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STRESS AND STRAIN ANALYSIS IN THE ROCK MASSIF DURING COAL EXPLOITATION WITH LARGE DIAMETER BOREHOLES IN EAST FIELD PIT RMU BOGOVINA

Abstract

This paper presents stress and strain analysis in massif during exploitation of out-of-balance coal layers in the BCM Bogovina. Behavior of the surrounding rock mass was tested during application of large diameter boreholes exploitation. Based on the proposed solutions for stope geometry and known geological conditions in deposit, physical and mechanical properties of coal and surrounding massif, the numerical analysis of the stress and strain of excavation area and surrounding massif was done. Numerical modeling of excavation area behavior was done using the software package Phase2, whose calculations are based on the finite element method. The analysis, conducted in this paper, has shown that there is a possibility for applying this kind of excavation in terms of stability the rock mass.

Keywords: large diameter boreholes, coal, Bogovina, Phase2

INTRODUCTION

BCM Bogovina is going through a difficult period as a consequence of a number of related factors. In order to overcome these problems, the possibility of exploitation the off-balance coal seams of coal is considered using mechanized mining methods - large diameter boreholes.

The high-quality brown coal is mined in the mine Bogovina by the traditional column method. Due to the underlying stratum of clay prone to swelling, the excavated raise is often reconstructed repeatedly and invested great effort in order to maintain the designed room dimensions. Therefore, it is necessary to change the exploitation method and increase coal production. Since there

are no requirements for high investments, as the cheapest applicable model to increase the production solution is proposed the mechanized mining of off-balance reserves in the hanging wall and foot layer by drilling machine. This method would cause an increase in the production capacity of the mine, increase the total excavation reserves of thin seams in the deposit, and contribute to better working conditions and greater safety at work. Coal reserves of small thickness in the deposit East Field are shown in Table 1.

In order to study the possibility of applying the proposed method it is necessary to analyze the stress state.

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Table 1 Calculation the total amount of reserves of small thickness in the East Field deposit [1]

Serial number (n)	Blok K- roof P- floor	Block area S (m ²)	Average thickness (m)	Exploitation thickness d _{eks} (m)	Exploited coal reserves in block Q _{eks} = S•d _{eks} •γ _{sr} (t)
1	B-3P	197 261	1.36	0.780	200 023
2	B-2P	79 428	1.10	0.780	80 540
3	B-1P	274 402	1.14	0.780	278 244
4	B-1K	182 441	1.10	0.780	184 995
5	B-3K	205 080	1.86(1.20)	0.780	207 951
6	B-4K	85 358	1.24	0.780	86 553
Σ		1023970			1,038,306

γ_{sr} - average specific density

The analysis is performed to determine the behavior of surrounding rock mass during excavation by the adopted geometry. Calculation of roofing and shelf deformation was carried out as well as study the possibility of caving mining drill holes as well as the behavior of underlying swelling clay. Checking the stress state of surrounding rock mass in preparing the excavation of drill holes, and the preparation was done with the help of software package Phase2. Tests were carried out on the basis of data taken from physical - mechanical properties of rock mass [1, 7] and adopted geometry of excavation panel.

Possibility of exploitation of off-balance deposits in parts of the BCM Bogovina so far has not been considered, but detailed tests were carried out of physical and mechanical characteristics the underlying stratum of clay and accompanied rocks and geological investigation. The resulting download data [1, 7] were used as the input parameters in the analysis program Phase2.

The method of excavation the drill holes of large diameter is used for the exploitation of small thickness seams ranging from coal mines in Poland, the Czech Republic (Paskov), China (Xinwen), USA (Appalachian), the Ukraine (Donbas), North Africa (Manto mine). Drilling machine VS 625 - Seal created as a prototype machines BŠK 2M Ukrainian producers, is proposed for the exploitation of thin coal seams in Bogovina [10]. Stability testing of drill holes at suggested geometry was considered the needs of mines in Poland. The obtained positive

results were processed in the program FLAC 3D [5]. Analysis the effects of drilling machines BUA 600 mines Manto for seam thicknesses of 1.00 to 1.80 m showed that the machine can be successfully used in the underground mining [3]. This system of obtaining coal is characterized by a high degree of security and safety at work. The applicability of the method and effects depend primarily on the geological characteristics of seams and stability of the surrounding massifs. Frequent problem is demolishing of drill holes of great length in progress. To prevent the demolishing protective pillars of greater width should be left. Stability Analysis of the rooms in the underground construction and mining are often tested by the software packages that include in their calculations the finite element method. Depending on the parameters of the surrounding rock mass obtained results show whether the room is necessary to be supported or not. In coal mines, all development rooms have to be supported as a rule, except stope, so the condition of stress and strain was analyzed in terms of support durability [2, 3, 4, 5, 6, 8, 9].

1 EXCAVATION OF THIN SEAMS OF COAL DEPOSIT IN THE EAST FIELD BY DRILLING

An important area of application this technology of coal mining is in coal deposits of small thickness that are not tectonically disturbed (deposits without occurrence of micro faults). Principle of mining techno-

logy by drilling is that coal obtained directly by drilling the drill holes of large diameter that is smaller than the thickness of coal seam in order to achieve maximum utilization and waste web to minimum. In order to ensure stability, depending on the intensity of stress and mechanical properties of coal and overlying sediments, between individual drill holes, the protective coal pillars, width of 0.2 - 1.0, have to be left in and for the case analysis were

adopted pillars, width of 0.9 m. Losses during excavations can reach 38 - 45%, which is not rational, but it is acceptable because the excavation of these seams by conventional methods is not profitable, i.e. possibility for recovery is 0%. In favorable operating conditions in the coal seam thickness ranging from 0.6 to 0.7 m, the achieved production is 140 tons/day, while the effects on the excavation are 11.7 t/day [2].

Figure 1 Cross section of the underground rooms with dimensions of drilling machine VS 625 -Seal P2 [3]

Mining methods with drilling machine is simple and depends on characteristics and capacity of the applied machines. Selected VS SEAL-625 P2 drilling machine is shown in Figure 1, which makes excavation with height of 0.625 to 0.825 m, width of 2.005 to 2.105 m, with resistance of coal to 350 kN/m [7]. In the event that the seam has the appearance of methane, machine has a system of ventilation and degassing led worksite capacity of 30 l/min.

The adopted excavation geometry involves making the basic premises prepared on the charcoal seam. Two parallel inclines will be located in the central part of the block. At every 200 meters length of in

cline, the transverse corridors will be developed that allow flow ventilation and share panels on excavation fields. Excavation field is wide 200 m plus width of two protective pillars of 10 m. Among mining drill holes in the field column width of 0.9 m will be left. Geometry excavation field is shown in Figure 2. It is foreseen that the inclines exploited bilaterally on the left and right and pulls the room with the progress of excavation. The proposed profile room preparation needed to be settled. Drilling machine is shown in Figure 1. The room will be supported by permeable steel roof support, and the sides and ceiling will be pledged wooden pawns.

Figure 2 View of excavation field geometry in exploitation with drilling machines in the BCM Bogovina

As the advantages of selection this kind of exploitation of coal in the coal mine Bogovina, the following could be indicated:

- mechanized excavation,
- involvement of a small number of workers and the excavation and transportation of coal,
- low initial investments,
- excavation of reserves that cannot be exploited by the traditional methods,
- shorter transport of coal,
- depth of exploitation and up to 80 m,
- possibility of exploitation of small seam thickness below 1 m,
- stable production,
- small volume of preparatory work,
- direct sales of coal to the power plants, there is no additional cost of deposits and transportation of coal, and
- high level of security and safety at work.

2 ANALYSIS OF STRESS AND STRAIN IN THE ROCK MASS USING THE PROGRAM PHASE2

The analysis covered the preparing room for excavation of the panel, as well as the analysis of stress and strain in excavated drill holes that occur as a consequence of use

the method of extraction the drill holes of large diameter. Input parameters relating to a given model are defined by the position of excavation panels in massive, thick supporting wall, thickness of coal seam and type of rock material beneath and above, position of the rooms to the surface of the field, which primarily depends on the thickness of rock mass above the excavation.

Panel, width of 251 m, is adopted as a calculation model, representing a vertical section of the rock mass, is shown in Figure 3. Two cross halls are made in this panel in the upper coal seam (PTn1 and PTN2) (Figure 3) and two identical corridors in the foot wall coal seam (PTN3 and PTN4) (Figure 3), which allow the transport of coal, transport of raw materials and ventilation work site. Excavation drill holes, width of 2.10 m, height of 0.8 m, are made in the coal seam them in a single excavation panel has under 65 (the top and bottom coal seam). A protective pillar is designed between the drill holes 0.9 m in width as shown in Figure 2. After making the excavation drill hole, machine is moved to the undisturbed environment and exploiting of new drill holes have to be done at given dynamics.

The model is divided into ten phases that representatively describe the state in the massif at key moments:

1. The first stage is an undisturbed massif,
2. The second stage is the state of the massif after making the cross hall in the upper coal seam (PTn1 and PTN2)
3. The third phase represents the state after the supporting steel support (PTN 1 and 2)
4. The fourth phase state of the massif after the first twenty drill holes in the upper coal seam,
5. The fifth phase of the state after making forty wells in the upper coal seam,
6. The sixth stage is a state in the massif after making all sixty-five drill holes in the upper coal seam, i.e. exploitation of coal in the top layer,
7. The seventh stage is massive after making a transverse corridor in the foot wall carbon layer (PTN3 and PTN4)
8. The eighth stage is a condition for support after these two rooms a steel arch support,
9. The ninth stage after making the top ten drill holes in the foot wall coal seam, and
10. The tenth stage shows end exploitation in the foot wall carbon layer and the condition observed the model after coal mining in the observed block.

After determining the phases, the mesh generation and discrediting were made, which is determined by the total number of finite elements in the model with the specified parameters. The parameters are: type of mesh gradient factor, the node number (17294), the number of elements (8553) depending on the considered phase. On the basis of laboratory tests of rock mass [1, 7] geomechanical features of the model studied were determined. Tests have shown what kind of rocks they are, and their geomechanical features are shown in Table 2.

Table 2 *The physical and mechanical properties of rocks in the pit East Field RMU Bogovina [1, 7]*

Name of material	Co-lour	Unit weight [MNm ³]	Young's Modulus [MPa]	Pois-son's Ratio	Failure criterion	Kind of a material	Shear strength [Mpa]	Angle of internal friction (°)	Angle of internal friction	Cohesion max. [MPa]	Cohesion reduced [Mpa]
SAND- STONE		0.03	31.966	0.16	Mohr Coulomb	Plastic	0.3	33	48	0.28	0.176
MARL		0.0206	80.43	0.36	Mohr Coulomb	Plastic	1.4	35	40	1.79	1.78
MARL 2		0.01904	45.77	0.36	Mohr Coulomb	Plastic	1.1	40	38	0.66	0.65
CLAY		0.022	0.5	0.35	Mohr Coulomb	Plastic	0.06	22	21	0.3	0.3
ROOF COAL		0.013	57.14	0.37	Mohr Coulomb	Plastic	0.76	57	56	1.75	1.74
FLOOR COAL		0.013	57.14	0.37	Mohr Coulomb	Plastic	0.76	57	56	1.75	1.74

RESULTS AND DISCUSSION

The boundaries of the model are determined such as the observation of infinite areas set aside part of the real performance of excavation panels to scale up to the surface. Boundary conditions are specify that it is permitted to move only the ground surface while the other borders without moving (bottom, left and right).

Figure 3 and 4 shows the contour of the axial stress (σ_1) in the massif. In order to get a representative view for analyzing contours of axial stress in the model were selected following phases: Phase 1 - undisturbed massif, Phase 2 - situation in the massif after making facilities PTn1 and PTN2, phase 6 presents contours axial

stress after excavation of the entire upper coal seam and phase 10 contour axial stress upon termination of exploitation in the reporting panel.

Figure 3 Display of contours of axial stress σ_1 in the model switching panels Phase 1

Figure 4 Contour axial stress σ_1 in the model of excavation panels in phases 6 and 10

The highest intensity of axial stress in undisturbed massif is in vicinity of mining preparations in the upper and lower coal seam, and the lowest intensity is observed in the foot wall section of green clay, which opposes the action of axial stress of masses.

With the progress of excavation, contour reduced axial stress over the excavation of drill holes grows under the influence of stress underlying stratum of clay. In the vicinity of the room excavation preparation upper coal seam in safety pillars between

the mining panels are concentrated axial stresses of greatest intensity.

Figure 5 shows the fracture zones in the vicinity of mining drill holes, reveals that the elements of fracture in all excavated drill holes and increasing the value of the axial stresses in the vicinity of drill holes as a result of the excavation progress. The elements on the edges of fracture drill holes in the upper indicating the possible collapse of coal to the border with marl roof.

Figure 5 Display of axial stress σ_1 , with elements of fracture in excavated drill holes upper and lower coal seam

In the lower coal seam fracture elements are concentrated in the foot wall part and consequence of the proliferation of underlying stratum of clay, as indicated by displacement vectors. The surrounding

rock mass no occurrence of elements fracture. Stress state is changing in terms of increasing the axial stress in the safety pillars between the drill holes because they now assume the new load.

Figure 6 Layout view of total movement in the lower coal seam after making the top 10 mining walked

During excavations in the lower coal seam in the excavated drill holes due to proliferation of the foot wall of green clay comes to filling the open unsupported area. The direction and size of displacement in this part of the model is seen in Figure 6 where it shows the total displacements in lower seam after excavation. This shift amounts to 2.00 m, affect the increase in stability at further exploita-

tion because it naturally fills the excavated space.

To analyze the stress strain state around the rooms excavated preparation upper coal seam in Figure 7 presents a comparative view of the total displacement after making facilities (Figure 7a) and the appearance of vector and contour of the total displacement after the supporting steel arch support (Figure 7b).

Figure 7 Contour and Vectors total movement after
a) making PTn1 b) the supporting steel support

During creating of transverse corridors PTn1 in the top layer of carbon displacement vectors are concentrated in the ceiling of the room in the hips, where the values range from 0 to 1.30 m.

After installing the supporting overall shifts in relation to the previous phase have a value of 0.00 m, because the sub-urb assumed the burden of the surrounding massifs.

Figure 8 Contour and Vectors total movement after a) making PTn1 b) the supporting steel support

Analysis of movement during making room PTN3 points to the emergence of great pressure from the shelf as a consequence of a swelling green clay, figure 8 a), while the ceiling part of the room is almost does not suffer deformation. After the supporting facilities Figure 8 b), there is a reduction in the value of total displacement. At the foot wall section are observed less displacement distributed around observed the excavation which are in the range of 0.00 to 0.05 do not threaten the stability made the room. Preparation of room excavation for the significant

amount of movement to contour around the excavation must stabilize the steel support to prevent collapses.

The stability of the panel excavation was presented by the contours of strength factor (SF) according to the stages in development of excavation. Caving excavation in with the progress of mining drill holes in the panel is not a problem in the coal exploitation using this method. It is important to avoid collapses during operation of the drill holes in order to avoid being stuck twist drills.

Figure 9 Showing the strength factor contours a) undisturbed massif b) after excavation around the observed model

The value of the strength factor in an area that is exploited is greater than one in all parts of the massif because the rock mass behaves plastically [8].

Green Zone (Figure 9) above the excavation of drill holes indicates an increase in the value of the strength factor in exploitation.

In order to explain the movement of factors of strength values are set check-points in security pillars of the room preparing the width of ten meters, Figure 10, item 1 and 3, and in security pillars between the drill holes in the upper and lower seams, Figure 10, item 2 and 4.

Figure 10 Locations of sampling points of the strength factor in safety pillars

Figure 11 Diagram of values strength factor according to the stage of excavation

Graphic shows changes in value of the strength factor as a function of the excavation phase is shown in diagram (Figure 11). The factor of strength in the safety pillars at all control points with the progress of exploitation indicates growth.

Curve 1 from diagram for the upper coal seam, growth in value between the undisturbed massif (phase 1) and making room PTn1 (Phase 2), is the result of secondary redistribution of stress due to the creation of a new open area in the multi-rock environment. The value is still constant (between phases 2 and 3) because support is the new load. Excavation area on the other side of the seat pillar (Phase 3) comes to relaxation and growth factors of strength. After phase 4, further excavation has no significant effect on the value of strength factor in the security pillar of the upper coal seam.

Curve 2 from the diagram represents the value of the strength factor in the security pillar between the drill holes of the upper seam, width of 0.9 m. Since the beginning of coal exploitation in the top seam (phase 1-4) the value of the strength factor is not changed until the progress of excavation comes to the pole (phase 5), when the strength factor rises sharply. Further progress of excavation front and end of exploitation the upper seam (phase 6) lead to a slight fall in the strength factor value in the security pillar. This decline in value is the result of transfer the loads of rock mass lying on the pillars between the drill holes.

Constant values of strength factor (stage 7-10) Curve 1 and 2 with the diagrams show that works in the lower coal seam does not affect the strength factor in safety pillars of the upper coal seam, in terms of reducing its value.

Curves 3 and 4 in the diagram show the change of the strength factor value in the safety pillars during exploitation the lower coal seam. Works in the top coal seam have no impact on the strength factor value in the lower coal seam. This can be seen from the chart, where the curves 3 and 4 do not change the value until the end of exploitation in the upper seam (step 6). After excavation the upper seam, the strength factor in both safety pillars increases (step 7). Growth factor values of strength is the result of flourishing the underlying stratum of clay, which meets for digging wells and taking the load stabilizes the surrounding mountain range. Further excavation of the lower coal seam (stage 8-10) does not change the strength factor value in the security pillar between the panels, which shows the curve 3 with a diagram. The value is constant on curve 4 in stages 8 and 9. Excavation of drill holes in the vicinity of the security pillar (stage 10) leads to an increase in the value on curve 4 from diagram. The growth is a result of flourishing underlying stratum of clay that fills the drill holes and takes on the load of the surrounding rock mass.

Such high values of strength factors indicate that the caving will not be in massif

in the coal exploitation of coal drilling machines with the excavation geometry.

CONCLUSION

Mechanized excavation of off-balance seams of small thickness ranging from the RMU Bogovina would provide a long-term increase in production, increased security and safety at work as well as increasing the total reserves in the deposit.

When analyzing the given model led to the conclusion that the described behavior of the rock mass about real events in seam, in particular of the analysis relating to the proliferation of clay and deformations that occur during the excavation. During the excavation of the lower coal, seam clay will soon be filled with exploitation drill holes and contribute to better stability of the observed part of panel. The excavated drill holes of the upper coal seam, demolishing small-scale, does not threaten the exploitation circumferential borehole to move marl. The analysis showed a high amount of movement around the room excavation preparation and this should be permissive steel roof supports to prevent deformation.

It can be concluded from the above that the BCM "Bogovina" may consider this type of excavation in the current situation, but it is necessary to do a series of geotechnical analyses to confirm the received data. It is also required to explore the possibility of exploitation the other parts of the deposit at lower excavation geometry, the one that would contribute to better recovery of the deposit.

REFERENCES

- [1] Study on Coal Reserves of the Deposits BCM "Bogovina" - Bogovina, JP PEU "Resavica" in Restructuring, Bureau for Design and Development, Belgrade, 2011;
- [2] Z. Milicevic, Methods of Underground Exploitation the Mineral Deposits, Technology of Development the Underground Rooms Using the Combined Machines, Working Script, Bor, 2008;
- [3] I. L. Follington, R. Deeter, D. Share, C. Moolman, A New Underground Auger Mining System, The Journal of The South African Institute of Mining and Metallurgy 101, (2001), 25-32;
- [4] F. Wang, S. Tu, Q. Bai, Practice and Prospects of Fully Mechanized Mining Technology for Thin Coal Seams in China, The Journal of The Southern African Institute of Mining and Metallurgy 112, (2012), 161-170;
- [5] Z. Luboski, Assessment of Auger Mining Application in Polish Hard Coal Deep Mines, Mining of Mineral Deposits, (2013), 133-142, ISBN: 978-1-138-00108-4;
- [6] Z. Rak, J. Stasica, K. Skrzypkowski, Eksploatacja Pokładów Cienkich Metodą Zwiercania, PRZEGLĄD GÓRNICZY, (2014), 18-24;
- [7] Report on Performed Testing on Samples of Bentonite from BCM Bogovina from Bogovina, Copper Institute Bor, Bor, June 2002;
- [8] Lj. Tadic, Analysis of Occurrence the Plastic Fracture in the Rock Mass along the Tunnel Opening, Proceedings of Faculty of Civil Engineering 19 (2010), 63-77,
- [9] R.E. Hammah, T. Yacoub and B. Corkum, J. H. Curran, The Practical Modelling of Discontinuous Rock Masses with Finite Element Analysis, 42nd US Rock Mechanics Symposium and 2nd US-Canada Rock Mechanics Symposium, San Francisco, San Francisco June 29-July 2, 2008;
- [10] M. Stoniš, V. Hudeček, Mining of Coal Pillars Using the Drilling Method, Acta Montanistica Slovaca Ročník 14 (2009), 241-249;
- [11] Rocscience Inc. 2005 Phase2 v6.0 - Two Dimensional Finite Element Slope Stability Analysis.

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ANALIZA STANJA NAPONA I DEFORMACIJA U STENSKOM MASIVU PRILIKOM PRIMENE METODE EKSPLOATACIJE UGLJA BUŠOTINAMA VELIKOG PREČNIKA U JAMI ISTOČNO POLJE RMU BOGOVINA

Izvod

U radu se analizira stanje napona i deformacija u masivu prilikom eksploatacije vanbilasnih slojeva uglja u RMU Bogovina. Ispitivano je ponašanje okolnog stenskog masiva prilikom primene metode otkopavanja bušilicama velikog prečnika. Na osnovu predloženih rešenja geometrije otkopa, i poznatih geoloških uslova u ležištu, fizičko-mehaničkih osobina uglja i okolnog masiva, izvršena je numerička analiza stanja napona i deformacija otkopnog prostora i okolnog masiva. Numeričko modeliranje ponašanja otkopnog prostora urađena je primenom softverskog paketa Phase2, čiji se proračuni baziraju na metodi konačnih elemenata. Analiza sprovedena u ovom radu pokazala je da postoji mogućnost ovakvog načina otkopavanja sa aspekta stabilnosti stenske mase.

Ključne reči: bušotine velikog prečnika, ugalj, Bogovina, Phase2

UVOD

RMU Bogovina prolazi kroz težak period koji je posledica više povezanih faktora. U cilju prevazilaženja ovih problema razmatra se mogućnost eksploatacije vanbilasnih slojeva uglja primenom mehanizovane metode otkopavanja - bušotinama velikog prečnika.

U rudniku Bogovina otkopava se visoko kvalitetan mrki ugalj tradicionalnom stubnom metodom. Zbog podinske gline sklone bujanju otkopni uskopi se vrlo često rekonstruišu, podina se više puta pouzima i ulaže se veliki napor kako bi se prostorije održale na projektovane dimenzije. Zato je potrebno izmeniti način eksploatacije i povećati proizvodnju uglja. Obzirom da ne postoje uslovi

za visoka investiciona ulaganja, kao najjeftiniji primenljiv model za povećanje proizvodnje predloženo je rešenje mehanizovanog otkopavanja vanbilasnih rezervi u krovinском i podinskom sloju mašinama za bušenje. Ova metoda uslovia bi povećanje proizvodnih kapaciteta rudnika, uvećala bi ukupne rezerve otkopavanjem tankih slojeva u ležištu, i doprinela boljim uslovima rada kao i većoj bezbednosti pri radu. Rezerve uglja male moćnosti u ležištu Istočno polje prikazane su u tabeli 1.

Da bi se ispitala mogućnost primene predložene metode neophodno je izvršiti analizu naponsko deformacionog stanja.

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Tabela 1. Proračun ukupne količine rezervi male moćnosti u ležištu Istočno polje [1]

Redni broj (n)	Blok K- krovinski P- podinski	Površina bloka S (m ²)	Srednja debljina (m)	Eksploataciona debljina d _{eks} (m)	Eksploatacione rezerve uglja u bloku Q _{eks} = S • d _{eks} • γ _{sr} (t)
1	B-3P	197 261	1,36	0,780	200 023
2	B-2P	79 428	1,10	0,780	80 540
3	B-1P	274 402	1,14	0,780	278 244
4	B-1K	182 441	1,10	0,780	184 995
5	B-3K	205 080	1,86(1,20)	0,780	207 951
6	B-4K	85 358	1,24	0,780	86 553
Σ		1023970			1.038 306

γ_{sr} srednja specifična težina

Analiza se vrši da bi se utvrdilo ponašanje okolnog stenskog masiva prilikom otkopavanja po usvojenoj geometriji. Izvršen je proračun deformacija krovine i podine, ispitana mogućnost zarušavanja otkopnih bušotina kao i ponašanje podinske bujave gline. Provera naponskog stanja okolnog stenskog masiva pri izradi otkopnih bušotina i prostorija pripreme urađena je uz pomoć programskog paketa Phase2. Ispitivanja su izvršena na osnovu preuzetih podataka fizičko-mehaničkih osobina stenskog masiva [1, 7] i usvojene geometrije otkopnog panela.

Mogućnost eksploatacije vanbilasnih delova ležišta u RMU Bogovina do sada nije razmatrana, već su vršena detaljna ispitivanja fizičko-mehaničkih karakteristika podinske gline i pratećih stena, kao i geološka istraživanja ležišta. Dobijeni preuzeti podaci [1, 7] korišćeni su kao ulazni parametri analize u programu Phase2.

Metoda otkopavanja bušotinama velikog prečnika se primenjuje za eksploataciju slojeva male moćnosti u rudnicima u Poljskoj, Češkoj (Paskov), Kini (Xinwen), SAD (Appalachian), Ukrajni (Donbas), Severnoj Africi (Mantla mine). Bušaća mašina VS – SEAL 625 nastala kao prototip mašine BŠK 2M ukrajinskog proizvođača, predložena je za eksploataciju tankih slojeva uglja u Bogovini [10]. Ispitivanje stabilnosti bušotina po predloženoj geometriji razmatrano je za potrebe rudnika u Poljskoj. Dobijeni su pozitivni rezultati koji su obrađeni u

programu FLAC 3D [5]. Analiza učinaka bušće mašine BUA 600 u rudniku Mantla za slojeve debljine od 1,00 do 1,80 m pokazala su da se mašina može uspešno koristiti i u podzemnoj eksploataciji [3]. Ovaj sistem dobijanja uglja karakteriše se visokim stepenom sigurnosti i bezbednosti pri radu. Primenljivost metode i učinci prvenstveno zavise od geoloških karakteristika sloja i stabilnosti okolnog masiva. Učestali problem je zarušavanje bušotina velike dužine u napredovanju. Da bi se sprečilo zarušavanje ostavljaju se zaštitni stubovi veće širine. Analiza stabilnosti prostorija u podzemnoj gradnji i rudarstvu vrlo često se ispituje programskim paketima koje u svojim proračunima koriste metodu konačnih elemenata. U zavisnosti od parametara okolnog stenskog masiva dobijeni rezultati pokazuju dali je prostoriju potrebno podgrađivati ili ne. U rudnicima uglja se sve pripremljene prostorije izuzev otkopa po pravilu podgrađuju, tako da je analizirano stanje napona i deformacija u smislu izdržljivosti podgrade [2, 3, 4, 5, 6 i 8, 9].

1. OTKOPAVANJA TANKIH SLOJEVA LEŽIŠTA UGLJA ISTOČNO POLJE BUŠENJEM

Značajna oblast primene ove tehnologije eksploatacije uglja je u ležištima uglja male moćnosti koja nisu tektonski poremećena (ležišta koja nemaju pojave mikro raseda). Princip tehnologije otkopavanja bušenjem je

da se ugalj direktno dobija bušenjem bušotina velikog prečnika koji je manji od debljine ugljenog sloja, kako bi se ostvarilo maksimalno iskorišćenje a zahvat jalovine sveo na minimum. U cilju obezbeđenja stabilnosti, u zavisnosti od intenziteta napona i mehaničkih karakteristika uglja i krovinskih naslaga, između pojedinih bušotina ostavljaju se zaštitni stubovi uglja širine 0,2 - 1,0 m, a za konkretan slučaj

analize usvojen su stubovi širine 0,9 m. Gubici prilikom otkopavanja mogu dostići 38 - 45 %, što nije racionalno, ali je prihvatljivo pošto otkopavanje ovakvih slojeva konvencionalnim metodama nije rentabilno tj. mogućnost iskorišćenja je 0 %. Pri povoljnim radnim uslovima, u sloju uglja moćnosti 0,6 - 0,7 m, postiže se proizvodnja od 140 t/dan, pri učincima na otkopavanju 11,7 t/nad [2].

Sl. 1. Poprečni profil prostorija sa dimanzijama bušeće mašine VS –SEAL 625 P2 [3]

Metoda otkopavanja mašinama za bušenje je jednostavna i zavisi od karakteristika i kapaciteta primenjene mašine. Odabrana je VS SEAL-625 P2 bušača mašina prikazana na slici 1 koja izrađuje otkope visine od 0,625 do 0,825 m, širine od 2,005 do 2,105 m, pri otpornosti uglja do 350 kN/m [7]. U slučaju da u sloju ima pojave metana mašina poseduje sistem za ventilaciju i otplinjavanje na čelu radilišta kapaciteta 30 l/min.

Usvojena otkopna geometrija podrazumeva izradu prostorije osnovne pripreme po ugljenom sloju. Dva paralelna niskopa biće locirana u središnjem delu bloka. Na svakih 200 metara dužine niskopa izrađivaće se

prečni hodnici koji omogućavaju protočno provetravanje i dele panele na otkopna polja. Otkopno polje je široko 200 m plus širina dva zaštitna stuba od 10 m. Između otkopnih bušotina u polju biće ostavljen stub širine 0,9 m. Geometrija otkopnog polja prikazana je na slici 2. Predviđeno je da se iz niskopa otkopava dvostrano na levu i desnu stranu i povlači prostorija sa napredovanjem otkopa. Predloženi profil prostorija pripreme potreban da bi se smestila bušeća mašina prikazan je na slici 1. Prostorija će se podgrađivati čeličnom popustljivom podgradom a bokovi i strop biće založeni drvenim zalagačima.

Sl. 2. Izgled geometrije otkopnog polja pri eksploataciji bušačim mašinama u RMU Bogovina

Kao prednosti izbora ovakvog načina eksploatacije uglja u RMU Bogovina može se navesti:

- mehanizovano otkopavanje,
- angažovanje malog broja radnika i na otkopavanju i na transportu uglja,
- niska početna investiciona ulaganja,
- otkopavanje rezervi koje se ne mogu eksploatirati tradicionalnim metodama,
- kraći transport uglja,
- dubina eksploatacije i do 80 m,
- mogućnost eksploatacije sloja male debljine ispod 1 m,
- stabilna proizvodnja,
- mali obim pripremnih radova,
- direktni plasman uglja toplanama, nema dodatnih troškova deponovanja i prevoza uglja, i
- visok nivo bezbednost i sigurnosti pri radu.

2. ANALIZA STANJA NAPONA I DEFORMACIJA U STENSKOM MASIVU PRIMENOM PROGRAMA PHASE2

Analizom su obuhvaćene prostorije pripreme otkopnog panela, kao i analiza napona i deformacija u otkopnim bušotinama koji se javljaju kao posledica

primene metode otkopavanja bušotinama velikog prečnika. Ulazni parametri koji se odnose na zadati model, definisani su položajem otkopnog panela u masivu, debljinom pratećih stena, debljinom samog ugljenog sloja i vrstom stenskog materijala podine i krovine, položajem prostorija u odnosu na površinu terena, koji u prvom redu zavise od debljine stenske mase iznad iskopa.

Kao proračunski model usvojen je deo panela širine 251 m koji predstavlja vertikalni presek stenskog masiva prikazan na slici 3. U panelu su izrađena dva poprečna hodnika u gornjem ugljenom sloju (PTN1 i PTN2) (slika 3) i dva identična hodnika u podinskom ugljenom sloju (PTN3 i PTN4) (slika 3), koja omogućavaju transport uglja, dopremu repromaterijala i ventilaciju radi lišta. Otkopne bušotine širine 2,10 m, visine 0,8 m izrađuju se u samom ugljenom sloju i njih u jednom otkopnom panelu ima po 65 (u gornjem i donjem ugljenom sloju). Predviđen je zaštitni stub između bušotina širine 0,9 m kao što je prikazano na slici 2. Nakon izrade otkopne bušotine mašina se pomera prema neporemećenoj sredini i eksploatiše se nova bušotina po zadatoj dinamici.

Sam model podeljen je u ukupno deset faza koje reprezentativno opisuju stanje u masivu u ključnim momentima:

1. prva faza predstavlja neporemećeni masiv,
2. druga faza predstavlja stanje u masivu nakon izrade prečnih hodnika u gornjem ugljenom sloju (PTN1 i PTN2),
3. treća faza predstavlja stanje nakon podgrađivanja čeličnom podgradom (PTN 1 i 2),
4. četvrta faza stanje u masivu nakon prvih dvadeset bušotina u gornjem ugljenom sloju,
5. peta faza je stanje nakon izrade četrdeset bušotina u gornjem ugljenom sloju,
6. šesta faza je stanje u masivu nakon izrade svih šezdeset i pet bušotina u gornjem ugljenom sloju, tj. završetka eksploatacije uglja u gornjem sloju,
7. sedma faza je masiv nakon izrade prečnih hodnika u podinskom ugljenom sloju (PTN3 i PTN4),
8. osma faza predstavlja stanje nakon podgrađivanja ove dve prostorije čeličnom lučnom podgradom,
9. deveta faza nakon izrade prvih deset bušotina u podinskom ugljenom sloju, i
10. deseta faza prikazuje završetak eksploatacije u podinskom ugljenom sloju i stanje posmatranog modela nakon otkopavanja uglja u posmatranom bloku.

Nakon određivanja faza izvršeno je generisanje mreže i diskretizacija koja je odredila ukupan broj konačnih elemenata u modelu po zadatim parametrima. Parametri su: tip mreže, faktor gradijenta, broj čvorova (17294), broj elemenata (8553) u zavisnosti od posmatrane faze. Na osnovu laboratorijskih ispitivanja stenske mase [1, 7] određene su geomehničke karakteristike za ispitivani model. Ispitivanja su pokazala da su u pitanju stene sledećih geomehničkih osobina prikazanih u tabeli 2.

Tabela 2. Fizičko-mehaničke karakteristike stena u jami Istočno polje RMU Bogovina [1, 7]

Ime materijala	Boja	Jedinica težine [MN m ⁻³]	Young's Modulus [MPa]	Poisson's Ratio	Kriterijum loma	Vrsta materijala	Smičući napon [Mpa]	Ugao unutrašnjeg trenja (°)	Ugao unutrašnjeg trenja	Kohezija maks. [MPa]	Kohezija red. [Mpa]
PEŠČAR		0,03	31,966	0,16	Mohr Coulomb	Plastičan	0,3	33	48	0,28	0,176
LAPORAC		0,0206	80,43	0,36	Mohr Coulomb	Plastičan	1,4	35	40	1,79	1,78
LAPORAC 2		0,01904	45,77	0,36	Mohr Coulomb	Plastičan	1,1	40	38	0,66	0,65
GLINA		0,022	0,5	0,35	Mohr Coulomb	Plastičan	0,06	22	21	0,3	0,3
UGALJ KROVINSKI		0,013	57,14	0,37	Mohr Coulomb	Plastičan	0,76	57	56	1,75	1,74
UGALJ PODINSKI		0,013	57,14	0,37	Mohr Coulomb	Plastičan	0,76	57	56	1,75	1,74

REZULTATI I DISKUSIJA

Granice modela određene su tako što je iz posmatranog beskonačnog područja izdvojen deo koji je realna predstava otkopnog panela u razmeri sve do površine terena. Granični uslovi su zadati tako da je dozvoljeno pomeranje samo prema površini terena dok su ostale granice bez pomeranja (donja, leva i desna).

Na slici 3 i 4 prikazana je kontura aksijalnog napona (σ_1) u masivu. Kako bi dobili reprezentativni prikaz za analizu konture aksijalnog napona u modelu izdvojene su sledeće faze: faza 1 - neporemećen masiv, faza 2 - stanje u masivu nakon izrade prostorija PTN1 i PTN2, faza 6 izgled konture

aksijalnog napona nakon otkopanog cello-
kupnog gornjeg ugljenog sloja i faza 10

kontura aksijalnog napona nakon završetaka
eksploatacije u posmatranom panelu.

Sl. 3. Prikaz konture aksijalnog napona σ_1 u modelu otkopnog panela faza 1

Sl. 4. Prikaz konture aksijalnog napona σ_1 u modelu otkopnog panela po fazama 6 i 10

Najveći intezitet aksijalnog napona u neporemećenom masivu je u okolini otkopnih priprema u gornjem i donjem ugljenom sloju, a najmanji intezitet se uočava u podinskom delu od zelene gline koja se suprotstavlja dejstvu aksijalnih naprezanja višeležećih masa.

Sa napredovanjem otkopavanja, kontura smanjenih aksijalnih naprezanja iznad otkopnih bušotina raste pod uticajem naprezanja podinske gline. U okolini prostorije otkopne pripreme gornjeg ugljenog sloja i u

zaštitnim stubovima između otkopnih panela koncentrisana su aksijalna naprezanja najvećeg inteziteta.

Na slici 5 prikazana je zona loma u okolini otkopnih bušotina, uočavaju se pojave elemenata loma u svim otkopanim bušotinama kao i povećanje vrednosti aksijalnog naprezanja u okolini bušotina kao posledica napredovanja otkopavanja. Elementi loma na obodima bušotina u gornjem sloju ukazuju na mogućnost obrušavanja uglja do granice sa loporovitom krovinom.

Sl. 5. Prikaz aksijalnog napona σ_1 , sa elementima loma u otkopnim bušotinama gornjeg i donjeg ugljenog sloja

U donjem ugljenom sloju elementi loma su koncentrisani u podinskom delu i posledica su bujanja podinske gline na šta ukazuju i vektori pomeranja. U okolnom stenskom masivu nema pojave elemenata

loma. Naponsko stanje se menja u smislu povećanja aksijalnog napona u sigurnosnim stubovima između bušotina jer oni sada preuzimaju novonastala opterećenja.

Sl. 6. Prikaz izgleda totalnih pomeranja u donjem ugljenom sloju nakon izrade prvih 10 otkopnih prohoda

Prilikom otkopavanja u donjem ugljenom sloju u otkopnim bušotinama zbog bujanja podinske zelene gline dolazi do zapunjavanja otvorenog nepodgrađenog prostora. Smer kao i veličinu pomeranja u ovom delu modela uočavamo na slici 6 gde su prikazana ukupna pomeranja u donjem sloju nakon otkopavanja. Ova pomeranja iznose do 2,00 m i utiču na povećanje stabil-

nosti pri daljoj eksploataciji jer se prirodno zapunjava otkopani prostor.

Kako bi analizirali naponsko deformaciono stanje u okolini prostorija otkopne pripreme gornjeg ugljenog sloja na slici 7 dat je uporedni prikaz ukupnih pomeranja nakon izrade prostorije (slika 7a) i izgled vektora i kontura ukupnih pomeranja nakon podgrađivanja čeličnom lučnom podgradom (slika 7b).

Sl. 7. Kontura i vektori ukupnih pomeranja nakon a) izrade PTN1 i b) podgrađivanja čeličnom podgradom

Prilikom izrade poprečnih hodnika PTN1 u gornjem ugljenom sloju vektori pomeranja koncentrišu se u stropnom delu prostorije i u bokovima, gde se vrednosti kreću od 0 do

1,30 m. Nakon ugradnje podgrade ukupna pomeranja u odnosu na prethodnu fazu imaju vrednost 0,00 m jer je podgrada preuzela opterećenje okolnog masiva.

Sl. 8. Kontura i vektori ukupnih pomeranja nakon a) izrade PTN1 i b) podgrađivanja čeličnom podgradom

Analiza pomeranja prilikom izrade prostorije PTN3 ukazuje na pojavu velikih pritisaka iz podine koji su posledica bujanja zelene gline (slika 8 a), dok u stropnom delu prostorije skoro da ne trpi deformacije. Nakon podgrađivanja prostorije (slika 8 b) dolazi do smanjenja vrednosti ukupnih pomeranja. U podinskom delu se uočavaju manja pomeranja raspoređena oko posmatranog iskopa koja se kreću u granicama od 0,00 do 0,05 m i ne ugrožavaju stabilnost izrađene prostorije. Prostorije otkopne pripreme se zbog značajnih vrednosti pome-

ranja na konturi oko iskopa moraju stabilizovati čeličnom podgradom kako bi se sprečilo zarušavanje.

Stabilnost otkopnog panela predstavljena je pomoću kontura faktora čvrstoće (SF) prema fazama u razvoju otkopavanja. Zarušavanje otkopa sa napredovanjem otkopnih bušotina u panelu ne predstavlja problem prilikom eksploatacije uglja ovom metodom. Važno je da ne dođe do zarušavanja u toku eksploatacije same bušotine kako ne bi dolazilo da zaglave spiralnih burgija.

Sl. 9. Prikaz kontura faktora čvrstoće a) neporemećenom masivu i b) nakon otkopavanja celog posmatranog modela

Vrednost faktora čvrstoće u oblasti koja se eksploatiše je veća od jedan u svim delovima masiva jer se stenska masa ponaša plastično [8].

Zelena zona (na slici 9) iznad otkopnih bušotina ukazuje na povećanje vrednosti faktora čvrstoće u toku eksploatacije.

Kako bi pojasnili kretanje vrednosti faktora čvrstoće postavljene su kontrolne tačke u sigurnosnim stubovima prostorije pripreme širine deset metara, slika 10. tačka 1 i 3, i u sigurnosnim stubovima između bušotina u gornjem i donjem sloju slika 10. tačka 2 i 4.

Sl. 10. Prikaz lokacija tačaka ispitivanja faktora čvrstoće u zaštitnim stubovima

Sl. 11. Dijagram vrednosti faktora čvrstoće prema fazama otkopavanja

Grafička predstava promene vrednosti faktora čvrstoće u funkciji od faze otkopavanja prikazana je na dijagramu (slika 11). Faktor čvrstoće u sigurnosnim stubovima na svim kontrolnim tačkama (Slika 10) sa napredovanjem eksploatacije pokazuje rast.

Na krivi 1 sa dijagrama za gornji ugljeni sloj, rast vrednosti između neporemećenog masiva (faza 1) i izrade prostorije PTN1 (faza 2), posledica je sekundarne preraspodele napona usled stvaranja nove otvorene površine u višestenskoj sredini. Vrednost je nadalje konstantna (između faze 2 i 3) jer podgrada preuzima novonastala opterećenja. Otkopavanjem površine sa druge strane sigurnosnog stuba (faza 3) dolazi do rasterećenja i rasta faktora čvrstoće. Nakon faze 4, dalje otkopavanje nema značajnijeg uticaja na vrednost faktora čvrstoće u sigurnosnom stubu gornjeg ugljenog sloja.

Kriva 2 sa dijagrama predstavlja vrednost faktora čvrstoće u sigurnosnom stubu između bušotina gornjeg sloja širine 0,9 m. Od početka eksploatacije u gornjem ugljenom sloju (faza 1-4) vrednost faktora čvrstoće se ne menja, sve dok se napredovanjem otkopavanja ne dođe do samog stuba (faza 5), kada faktor čvrstoće naglo raste. Daljim napredovanjem otkopnog fronta i završetkom eksploatacije gornjeg sloja (faza 6) dovodi do blagog pada vrednosti faktora čvrstoće u sigurnosnom stubu. Ovaj pad vrednosti posledica je prenosa opterećenja

ležeće stenske mase na stubove između bušotina.

Konstantne vrednosti faktora čvrstoće (faze 7-10) za krive 1 i 2 sa dijagrama pokazuju da radovi u donjem ugljenom sloju ne utiču na faktor čvrstoće u sigurnosnim stubovima gornjeg ugljenog sloja, u smislu smanjenja njegove vrednosti.

Krive 3 i 4 na dijagramu prikazuju promenu vrednosti faktora čvrstoće u sigurnosnim stubovima pri eksploataciji donjeg ugljenog sloja. Radovi u gornjem ugljenom sloju nemaju uticaja na vrednost faktora čvrstoće u donjem ugljenom sloju. Na to ukazuju krive 3 i 4 koje sve do završetka eksploatacije u gornjem sloju (faza 6) ostaju sa istim vrednostima. Nakon otkopavanja gornjeg sloja faktor čvrstoće u oba sigurnosna stuba raste (faza 7). Rast vrednosti faktora čvrstoće je posledica bujanja podinske gline, koja ispunjava otkopne bušotine i preuzimajući opterećenje stabilizuje okolni masiv. Dalje otkopavanje u donjem ugljenom sloju (faze 8-10) ne menja vrednost faktora čvrstoće u sigurnosnom stubu između panela, što prikazuje kriva 3 sa dijagrama. Na krivi 4 faktor čvrstoće je konstantan u fazama 7-9. Otkopavanje bušotina u okolini samog sigurnosnog stuba (faza 10) dovodi do rasta vrednosti na krivi 4 sa dijagrama. Rast je posledica bujanja podinske gline koja zapunjava bušotine i preuzima opterećenje okolnog stenskog masiva.

Ovako visoke vrednosti faktora čvrstoće ukazuju da neće doći do zarušavanja u masivu pri eksploataciji uglja bušaćim mašinama sa ovom otkopnom geometrijom.

ZAKLJUČAK

Mehanizovano otkopavanje vanbilasnih slojeva male moćnosti u RMU Bogovina obezbedilo bi dugoročno povećanje proizvodnje, veću sigurnost i bezbednost pri radu kao i povećanje ukupnih rezervi u ležištu.

Prilikom analize zadatog modela došlo se do zaključka da je opisano ponašanje stenske mase približno realnim dešavanjima u sloju, posebno deo analize koji se odnosi na bujanje gline i deformacije koje pri otkopavanju nastaju. Prilikom otkopavanja donjeg ugljenog sloja glina će vrlo brzo zapuniti eksploatacione bušotine i doprineti boljoj stabilnosti posmatranog dela panela. U otkopnim bušotinama gornjeg ugljenog sloja, zarušavanje manjeg obima, ne ugrožava eksploataciju po obodu bušotine do podinskog laporca. Analiza je pokazala visoke vrednosti pomeranja u okolini prostorije otkopne pripreme pa je iste potrebno podgraditi čeličnom popustljivom podgradom kako bi se sprečile deformacije.

Iz svega navedenog može se zaključiti da RMU "Bogovina" može razmotriti ovakav vid otkopavanja u sadašnjim uslovima, ali je potrebno uraditi niz geomehaničkih analiza kako bi se potvrdili preuzeti podaci. Potrebno je takođe istražiti mogućnost eksploatacije drugih delova ležišta po povoljnijoj otkopnoj geometriji, onoj koja bi doprinela boljem iskorišćenju ležišta.

LITERATURA

- [1] Elaborat o rezervama uglja ležišta „Bogovina“ RMU „Bogovina“ – Bogovina, JP PEU „Resavica“-u restrukturiranju, Biro za projektovanje i razvoj, Beograd, 2011. god.
- [2] Ž. Milićević, Metode podzemnog otkopavanja ležišta mineralnih sirovina, Tehnologija izrade jamskih prostorija kombinovanim mašinama, radna skripta, Bor, 2008 god.
- [3] I. L. Follington, R. Deeter, D. Share, C. Moolman, A new underground auger mining system, The Journal of The South African Institute of Mining and Metallurgy 101, (2001), 25-32.
- [4] F. Wang, S. Tu, Q. Bai, Practice and prospects of fully mechanized mining technology for thin coal seams in China, The Journal of The Southern African Institute of Mining and Metallurgy 112, (2012), 161-170.
- [5] Z. Luboski, Assessment of auger mining application in Polish hard coal deep mines, Mining of Mineral Deposits, (2013), 133–142, ISBN: 978-1-138-00108-4.
- [6] Z. Rak, J. Stasica, K. Skrzypkowski, Eksploatacja pokładów cienkich metodą zwiercania, PRZEGLĄD GÓRNICZY, (2014), 18-24.
- [7] Izveštaj o obavljenim ispitivanjima na uzorcima bentonita iz RMU Bogovina iz Bogovine, Institut za bakar Bor, Bor, jun 2002. god.
- [8] Lj. Tadić, Analiza pojave plastičnog loma u stenskoj masi uz tunelski otvor, Zbornik radova građevinskog fakulteta 19, (2010), 63-77.
- [9] R. E. Hammah, T. Yacoub and B. Corkum, J.H. Curran, The Practical Modelling of Discontinuous Rock Masses with Finite Element Analysis, 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium, San Francisco, San Francisco June 29-July 2, 2008.
- [10] M. Stoniš, V. Hudeček, Mining of Coal Pillars Using the Drilling Method, Acta Montanistica Slovaca Ročník 14 (2009), 241-249.
- [11] Rocscience Inc. 2005. Phase2 v6.0 – Two dimensional finite element slope stability analysis.