stena u podzemnim prostorijama bi moglo da se javi iz nekoliko razloga. Glavni uzrok je koncentracija napona u neposrednoj krovini i podinskim stenama, kao i u bokovima prostorije. Ova koncentracija se generiše poremećajem inicijalne ravnoteže nakon izrade prostorije, stvarajući koncentraciju vertikalnog napona u bokovima prostorije, dok je horizontalni napon koncentrisan u krovnom delu i podu. Propadanje stena bi se manifestovalo kao formiranje zone narušene stenske mase u stropu prostorije. Ovo je

zabeleženo u jednom od prethodnih istraživanju. U takvim zonama stena je veoma rastresena, a zona propadanja takođe nastavlja dalje širenje u neposrednoj krovini prostorije. [11]

Buduća istraživanja

Buduća istraživanja svakako moraju uključiti merenje naponskog stanja u rudnom telu Borska reka, ali i utvrđivanjem pravca njegovog delovanja. U tom slučaju bi naponsko polje bilo definisano sa komponentama napona σ_1 , σ_3 , i σ_v uz uzimanje u obzir promenu pravca delovanja napona zbog mogućeg uticaja Borske rasedne zone kao i samog ugla zaleganja rudnog tela "Borska reka", mogao u mnogome da promeni sliku o stabilnosti.

Prilikom otvaranja svakog sledećeg nivoa, izvršiti dodatna geomehnička istraživanja. Ovim istraživanjima će se odrediti fizičko-mehanički parametri stenskog masiva koji bi se koristili za dalju numeričku analizu i proračune, a ujedno bi se upoređivale sa rezultatima prethodnih laboratorijskih ispitivanja. Takođe bi se utvrdile korelacione veze između fizičko-mehaničkih, strukturnih svojstava i rezultata kategorizacije stenskih masa, kao i definisanje čvrstoće stenskog masiva po Hoek-Brown-ovom kriterijumu loma. Na osnovu toga se mogu pažljivo proceniti i odrediti parametri koji će biti relevantni da karakterišu ponašanje stenske mase i sa time ući u dalje modeliranje stenskog masiva i novu prognozu za dublje nivoe.

ZAKLJUČAK

U ovom radu prikazana je analiza slučaja prognoze ponašanja stenskog masiva za dublje nivoe u rt „Borska reka“ gde je naponsko polje definisano samo sa gravitacionom silom i vertikalnim delovanjem

napona, pri čemu su glavne komponente napona definisane odnosom proizašlim iz merenja napona u rt Tilva Roš.

Na osnovu prethodnih rezultata laboratorijskih ispitivanja gde je obuhvaćen stenski masiv sa XVII horizonta (K -155 m) u rudnom telu "Borska reka" i odgovarajućih istraživanja i triaksijalnih ispitivanja koja su rađena na probnim telima iz uzetih uzoraka, dobijeni rezultati obrađivani su po Hoek-ovoj metodologiji i direktno su se koristili kao ulazne veličine za numeričko modeliranje.

Ovde je bio ograničavajući faktor u proizvoljnosti uzimanja vrednosti za definisanje naponskog stanja, jer merenja napona za datu lokaciju nije bilo. Naponsko stanje je određeno na osnovu gravitacijske komponente, a dok je odnos glavnih napona procenjen na osnovu izvršenih merenja napona za rudno telo "Tilva roš" još pre 20 i više godina.

Numerički model je baziran na metodi konačnih elemenata (MKE) i za tu svrhu je korišćen programski paket PHASE². Analiza i interpretacija rezultata istraživanja je urađena i prikazana za projektovanu i izvedenu prostoriju. Rezultatima su obuhvaćeni vektori pomeranja, raspodela napona sa izolinijama glavnih napona kao i zone plastifikacije oko analiziranih objekata.

Analiza stabilnosti je obuhvatila prvo XVII horizont za čiju radnu sredinu imamo definisan kriterijum loma i potrebne ulazne podatke za sam tok proračuna. Na osnovu njih je u drugoj fazi vršena prognoza stabilnosti za dublje horizonte. Obuhvaćeni su nivoi XIX (K -235), XXI (K -315), XXIII (K -395) i XXV (K -475).

Rezultati i prognoza stabilnosti prostorija na dubljim horizontima sa pretpostavljenim osobinama stenskog masiva i naponskog stanja, pokazuju da se stabilnost prostorija na analiziranim profilima smanjuje. Prime-njeni model u analizi ostaje stabilan do nivoa XIX horizonta, dok za dublje hori-

zonte morao bi biti osiguran i podgrađen. Ovaj zaključak se izvodi na osnovu parametara radne srednine sa XVII horizonta koji su po obimu i pretpostavljenom naponskom stanju sami po sebi nedovoljni za kvalitativnu prognozu stabilnosti, a pogotovu na dubljim horizontima. Iz tih razloga je neophodno da se za svaki novi horizont urade sva potrebna geomehnička istraživanja. Kako se radovi budu spuštali na veću dubinu, sa tim podacima bi se verifikovali ili korigovali rezultati prognoza za isti nivo, a ujedno i vršila prognoza za ponašanja stenskog masiva sledećeg dubljeg nivoa.

Naravno da bi jedna kvalitativna analiza, poput analize stabilnosti, bila odrađena do kraja, ne bi smelo da u nju ulazi ni jedna procenjena vrednost, kao što je u ovom slučaju bila vrednost napona u masivu kao i njegov pravac. U tom cilju, za ocenu naponskog stanja u rudnom telu "Borska reka" kao i za definisanje parametara bitnih za sagledavanje ponašanja stenskog masiva potrebno dosadašnja geomehnička istraživanja upotrebiti i sa primenom adekvatnih metoda za merenje naponskog stanja.

Sinteza dosadašnjih i predloženih istraživanja bi dala potpuniju sliku o rudnom telu "Borska reka". Sa tog aspekta bi bilo moguće kroz odgovarajuće modele analizirati sve vrste rudarskih radova koji bi se izvodili. Rezultati tih analiza bi se mogli sa većom pouzdanošću primeniti u praksi.

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