Some methods of analysing caving processes in sublevel coal mining

Nekateri načini analiziranja rušnih procesov pri podetažnem odkopavanju premoga

Jakob Likar[1], Evgen Dervarič[2], Milan Medved[3], Jurij Čadež[4], Gregor Jeromel[2]

[1]Faculty of Natural Science and Engineering, University of Ljubljana, Aškerčeva cesta 12, SI-1000 Ljubljana, Slovenia; E-mail: jakob.likar@ntf.uni-lj.si
[2] Premogovnik Velenje, d.d., Partizanska 78, SI-3320 Velenje, Slovenia; E-mail: evgen.dervaric@rlv.si, gregor.jeromel@rlv.si
[3] HSE,d.o.o., Koprska ulica 92, SI-1000 Ljubljana; E-mail: milan.medved@hse.si
[4] Geoportal, d.o.o., Brnčičeva ul.13, SI-1000 Ljubljana; E-mail: jurij.cadez@geoportal.si

Received: October 11, 2006 **Accepted**: October 20, 2006

Abstract: The formation of large disturbed areas around coal mining activities, including sublevel stoping, is due to various factors which directly or indirectly influence the surrounding rocks and soils. Even though the analytical methods for determining these impacts are not strictly determined, the elastic and elastoplastic theory can be successfully applied to calculate the impacts of the caving process on the surrounding mine objects and assessing the intensive caving process height in the hanging wall. In this paper some results of the classic theory calculation of the caving process are presented with the results obtained by 2D and 3D analyses using Finite Difference Method with FLAC 3D computer code. For geometrical data preparation, a special numerical code was developed which allows for rapid and high quality construction of large meshes of the Finite Difference up to 50,000 space elements. Large numerical analyses, which were carried out specifically to analyse the caving processes in the Velenje Coal Mine, show that this type of analytical methods could be used in the future to analyse complex processes in various material models considering multi caving and compressed coal and soil layers.

Izvleček: Nastanek obsežnih porušenih območij na širšem prostoru odkopavanja premoga od zgoraj navzdol je posredno odvisen od več faktorjev z direktnim in posrednim vplivom na okoliške hribine. Čeprav način analiziranja teh vplivov ni enolično določen je moč nekatere ravnotežne enačbe elasto in plastomehanike koristno uporabiti za določitev vpliva odkopa na sosednje objekte v jami ter narediti ocene višine intenzivnih rušnih procesov v krovninskih plasteh. Prikazani so rezultati t.i. klasičnih računskih postopkov analiziranja rušnih procesov ter osnovne analize teh procesov z 2D in 3D numerično metodo končnih diferenc. Za geometrično pripravo podatkov je bil v ta namen razvit poseben računalniški program, ki omogoča hitro in kakovostno načrtovanje in uporabo velikih mrež končnih diferenc velikostnega reda več kot 50000 prostorskih elementov. Obsežne simulacije, ki so bile narejene posebej za potrebe analiziranja rušnih procesov pri odkopavanju lignita v Premogovniku Velenje so pokazale, da je v bodoče na takšen način moč analizirati zapletene procese v več materialnih modelih ob upoštevanju večkrat porušene in ponovno komprimirane krovnine.

Key words: sublevel mining method, coal, hanging wall, footwall, longwall support system, geotechnical parameters, empirical methods, numerical methods, Finite Difference Method, plastic zones, secondary stress field

Ključne besede: podetažna metoda odkopavanja, premog, krovnina, talnina, samohodno hidravlično podporje, geotehnični parametri, empirične metode, metoda končnih diferenc, plastićna območja, sekundarno napetostno polje

Scientific paper

Introduction

Sublevel mining of minerals and energy resources triggers various deformation processes in the earth crust which depend on many factors. Deformations, which are the result of caving processes, are defined as partially controlled rock fractures during which mechanical energy is released, which results in crushing of rocks of different sizes (Cook, N. G. W. et. al.[1]). Caving processes can be rapid or slow, or, are the result of fractured materials, which can cause seismic effects of different size. Since sublevel coal mining methods are designed so that caving processes occur on a wider hanging wall area, which extend high into the layers above coal layers, the effects which have impact on the development of mining (and consequently on the environment), are crucial for engineering appraisal of the situation of a wider impact area. The effects are due to intensive fractures in natural, and in some cases artificial materials, exposed to extreme stress deformation changes.

The physical aspect of fracturing of hanging wall layers of natural and soil or rock materials in sublevel coal mining refers to partially controlled process of caving of these materials into the mined – empty spaces due to the stress deformation field changes which are the result of advancement of mining. Fracturing of hanging wall materials, including coal, occurs in different ways, either continuously or discontinuously, which additionally causes stress in the surrounding rocks. Such discontinuous fractures are frequently due to man-made activities with the purpose of activating caving processes in order to achieve continuus subsiding of upper hanging wall layers on the layers below and to prevent uncontrolled movement or leaching of mine water and other liquid masses which are located close to the mining operations. Such phenomena or processes in hanging wall layers can significantly change the course of deformation in terms of time and geometrics.

The risk level of the whole mining system in such cases is quite significant due to the possibility of inrush of mine water or liquid masses of natural materials into the caves. Particularly dangerous are inrushes which can hinder the advancement in coal mining or even stop the works for a period of time. In case of a smaller inrush, mining works can still proceed with shorter break intervals. It needs to be noted that inrushes present risk factors not only for the equipment, but also for the people involved in mining operations. In longwall sublevel mining it is important to condier the geometric design of the whole system of coal extraction which depends on the caving height. Geometric design has indirect impacts on fracturing at a certain longwall length, located in the coal layer between the hanging wall and footwall layers with different geomechanical properties. The factors which have direct impacts on technical mining characteristics are geological and geotechnical properties of the layers, the faults which are due to tectonics and structure of layers, hydrogeological conditions, as well as primary stress conditions on a wider working space. From physical point of view, the displacement vectors of hanging wall layers are directed towads the space which is in the phase of hanging wall caving, while the length of displacements is limited by the floor level.

Caving processes can significantly change the structure of a rock or weak rock and cause impacts on mine infrastructure, which plays a particular role and is vital for normal operation of the cave. The supporting systems which are used to reduce the effect of the caving processes on the existing mine infrastructure, are adjusted to real geotechnical conditions and need to have a particular flexibility and adaptability to changeable stress. Therefore, for economic and safe exploitation of coal it is of primary importance to know geotechnical properties of the layers which occur in the rocks and soils in the hanging wall, in the footwall and the properties of coal layers, and mining impact factors. The analyses of stress deformation changes in mining by fracturing the direct hanging wall were made by 2D and 3D numericalal analyses by finate difference method (FDM). This method allows for complex calculations in the so called large deformations which occur during caving processes in coal mining.In this article we present the results of extensive numerical analyses, carried out by special computer interfaces which allowed for similations of mining and fracturing of the hanging wall in 2D and 3D weak rock environment. In this way we obtained good quality geotechnical results of the complex phenomena which occur in a wider area of coal sotping.

Some analytical methods of caving processes in sub-level coal mining

The complexity of caving processes in sub-level coal mining is related to time-dependant changes in weak soil layers, including coal layer, geological and geotechnical properties of weak soil layers, their structural, hydrological and mechanical changes and other natural and technological impacts. The reports in professional literature refer mainly to describing different methods for analysing stress deformation changes in the immediate or wider mining area, with focus on different aspects: studying technical parameters of excavation, e.g. caving height, the height of the immediate soil layer of the hanging wall, caving width, caving length, advancing speed, production loss, etc. The main purpose of this research was to prove suitability of the coal mining method in the given conditions. Further on we present some analyses of the different methods which describes caving processes during coal extraction.

Measurements and monitoring of caving processes

The layer of clay and coal, which breaks in after crossing the face, and which in its loose state fills up the excavated area is slowly subsided by overburden layers the weight of which makes the layer consolidated, depending on the depth and the speed of face retreat. The value of pressure due to compression ranges from very low values (0.1 MPa) to high values of 10 MPa in deeper excavations at a depth of around 500 m. The greatest height of caving-in occurs close behind the face. The scheme of a caving process in coal and clay is shown in Figure 1.

The height of caving-in is determined by computing the mass volume of the caved material, which in its loose state fills up the excavated area Kočar, F. et al.[2], as follows:

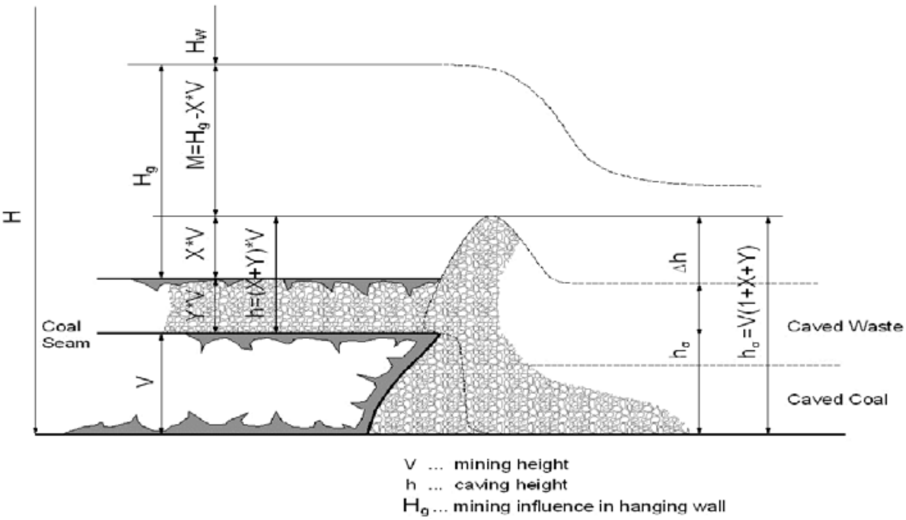

Figure 1. Figure of caving process in coal and clay
Slika 1. Shematski prikaz rušnega procesa v premogu in glini

The ratio of roof caving height/working height results in:

$$\frac{h}{V} \leq 1.5 \quad \text{or} \quad \frac{h_0}{V} \leq 1.5 \tag{1}$$

The ratio between the caving height and the working height is indicated either by coefficient "X" which is called the coefficient of caving of clay, or by "Y", when the face is deeper in the coal seam. Since the coefficient of caving was measured in situ and has not exceeded the value 1.5 it is accepted as $X_{max} = Y_{max} = 1.5$.

In case when the face is close under the clay layer, and when the caving-in gob process is completely in the clay, the ratio is as follows:

$$\frac{h}{V} \leq X_{max}; \quad \mathrm{Y} = 0\text{-}\mathrm{h}; \quad h = X - Y \tag{2}$$

When the caving-in gob process is completely in the coal and does not cover the clay layer, the relations are as follows:

$$\frac{h}{V} \leq Y_{max}; \quad X = 0; \quad \mathrm{h} = \mathrm{Y} \cdot \mathrm{V} \tag{3}$$

If the caving process covers also a part of a clay layer the relations are as follows:

$$\frac{h}{V} \leq (X + Y) = 1.5; \quad h = (X + Y) \cdot V \tag{4}$$

In these cases we calculated the thickness of the layer above the face, has been caved and has become loose. To determine the height of the caved bow the working height has to be added to these results. The equation is as follows:

$$h_0 = V \cdot [1 + (X + Y)] \tag{5}$$

The symbols in the equations above have the following meanings:

- H depth of the face floor from the surface [m],
- H_g thickness of isolating clay layer [m],
- H_w depth of water bearing strata [m],
- h height of roof caving - in goaf above the coal face [m],
- h_0 maximum height of caving in the goaf from the floor of the face [m],
- Δh subsiding of roof layer on the goaf [m],
- h_σ goaf height behind the face during the consolidation phase [m],
- X coefficient of caving height of isolating layer[/],
- Y coefficient of caving height of the coal in the roof of the face[/],
- V working height [m],
- M thickness of intact isolating clay layer [m].

Model laboratory tests

Model laboratory tests are intended for better understanding of caving processes and mechanism of fracturing, which are the constituent part of advancement in coal extracting. Tests can be made by using different materials, e.g. aluminium rods with approx. 4 mm diameter (3 mm and 5 mm in our case) with length of 50 to 70 mm (in our case 60 mm), sand with different granulation and humidity, glass balls with different diameter, etc. Due to high complexity of the simulation and analyses of caving processes some simplifications were needed (i.e. the measurements during experiments were adjusted to the measuring technique (the use of stationary photo camera, video camera, etc.). Similarly, the quality of measurements during tests depended on the analyses of measurement results and the interpretation of the results of deformation processes.

Figure 2 shows the Taylor-Sneebely simulation model of sublevel coal mining. Model test were performed using aluminium lamellas, representing mining levels. These were drawn against the dispositive framework at constant speed, while the aluminium rods, representing the hanging walls layer were moving – »caving« into the empty space which was formed by the moving framework of the aluminium lamellas (Sovinc, I. and Likar, J.[3]). We believe that the simulation model of sub-level coal mining is relatively good in that it provides better understanding of physical aspects of the hanging wall caving processes.

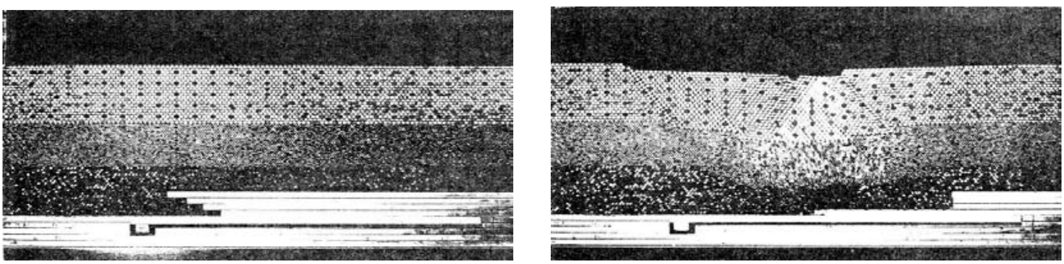

Figure 2. Dispositive model of Taylor-Sneebely test before the simulated excavation and during excavation in the third level in a three layer hangingwall

Slika 2. Prikaz modelnega poizkusa v Taylor-Sneebelijevem dispozitivu pred simulacijo odkopavanja in v fazi odkopavanja v tretji etaži v triplastni krovnini

It needs to be emphasized that our research was carried out by using synthetic materials which are different from natural materials, particularly in our case where we were dealing with the friction part of the shear strength and not the cohesive shear strength. The performance of »hanging wall materials« agree well with the Mohr-Coulomb yielding model. The displacement field of measurement points after the simulation of excavation of the upper three levels is shown in Figure 3. The direction of displacement vectors changes with regard to vertical direction.

VERTICAL STRESS IN THE AREA OF LONGWALL MINING

In professional literature there are several reports on similar studies based on hypotheses, which allow for direct or indirect calculations of stress distribution. WILSON, A.H. [5] made a hypothesis that vertical stress in the caved waste increases linearly from value 0 to the final value, at a distance where it is not possible to detect the impacts of instability in mine road ways.

WILSON [5] found out that pressure arch changes in the interval between factor 0.2 and 0.3 of the caving depth below the surface. Other authors, e.g. KING, H.J. and WHITTAKER, B.N.[6], CHOI, D.S. and MCCAIN, D.L.[6], MARK, C.[7] suggest similar ratios between the values of 0.12, (as suggested by SMART and HALEY[8]) and 0.6, as suggested by WILSON[5]. It needs to be noted that some studies, where numerical methods were used, indicate opposite results (e.g. TRUEMAN, R. [9] and THIN, I.G.T. ET. AL.[10], namely that the impact area decreases with the increasing caving depth. The National Coal Board[11], based on extensive studies and measurements in situ found out that the ratio between the size of rock pressures and their geometric distribution with regard to the primary pressure stress depends to a great extent on geotechnical properties of fractured material. This is normal, since the subsiding of hangingwall layers in the caved waste area depends on these properties.

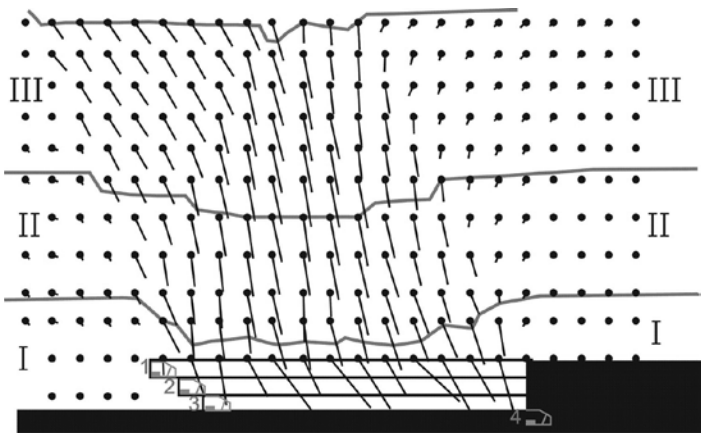

Figure 3. Displacement vectors of measurement points in a three-layer hangingwall after the simulation of mining of the first three panels from up to downwards

Slika 3. Ugotovljeni vektorji pomikov merskih točk v triplastni krovnini po končani simulaciji odkopavanja prvih treh etaž od zgoraj navzdol

Figure 4 shows the interpretation of the distribution of vertical stress, around a single longwall face. The vertical stress is zero at the face and the rib side. The stress increases rapidly with distance into the yield zone in the unmined coal, reaching a peak value near the excavation phase. Vertical stress can be in order of four or five times the overburden stress where *h* is the mining depth and γ is the volume weight of the hangingwall strata. With the increased distance into the unmined coal, the vertical stress reduces towards the overburden stress.

In the mined region, the stress on hydraulic support is relatively small compared with the area behind the mined region and on the sides of (as shown in profiles B-B and C-C). This is due to the deformability properties of the surrounding layers.

Simulation of the caving process by using 2D numerical method

Very complex caving processes of the geological materials which are part of sublevel coal extraction can be analysed using numerical method, i.e. Finite Difference Method, which we found appropriate for solving such problems. In this way software application using computer code FLAC 2D and FLAC 3D are useful ways for simulating caving processes connected with large displacement. FLAC 3D is also applicable for solving this type of geotechnical problems: in some cases of elements (250.000 or more) and longer computing time.

FLAC is an explicit finite difference program for engineering mechanics computation. This program simulates the behaviour of structures made of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Materials are represented by elements, or zones, which form a grid that is adjusted by the user to fit the shape of the object to be modelled. Each element behaves according to a prescribed linear or non-linear stress/strain law in response to the applied forces or boundary restraints. The material can yield and flow and the grid can deform (in large-strain mode) and move with the material that is represented. The explicit Lagrangian calculation mode and the mixed-discretization zoning technique used in FLAC ensure that plastic collapse and flow are modelled very accurately. Since no matrices are formed, large two-dimensional

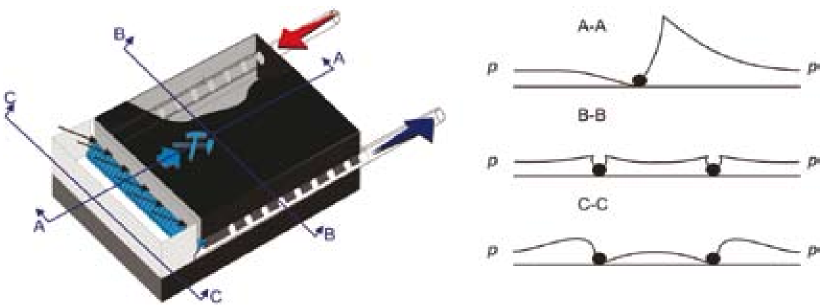

Figure 4. Interpretation of the distribution of vertical stress around a single longwall face
Slika 4. Prikaz prerazporeditve vertikalnih napetosti pri širokočelnemu odkopavanju premoga

Table 1. Geotechnical properties of geological materials used in the numerical simulations
Tabela 1. Geotehnične lastnosti geoloških materialov uporabljenih v numeričnih simulacijah

Type of the geological layer	Rock (soil) specific weight γ(kN/m^3)	Young modulus E(Pa)	Poisson ratio ν (/)	Shear modulus G(Pa)	Bulk Modulus K(Pa)	Angle of the internal friction φ (^{0})	Cohesion c(Pa)
Protection layer of clay	18.7	5.72E+08	0.32	2.17E+08	5.20E+08	35	2.0E+06
Sand with layers of clay	18.7	5.27E+08	0.32	2.00E+08	4.80E+08	30	7.0E+05
Coal	12.7	4.48E+08	0.33	1.68E+08	4.50E+08	30	1.5E+06
Comprimated coal in the gob	12.7	3.52E+08	0.35	1.30E+08	4.00E+08	25	1.0E+05

calculations can be made without excessive memory requirements. The drawbacks of the explicit formulation (i.e., small time step limitation and the question of required damping) are overcome to some extent by automatic inertia scaling and automatic damping that does not influence the mode of failure.

In the simulation of the caving process during longwall coal mining we used 2D and 3D analyses. The emphasis was on the simulation of the coal extracting by sublevel caving for different speeds of the coal extracting advancement.

Primary stress state was assumed on the basis of the weight of the handing wall layers. It needs to be emphasized that the primary stress estimation is the result of the analyses which were made in previous decades and were carried out in the Velenje Coal Mine. This refers to the average ratio between primary horizontal and vertical component of stress which is K_0 = 0.85. The table shows

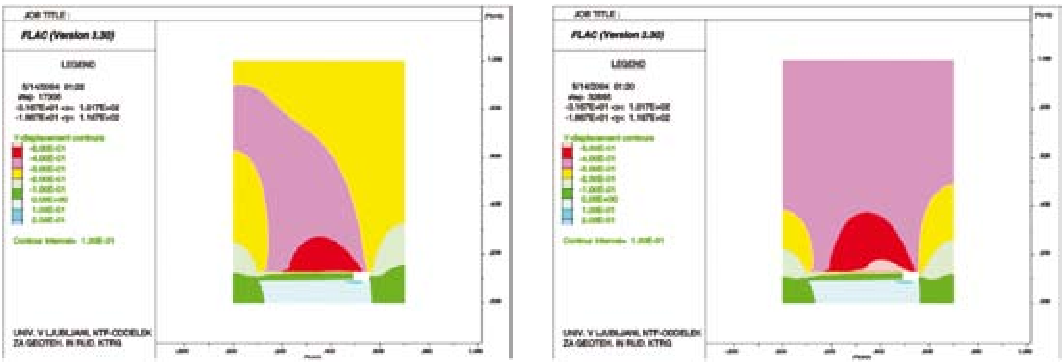

Figure 5. Vertical displacements during coal extracting when advancement is 3m/day and displacements when coal extracting has advancement 7m/day, JEROMEL [12]
Slika 5. Vertikalni pomiki pri napredku odkopa 3m/dan in vertikalni pomiki pri napredku odkopa 7m/dan, JEROMEL [12]

input data for calculations. In calculations we employed an additional program function FISH, which included the elements which allowed for the simulation of the speed of coal extracting from 1.0 m/day to 8.0 m/day.

Results of the simulation of caving process in longwall coal extracting

Caving processes of hangingwall in longwall coal mining are more intensive if mechanical properties of coal and the hanging wall are different, particularly when the direct hangingwall is harder than the coal layer. In such cases a spontaneous continuous fracturing of the hangingwall with subsequent large stress concentrations does not occur in the pillar of coal layer and in the immediate hangingwall layers, which is frequently caused by rock bursts (Old Coal Mine Zenica, Kakanj Coal Mine, BiH). In the case which we analysed, the properties of the hangingwall and the coal layer allowed for a continuous hangingwall caving.

A comparison of our analyses was made where we considered an equal distance from the initial point of excavation, meaning that different time periods were needed to reach a certain length of longwall; coal extraction with shorter advancement requires more time to reach a certain distance from the initial point of coal extraction. For this reason, the speed of extraction advancement and changes in secondary deformation fields related to time increases of displacements of the hanging wall layers, which is shown in Figure 5. If we compare the size of the calculated displacements for the advance coal extraction speed of 3 m/day and 7 m/day, we can see that the intensity of caving is significantly larger at a low extraction speed, which results in deformation processes which are less favourable as far as the distribution of plastic yield regions in the hangingwall seams is concerned.

There is less difference in the height and the shape of the area to which individual zones of additional effective vertical stress reach (Figure 6).

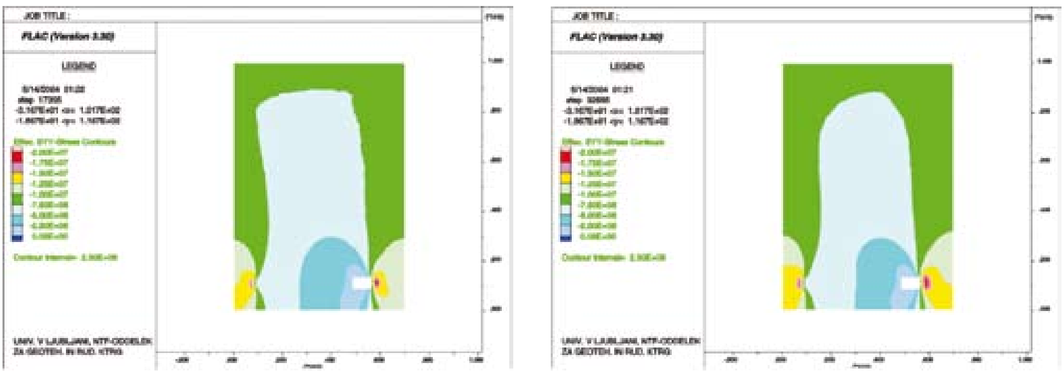

Figure 6. Effective vertical stress in the surroundings layers when extraction advancement are 3m/day and 7m/day Jeromel [12]

Slika 6. Efektivne vertikalne napetosti v okoliških plasteh pri napredku odkopa 3m/dan in 7m/dan Jeromel [12]

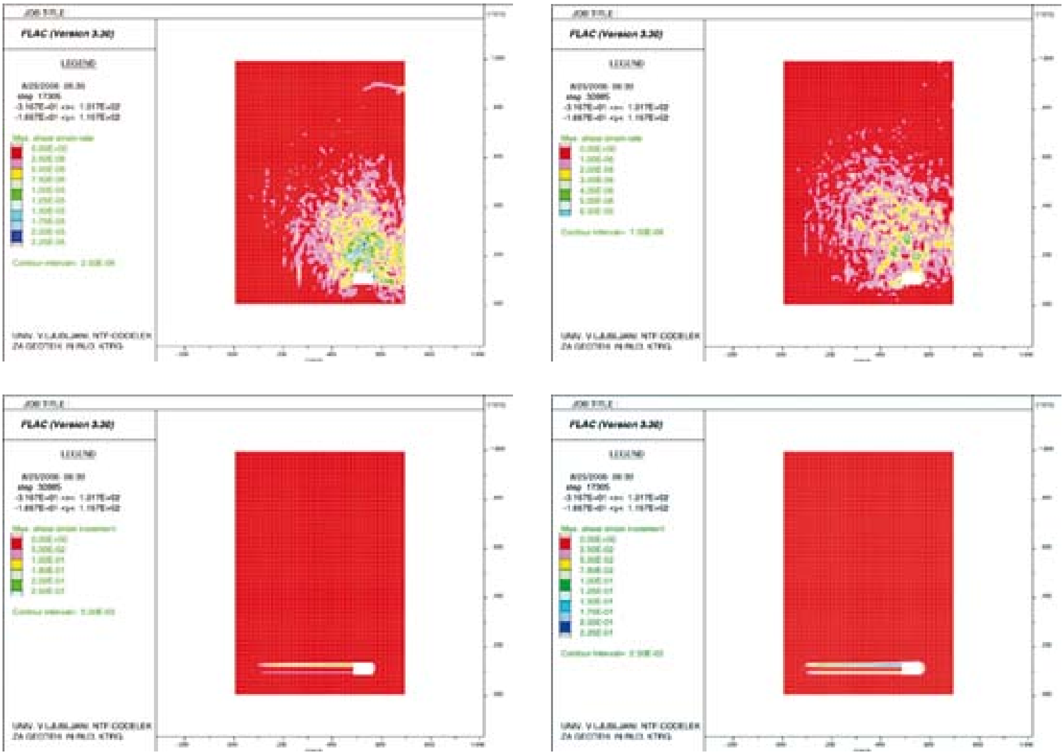

Figure 7. Effective shear stress in the hangingwall during coal extraction advance 3m/day and 7m/day JEROMEL [12]
Slika 7. Efektivne strižne napetosti v krovnini pri napredku odkopa 3m/dan in 7m/dan JEROMEL [12]

TOP CAVING ANALYTICAL PROCESS BY USING 3D FINITE DIFFERENCE METHOD

Analyses of the stress strain changes were carried out by using real geometrical data of the coal extracting advancement and other parameters which have impact on the coal extracting process in the Velenje Coal Mine. In the Finite Difference Model the following geological/geotechnical and technological units were included:

- hanging wall above clay protection layer,
- clay protection layer,
- coal (exploitation),
- footwall bellow the coal panel .

Mine production levels are situated below the so-called protection layer of clay, which prevents inrush of water, sand and mud into the longwall. In the last few years, excavation of coal has started under thinner layers of clay, which consequently increases the danger for miners working in such rock conditions (Figure 8). The continuous research work performed in the Velenje Coal Mine yielded numerous geotechnical parameters of the lignite seams, rocks and soils in the hanging wall and the footwall. Therefore, the exploitation space is better understood and mechanism of coal production has become the main issue for safe and productive exploitation. In this respect a large body of research

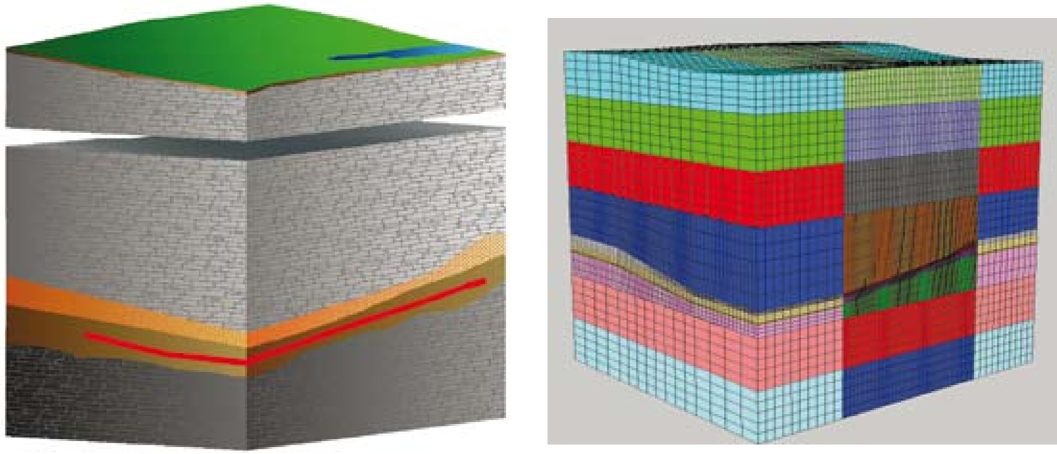

Figure 8. Geological profile trough the Velenje coal mine across the exploitation slice G1A and Finite Difference Mesh
Slika 8. Geološki profil Velenjskega premoškega nahajališča in odkopne plošče G1A ter mreža končnih diferenc

has been done, and in the past years a 3D numerical model has been developed which describes the mechanism of coal exploitation under a thin layer of protective clay. The numerical model has been developed with *FLAC3D* program.

The numerical model, developed for the coal exploitation analysis in the Velenje Coal Mine, consists of approx. 240,000 elements, and takes into account detailed geology in working space. For that reason, special software has recently been developed to transfer the geological geometry into the model. Figure 8 shows finite difference mesh and the geological profile through the Velenje Coal Mine across the exploitation slice G1A.

Input data

Geotechnical properties of coal seam, the hangingwall and the footwall were determined on the basis of laboratory tests and in-situ tests. In our calculations the Mohr-Coulomb failure criterion was used. The geotechnical properties of geological materials are shown in Table 1.

Table 2. Geotechnical properties of geological materials
Tabela 2. Geotehničmne lastnosti geoloških materialov

Geological material	Density $\rho\mu/\gamma\kappa(^3)$	Bulk modulus K (MPa)	Shear modulus G (MPa)	Cohesion c (kPa)	Internal friction angle φ (^{0})	Poisson ratio ν(/)	Tensile strength T(kPa)
Protection layer of clay	1960	240	180	700	17	0.20	590
Coal	1290	320	195	700	30	0.25	590
Layers below clay protection	2130	155	50	400	15	0.35	80

Initial stress state

Primary stress states in virgin rocks and soils were defined on several observations during carried out "in-situ" measurements. In many calculations the ratio between the horizontal and vertical components of stress field 0.85 was used. In same cases the determined values cause doubt. From this reason, value 0.85 needs to be proved in future.

Excavation geometry

The present analysis simulated the excavation of coal slice G1A, with dimensions approx. 200 m x 300 m. The designed mining height is 4m, and daily exploitation round was about 4m. To simulate the daily exploitation round, a single step in the numerical analysis consisted of elements which were removed inside the zone 200 m x 4 m x 4 m. As a result, 65 steps have been calculated, each step presenting a daily exploitation round. Figure 9 shows the exploitation field G1A within *FLAC3D* grid.

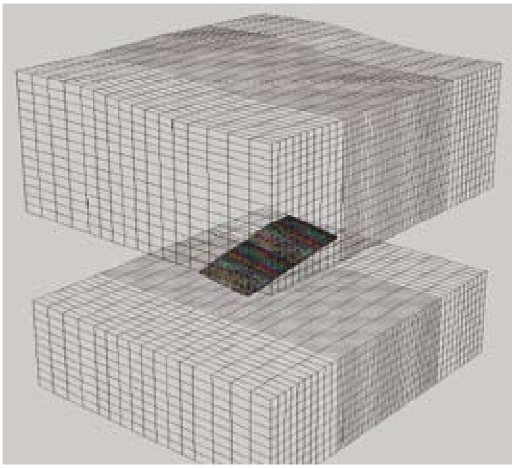

Figure 9. Exploitation field G1A within FLAC 3D grid
Slika 9. Odkopno polje G1A v FLAC 3D mreži

Calculation procedure

Firstly, the primary stress state was calculated under predefined conditions. Subsequently, 65 steps of mining sequences of the exploitation field G1A were carried out.
Each step included:

- Removing elements, which represented each exploitation step,
- Gradual reaching of the equilibrium until the vertical movements has not reached the level of the exploitation height (4 m in our case),
- Inserting the removed elements into the model before starting the subsequent calculation step.

Analyses of the top caving process

Owing to extensive "in-situ" and laboratory research which has been done in the past, the exploitation process in the Velenje Coal Mine is well studied. Therefore, the results of our numerical analyses could build upon previous experience and comparable parameters could be tested as well.
Some details about the sublevel mining method with caving immediate roof i.e. top caving, which is used in Velenje Coal Mine, regarding the displacement and stress changes are explained below.

According to our experience the hanging-wall failure height is approx. 1.5 - 2.0 times the mining height. This means that for the mining height of 4m the roof failure height is between 6m and 8m, measured from the top of the longwall face. The failure zone is determined, where the specific shear strain is under 3 %. The failure area is finished approx. 0.5 to 0.8 times the mining height behind the supported end. At the height three times the

Figure 10. The coal extracting in the Velenje Coal Mine
Slika 10. Odkop v Premogovniku Velenje

value of the caving height, the hangingwall layers were not equally destroyed Figure 10 shows the caving process in the Velenje Coal Mine. About two times the mining height in front of the longwall face a horizontal displacement occurs in magnitude of 0.5 m. In the area with longwall influence, horizontal movements are transformed in to a vertical displacement, the magnitude of which is close to the mining height.

The compression process in the hangingwall soil layers after the coal was mined out, continue to develop behind the longwall face exactly behind the hydraulic support. The caving process fills in the mined out area behind the support and the displacements stops. The stress in the surrounding rocks and soils behind the longwall face tends to increase close to the initial value. The compression part of deformation starts approx. 0.5-0.8 times of the failure height behind the support end, and about 6.0 times of the failure height behind the support-end, where the compression process is practically finished. The volume of mined coal was replaced with caving of the upper layers into the mining space. The volume loss in upper layers is close to 80 % of the total volume of the mined coal. That means that the deformation process is very intensive and continuous, following the longwall face, which is in the moving state during coal exploitation.

Initial changes of the stress state in the hangingwall, the coal seam and the footwall in front of the longwall, started developing when the extraction panel start to move ahead. Analyses have shown slow upward movements towards the excavation face. Close to the longwall face, the stress field started to increase rapidly from its initial value to about 85 % of overstress. Vertical stress started to increase causing an intensive compression process at the distance which was 0.5-0.8 the times of the mining height behind the longwall, Compaction of caving material from hangingwall is relatively fast. Usually six months were enough to receive suitable compacted material. This fact is very important for designing a new longwall below the current production level. At a distance about 60 m behind the longwall, vertical stress converges to the initial stress state value. The stress state around the exploitation field is shown in Figure 4.

Vertical stress distribution in the protection layer of coal and in the protection layer of clay in the hangingwall area is an important part of the present analyses. The stress in these layers undergoes similar changes as in the coal production level, but it is distributed in different places, while the stress changes are not so high.

Underground coal mining caused extensive surface movements in a large space above the coal production levels. In the analyzed case, caving and deformation processes moved to the surface vary fast. The impact angle was low and the surface above mine workings was usually damaged, filled with surface water in the form of artificial lake, with the area of about 1.35 km^2. Vertical movements are clearly shown in different levels in the hangingwall in Figure 11.

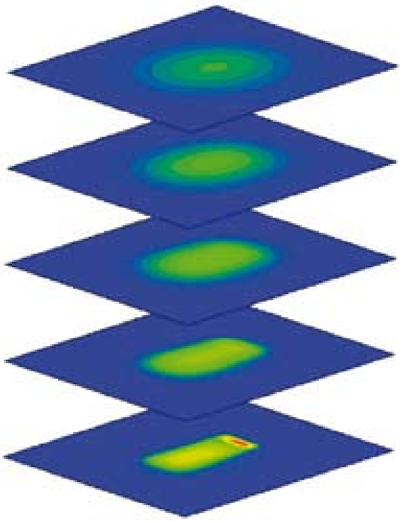

Figure 11. Vertical movements in different levels in the hangingwall
Slika 11. Vertikalni pomiki na različnih nivojih krovnine

Other impacts of the exploitation process

Coal mining has strong impacts on other parts of the mine, particularly on its infrastructure, which is located close to the coal production field. The changes of the stress strain were analyzed too, since underground connections (such as main mine roadways) are important for normal and continuous coal production. Sometimes mine roadways urgent reshaping, but that is only later, when stress concentration has decreased.

Results of numerical analyses

In our experience, the hangingwall failure height is approx. 1.5-2.0 times the mining height. In our case, the mining height was 4m and failure height between 6 m to 8 m, measured from the top of the longwall. However, the hanging wall failure area could be determined using shear strain increment condition. That means, if shear strain exceeded 3 %, a failure in the hangingwall was present. Generally, the hangingwall failure area must stop in the protection layer of coal. The thickness of the protection layer of the coal seam was between 5m and 20m.

Figure 12 shows shear strain increment from 3 % to 10 % in the protection clay layer above the longwall. At the edges of the longwall, the calculated shear strain in the clay protection layer was much higher than expected. This fact shows clear connection with the calculated stress concentration at the edges of the longwall.

The deformations in front of the longwall reached a value of 20-30 cm at the top of exploitation panel, which agrees well with

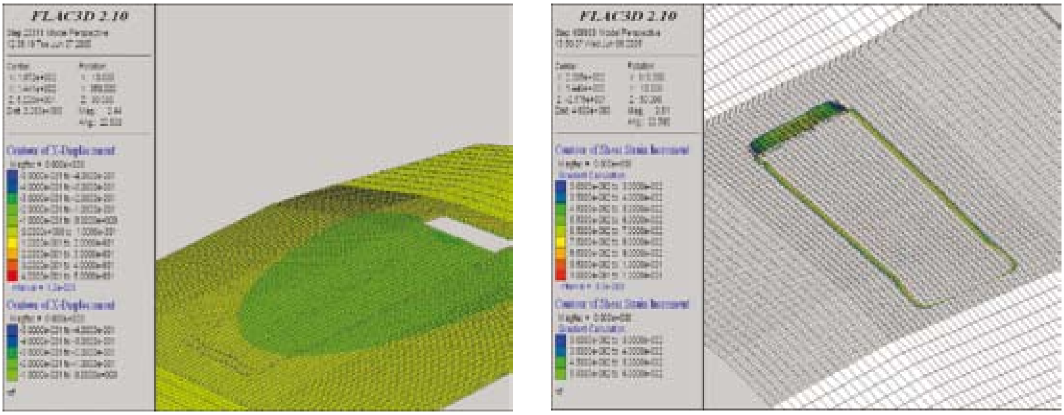

Figure 12. Shear strain increment from 3 % to 10 % in the clay protection layer above the longwall and the development of the deformation field in front of the longwall
Slika 12. Strižni prirastek od 3% do 10% v glinastem varovalnem sloju nad odkopnim poljem in razvoj deformacijskega polja pred čelom odkopavanja

our previous experience and the "in-situ" measurement results. However, more interesting is the impact area of the mining production process, which was much wider than previously expected. When 25 % of the coal mining of field G1A was finished, the displacements reached the end of the exploitation slice. This fact is shown in Figure 12.

The comprimation process began immediately behind the longwall hydraulic support. In the numerical analysis, by which we simulated mining and caving process, we used the removed elements which were installed back into the model, when vertical displacement reached the mining height. From this point of view, the stresses in those elements started to increase, depending on the distance

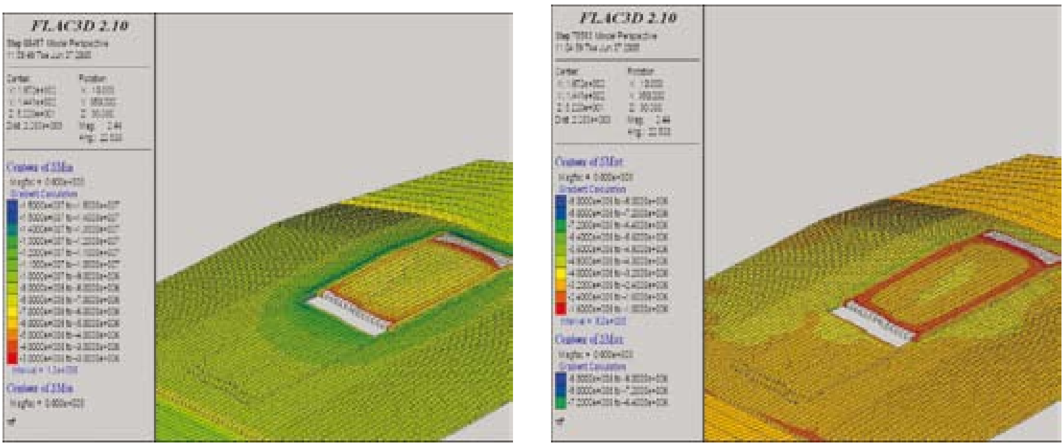

Figure 13. Stress δmax and Stress δmin – slice G1A
Slika 13. δmax in δmin napetosti – odkopno polje G1A

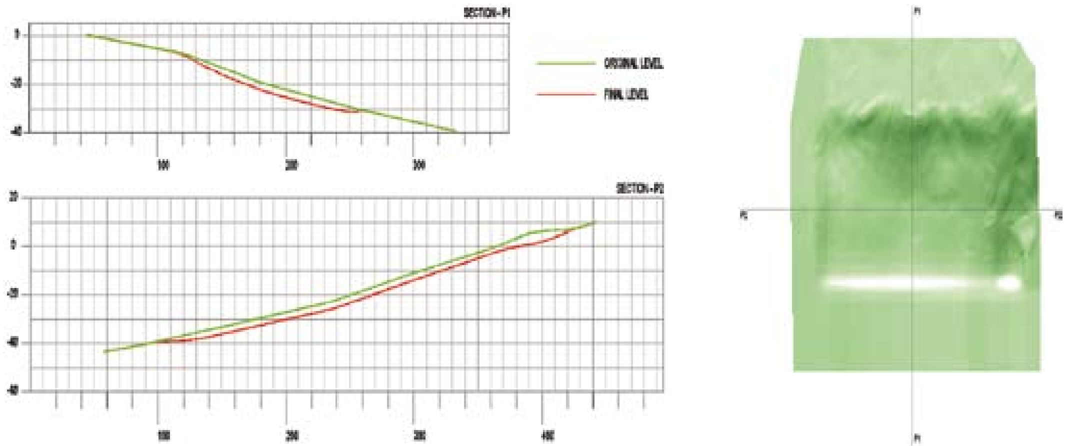

Figure 14. Deformed surfaces at the lower part of the clay protection layer
Slika 14. Deformirana površina spodnjega dela varovalne plasti gline

between the longwall face and the observation point. The level of the stresses in the caved waste was activated, if the comprimation of the surrounding damaged rocks and soils material was started. Figure 12 shows the stress convergence to the initial value, when it reached the value close to the initial stress in the surrounding rocks and the coal seam. This finding was in agreement with the observations carried out in our previous research (KOČAR ET.AL.)[2].

The volume, which can be calculated using the difference between the initial position of the specified surface and the deformed surface, is about 80% of the coal excavated volume. Figure 14 shows the deformed surface at the lower part of the clay protection layer. These values are close to the estimations from the observation part of the project.

CONCLUSIONS

The results of the analyses, based on the modelling by Finite Difference Method, have shown relatively good agreement between the calculated values and the observed data.

Numerical modelling and the results of extensive geotechnical analyses of the longwall mining method, which have been used in the Velenje Coal Mine with safety considerations, represent a contribution to better understanding of complicated stress strain processes in the larger space of the influence of the coal mining.

Strain and stress changes, calculated during the simulation of the longwall coal extraction in the hanging wall, the coal seam and in the footwall, have shown good agreement with our expectations.

There are some differences between the results of numerical analyses and observations regarding the area of deformation impact, caused by coal extraction in the analysed area.

The 3D numerical model will be tested in the future with different input data and elastic-plastic models. Some improvements need to be implemented with considerations to the impacts of underground water and different primary stress states in the cases analysed.

The current model took into account detailed geology and mining production geometry, which allowed for making calculations without usual simplifications.

Povzetki

Nekateri načini analiziranja rušnih procesov pri podetažnem odkopavanju premoga

Podetažno odkopavanje premoga je povezano z velikimi deformacijami v okoliških hribinah in predstavlja v geotehničnem pogledu časovno odvisen proces, pri katerem so prisotne različne porušitve hribinskih območij v okolici odkopa. Posamezne faze, ki se odvijajo z napredovanjem odkopavanja, so pomembne za oceno komprimacijskih učinkov v porušeni krovnini za odkopom ter v realnem merilu dajejo osnovo za možna predvidevanja procesov, ki so prisotni pri odkopavanju globlje ležečih etaž. Vsekakor je modeliranje rušnega procesa z metodo končnih diferenc s simulacijo napredovanja odkopa primeren način analiziranja intenzivnih sprememb v porušenih naravnih materialih, kar med drugim omogoča tudi do določene mere boljše vedenje o samem rušnem procesu ter primerjavo rezultatov izračunov z izmerjenimi vrednostmi. Pri tem je potrebno poudariti, da simulacije načina odkopavanja premoga v Premogovniku Velenje narejene z 2D in 3D dajejo možnost nadrobnejšega analiziranja konkretnih primerov odkopavanja, saj je iz dobljenih rezultatov moč relativno hitro preverjati dobljene vrednosti npr. pomikov v zapletenih napetostno deformacijskih procesih, ki se dogajaj v širšem območju, kjer poteka odkopavanje premoga.

Izračunane spremembe napetosti in deformacij pri podetažnem odkopavanju premoga se dobro ujemajo s pričakovanji, medtem ko je zaznati manjše neskladje med rezultati numeričnih analiz in opazovanji v velikosti območja deformacij v okoliških hribinah okrog neposrednega zaruševanja krovninskih plasti.

REFERENCES

[1] B.H.G. BRADY, E.T.BROWN, 1993, Rock Mechanics for Underground Mining; Second edition, Culver Academic Publisher, Dordrecht, Boston, London.

[2] J. LIKAR, Rušni procesi v rudniku lignita Velenje-raziskovalna naloga, reports for years 2001, 2002 and 2003, Ljubljana, University of Ljubljana, Faculty of Natural sciences and Engineering.

[3] ITASCA CONSULTING GROUP,2002 FLAC – 3D manual.

[4] S. JANEŽIČ, Študija za reševanje problematike varnega odkopavanja in določitev kriterijev za projektiranje in odkopavanje premoga pod vodonosnimi plastmi v jamah RLV, Rudnik Lignita Velenje,1987.

[5] A.H. WILSON, 1981, Stress, stability in coal ridsides and pillars. Proceedings of the First Conference on Ground Control in Mining, p.1-12.

[6] H.J. KING, B.N. WHITTAKER, 1971, A review of current knowledge on roadway behavior, especially the problems on which further information is required. Proceedigs of the Symposium on Strata Control in Roadways, London, Inst. Min. Met. p 73-87.

[7] D.S. CHOI, D.L MCCAIN, 1980, Design of longwall system. Trans Soc Min Eng AIME, 258: 1761-4.

[8] C. MARK, 1990, Pillar design methods for longwall mining, BuMines IC9247, p. 53.

[9] B.G.D. SMART, S.M. HALEY, 1987, Further development of the roof strata tilt concept for pack design and the estimation of the stress development in a caved waste. Min Sci Technol; 5:121-30.

[10] R. TRUEMAN, 1990, Finite element analysis for the establisment of stress development in a coal mine caved waste. Min Sci Technol; 10: 247-52.

[11] I.G.T. THIN, R.J. PINE, R. TRUEMAN, 1993, Numerical modelling as an aid to the determination of the stress distribution in the goaf due to longwall coal mining. Int J Rock Mech Min Sci Geomech Abst. 30:1409-9.

[12] G. JEROMEL, Numerična simulacija rušnih procesov pri odkopavanju premoga, Diplomsko delo, Ljubljana 2004.

[13] NCB. National Coal Board, 1975, Subsidance engineer’s handbook, NCB Mining Department; London, p. 111.