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Numerical Modeling and Computer Simulation of Ground Movement Above Underground Mine

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***Abstract*—**This paper describes topic of computer simulation with regard to the ground movement above an underground mine. Simulation made with software package ADINA for nonlinear elastic-plastic analysis with finite elements method. The one of representative profiles from Mine 'Stara Jama' in Zenica has been investigated. A collection and selection of both geo-mechanical data and geometric parameters of the mine was necessary for performing these simulations. Results of estimation have been compared with measured values (vertical displacement of surface), and then simulation performed with assumed dynamic and dimensions of excavation, over a period of time. Results are presented with bitmaps and charts.

***Keywords*—** Computer, finite element method, mine, nonlinear analysis, numerical modeling, simulation**,** subsidence.

I. Introduction

IT is possible to accomplish numerical modeling and simulation using various computer techniques and numerous software for different types of analysis. These ways of examinations are less costly and faster than practical experiments and obtained results are accurate enough.

As a result, successive layers of rock over the mine are working bend under the influence of gravity, until finally the movement reaches the upper earth surface. The surface, above underground mine excavation, can move in vertical and horizontal plane, or can perform complex movement making deformations on the buildings, cracks on the roads or earth surface [5,11,15,17,21].

Formation and development of subsidence trough has been explained by the subsequent triangle of vertical and horizontal component force [6,7,22]. Numerical modeling is one of the ways to predict the subsidence. This paper presents an application of the finite element method and computer simulation in the process of selecting an optimal method of exploitation at underground coal mines.

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The aim of selection of an optimal method is minimizing negative impact on the terrain surface and objects on the surface in the zone of influence of ground movements (subsidence). The methodology will be validated at the Zenica coal mine. The software ADINA for computer simulation will be used.

II. Methodology for Numerical Modeling of Subsidence

A. Theory of modeling

Methodology of modeling is based on principles of numerical analysis (finite element method) implemented in ADINA (Automatic Dynamic Incremental Nonlinear Analysis) software [1,6]. The finite element method is very versatile tool for solving geo-mechanical problems, because it can take care of variations in geological conditions. It can also handle changing boundary conditions and any material behavior models can be incorporated. The theory of the finite element method is well-documented in the literature [2,3,6,9,11,16,17]. Its application in mining involves mathematical simulations of ways how rocks respond to mining operations [4,6,12,18,20,23]. Approach to numerical simulation in geo-mechanics can be presented as follows:

1. Determining characteristics of soil (rock) from laboratory and in-situ testing.
2. Development of the numerical model.
3. Use of software for numerical analysis and simulation of geotechnical problems.

Movements of strata above excavation are propagated to the surface only when the dimension of cavity has reached a certain size [5,12,15]. With increasing this area it was recorded an increase of quantity of masses under movement. Displacement of a point at surface appears after some time from the start of exploitation and reaching defined dimensions of the trough of subsidence at the surface and depend on: physical-mechanical characteristics of mass in roof, rheology, depth of excavation, dimension of cavity, speed of mine work and time factor in relation to failure criteria [6,11,15,17].

B. Uncertainties of modeling

Limitations of the numerical simulation are related to the facts that models are a poor representation of the reality which necessarily contains simplifications. This element should be taken into account while analyzing obtained results. All models incorporate uncertainties such as:

1) Aleatory uncertainty which appears when an event occurs in a random manner.
2) Epistemic uncertainty is referred to as the state-of-knowledge uncertainty.

It is composed of three main components which are described in some more details below:

a. Parameter uncertainty: The model for expressing the aleatory uncertainty might be "perfect" but has one or more unknown parameters to be estimated with errors. In the case of models related to mining, it occurs trough process of determining characteristics of soil (rock) from laboratory and in-situ testing can be occurring errors what present a source of uncertainty. The parameter uncertainty is caused by factors such as statistical uncertainty due to finite data, or data-evaluation uncertainty due to subjective interpretations of data. The data-evaluation uncertainty may be greater than the statistical uncertainty because the latter could be reduced by a variety of traditional, theoretical approaches.

b. Modeling uncertainty: The models for the aleatory uncertainties may appear less realistic because of various approximations and assumptions that are made while developing a model. Uncertainties can be incorporated through the process of creating a geometric model because of made simplification. It is necessary to take into account fact that performed simplification mast not exceeds the permitted range (like extreme change in shape of system or items of system). Inaccuracies in modeling result in significant errors of estimations obtained by simulation. At this stage relevant items that contribute to an uncertainty of solution are listed as follows: analysis type (static, dynamic-implicit, dynamic explicit, modal stress, etc.), analysis assumptions (kinematics: type of displacement and strain; mass matrix, etc.), solution process (for nonlinear analysis type of iteration method and iteration tolerances), including miscellaneous options, geometric tolerances, boundary conditions, loading, etc [10,11,12,13,14,16,18,20].

c. Completeness uncertainty: The incompleteness is a scope limitation, and causes deviations from realism [24, 25]. The estimation lacks of realism due to the fact that all the contributors to an accurate result are not modeled or the level of details in a model is too coarse. If software for the simulation does not offer a wide range of options for modeling the latter will restrict the field of application and will reduce the capacity of simulation of different conditions in rock massive.

Based on above, results of various numerical simulations cannot be a solely basis for a final decision-making. Often, some intangible factors which cannot be modeled or could be hardly modeled might take over and change an outcome.

C. Mathematical approach to modeling

Deformation in y direction is:

$$\varepsilon_y = \frac{dv}{dy} \tag{1}$$

Relation stress-deformation is:

$$\sigma_y = E_y \cdot \varepsilon_y \ \ (\mathrm{MN/m^2}) \tag{2}$$

For conditions of plane strain matrix of properties is [2,3,6,9,11,16,17]:

$$D = \frac{E \cdot (1-\nu)}{(1+\nu)\cdot(1-2\cdot\nu)} \cdot \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\cdot\nu}{2\cdot(1-\nu)} \end{bmatrix} \tag{3}$$

E – Young's modulus (MN/m^2)
ν - Poisson's coefficient

Derivation of equation for an element:

$$[k]\cdot\{q\} = \{Q\} \tag{4}$$

k – stiffness array of elements
q – vector of unknown value for each node
Q – nodal forces

Global system of equation:

$$[K]\cdot\{r\} = \{R\} \tag{5}$$

K – global stiffness matrix
r – global vector of unknown value for each node
R – global vector of nodal forces for each element

Mohr-Coulomb yield criterion:

$$^t f_{MC} = {^t I_1} \cdot \sin\phi + \frac{1}{2}\cdot(3\cdot(1-\sin\phi)\cdot\sin{^t\theta} + \sqrt{3}\cdot (3+\sin\phi)\cdot\cos{^t\theta})\cdot\sqrt{^t J_2} - 3\cdot C \tag{6}$$

Appropriate potential function:

$$^t g_{MC} = {^t I_1}\cdot\sin\psi + \frac{1}{2}\cdot 3\cdot(1-\sin\psi)\cdot\sin{^t\theta} + \sqrt{3}\cdot(3+\sin\psi)\cdot\cos{^t\theta}\cdot\sqrt{^t J_2} - 3\cdot C \tag{7}$$

$$^t\theta = \frac{1}{3}\cdot\cos^{-1}\left(\frac{3\cdot\sqrt{3}\cdot {^t J_3}}{2\cdot {^t J_2^{3/2}}}\right) \tag{8}$$

φ – friction angle [°]
C – cohesion [MN/m^2]
ψ – dilatation angle [°]
$^tI_1$ – first invariant stress in time t
$^tJ_2$ – second invariant stress in time t
$^tJ_3$ – third invariant stress in time t

Nonlinear static analysis is used because of nonlinear behavior of material, kinematic assumptions and using special option like ‘birth/death’ and restart analysis.

D.Element birth and death feature

The element birth and death feature is useful for modeling processes during which material is added to and/or removed from the structure. Such processes are encountered in developing a structure, the reconstruction of a structure or during the excavation of earth materials [1,6].

Once an element is born, the element mass matrix, stiffness matrix and force vector are added to the total mass matrix, stiffness matrix and force vector. Once an element dies, the element mass matrix, stiffness matrix and force vector are removed from the total mass matrix, stiffness matrix and force vectors for all solution times larger than the time of death of the element.

The element 'birth/death' option applies to any mass effect so the mass matrix does not remain constant throughout the solution. To provide the appropriate loading of element that takes into account 'birth/death' option, you have to specify time functions on the loading that correspond to the proper elements [1].

E. Restart option

‘Restart’ is a useful feature in the ADINA System. A restart analysis is a continuation of a previous analysis, when we have to continue an analysis beyond its last end point, or when change the analysis type, loads or boundary conditions or tolerances [1,6].

The geometry and most element data cannot be changed in a restart analysis. The following changes are allowed:

- Type of analysis.
- Solution type. Implicit analysis to explicit analysis.
- Solution control variables.
- The material constants.
- Boundary conditions.
- Constraint equations and rigid element.
- Contact settings.
- Rayleigh damping coefficients.
- Time increment and number of solution steps can be modified.
- Time functions describing the load variations.

Solution of static equation was performed with Full Newton's iteration. New stiffness matrix is formed at beginning each new step and iteration.

III. Computer Simulation of Subsidence

Simulation of process development excavations can be achieved by calculating new stresses and displacements with progress of digging. For accurate analysis of subsidence it is necessary to model initial stresses [8,10,14,16,18]. Important influence on subsidence has value of Young’s modulus and Poisson’s coefficient, cohesion and friction angle. Young’s modulus has influence on value maximum of subsidence and cohesion and friction angle have influence on plasticity of surrounding materials [4,10,17,21].

Simulation is performed for condition of ‘Stara Jama’ Zenica mine – profile 200 for three variants height of room. Like primary stage in calculations is taken 1987 year, because there are data of geodetic measurements for that period. For that period is made validation of results of the estimations with measurements data [6].

A. Place of investigation

Stara Jama mine in Zenica is an example of which was conducted in calculation of settlement with the finite element method. Stara Jama mine belongs to medium-Bosnian coal basin with an area of propagation of 900 km^2 and is among the largest coal basin in Bosnia and Herzegovina. With the great depth of sediments and stratigraphic range, basin represents unique site stratigraphic-tectonic relations sediments in the interior of Dinaridi.

The analysis of available data of the Central Coal basin and functional connections (σ-H) it is possible to give an assessment of behavior, both coal seams and associated sediments from the point of primary geostatic stress state, the strength on the verge of proportionality and limit depth. From the function (σ-H) is seen to limit the depth of roof layers ranges up to about 480 m depth, which means that in case the primary balance disorders caused by excavating the lower lying coal seams, the same plunge depending on the dimensions of resulting open space. For marly limestone, which forms the immediate roof layer overlying the coal and overlying the main coal seam, considering the high value of uni-axial compressive strength limit proportionality (σ_f), limit the depth is almost three times higher, at around 1325 m in the roof layers.

Taking into account the depth of exploitation of 550-600 m geostatic primary state of stress reaches a value of σ_1=140-150 daN/cm^2 and σ_2=50-60 daN/cm^2 which is far below the strength at limit of proportionality for the marly limestone σ_f=204 daN/cm^2. This indicates fact that the immediate overlying the depth of to 50 m are potentially capable of accumulating elastic potential energy in the event of disruption of primary geostatic steady state. Practically this mean that the final subsidence directly overlying possible only if certain conditions are satisfied, relating to dimensions and surface cavities caused by the excavation occurred, as well as direct or indirect an influence of geotectonic, hydrological and other factors.

Defining the stress state around the excavation room is not so simple if we would not take into account the conditions that facilitate the solution using the mathematical theory of elasticity as follows:

- the relatively small areas (rock mass) that may be considered to be only elastic behavior,
- the work environment is not isotropic and
- the fact that the dimensions of the excavated space change in function of the time and direction of movement excavated forehead.

Regarding the influence of physical-mechanical characteristics of the working environment at the excavation and excavated pressure in Zenica mine can be say:

- Adopting the assumptions for workplace and considering that uni-axial strength of the immediate overlying is equal to threefold uni-axial strength of the coal layer at the depth of immediate roof supports of 20-50 m, depending on the depth of exploitation (200-600 m) and primary geostatic pressure (4.8 to 4.7 MN/m^2) confirm that the immediate overlying able to withstand reflected pressures (0.028 to 13.42 MN/m^2) with reaching a critical length from 43 to 81.5 m.
- An exploitable coal layer with thickness within 3-4 m unable to withstand the above reflected the pressure on forehead of the excavation so that the concentration of pressure transmitted to the depth of pillars in front of the excavation forehead for 1.5 to 11 m depth, which specifically means that the such part of the coal seam is directly influenced by excavation pressure exhibited elasto-plastic and plastic deformation.

B. Basic steps related to modeling and simulation

Steps in process of numerical modeling and computer simulations are [4,6,8,10,12,13,14,18,19,20,21]:

- Selection of characteristic profiles from situation map
- Development of geometric model for selected profiles
- Defining degrees of freedom
- Validation of idealized mesh
- Input parameters of materials
- Defining loading
- Defining time function
- Defining time steps
- Setting time of ‘death/birth’ elements
- Including ‘restart’ option in analysis with changes in material properties and load
- Defining groups of material
- Discretization of model on finite element mesh
- Performing of analysis
- Control of results
- If estimation is stopped make correction of input data
- Manual control of results (comparison results of estimation with measured in-situ data)
- Output list for all nodes of model and certain time steps
- Creation of bitmap output values for certain time steps
- End of analysis

TABLE I
GEO-MECHANICAL PROPERTIES OF MATERIALS

Type of material	γ [MN/m^3]	σ_p [MN/m^2]	τ [MN/m^2]	ν	φ [°]	E [MN/m^2]
Marl Sandy marl	0.022 0.0234	12-24 35-45.1	1.6-2.0 4.2-6.0	0.365 0.320	34 38	1200-1500 4500-6500
Marly limestone	0.025	35-57.1	9.0-11.0	0.350	30-40	7000-11500
Coal	0.0128	9-12.5	2.5-4.0	0.280	35	2000-3000
Sandy marl Marly limestone	0.022-0.0235 0.025	38-62 42.5-68.4	5.8-8.0 8.5-11.0	0.350	39 40	3000-7300 10100
Coal	12.8	9-20	2.5-4.0	0.280	30-40	2000-4000
Limestone-clay marl	25	40.9-51.2	7.0-10.0	0.350	34	1000-1200

C. Modeling option

First class of boundary conditions is used for 2D modeling and nonlinear elastic-plastic analysis with active z displacements on side of the model and complete fixed elements on the base of model. On the model is applied mass proportional type of loading [6,13,18,20].

Mohr-Coulomb yield criterion has been applied to predict the subsidence profile in performing the modeling. The model is linearly elastic until has satisfied the Coulomb yield criterion [3,9,16]. It was made 25 steps of time. Time steps were set in the relation to the time function so that it follows a linear load changes with the time progression of excavation and time filling of chamber with natural earth materials from roof in the previously excavated area. Each time step implies excavation of a certain height and length of the coal layer and then plugging with fill from the roof supports.

Time step 10 presents excavated a total length of the coal seam thick of 4 m, and it was backfilled with the roof material. The time step 18 presents excavated the overall tick of 9 m coal seam and the amount of old chamber was backfilled with the excavated overburden material.

Finally, with 25 steps was simulated excavation of the entire coal seam thickness of 14 m and a total length of 652 m. The changes in stress-deformation state is remembered by every subsequent iterative step and change the properties of the overlying and surrounding material due to the falling is defining with the restart option [2,3,6,9,10,11,14,16,17,18].

There are 13 geo-technical Mohr-Coulomb’s types of materials and 13 types groups of 2D solid elements [1,6]. Model has 2214 nodes and 2136 elements.

Some authors recommended that in order to eliminate the boundary effects, size of the model must be on both sides at least five times bigger than the half-width of the panel away from the centre-line of the panel, and five times bigger than the thickness seam coal below the seam floor [4,7,10,12,14,17,18,19,20,21].

IV. RESULTS OF ESTIMATIONS

Length of physical system is 4564 m, high is 790 m, length coal seam is 652 m, mined-out and abandoned working area which is closed up with collapsing the roof is 276 m (Fig. 1).

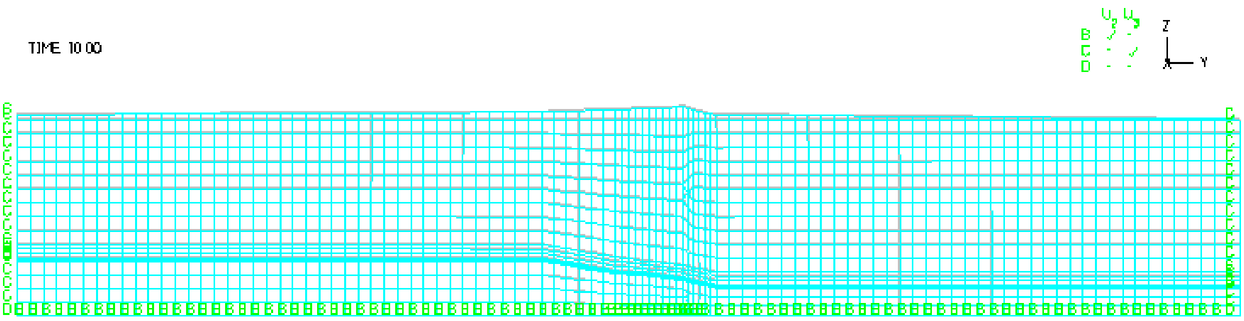

Fig. 1 2D finite element model for profile 200

Excavation of 367 m of coal seam was simulated on the next way: first layer with 4 m of tick and than next layers by 5 m tick. With 25 steps of time is defined time of 'death' and 'birth' of surfaces. Collapse of materials from the roof is defined by 'birth' new surface (elements) and excavation is simulated using 'death' options. Changing of properties materials and values of load is made with 'restart' option during process of calculation.

Results of performed restart analysis for profile 200 are presented on figure 2, 3, 4, 5, 6 and 7. Time 10 is time with digging up 4 m tick seam of the coal, 18 with 9 m tick seam of coal and 25 with excavated 14 m tick coal seam.

Fig. 2 and Fig. 3 show values of displacement for time 10. Distribution of displacements and plastic zones are presented on Fig. 4 and 5 for time step 18 with excavated 9 m tick of coal seam.

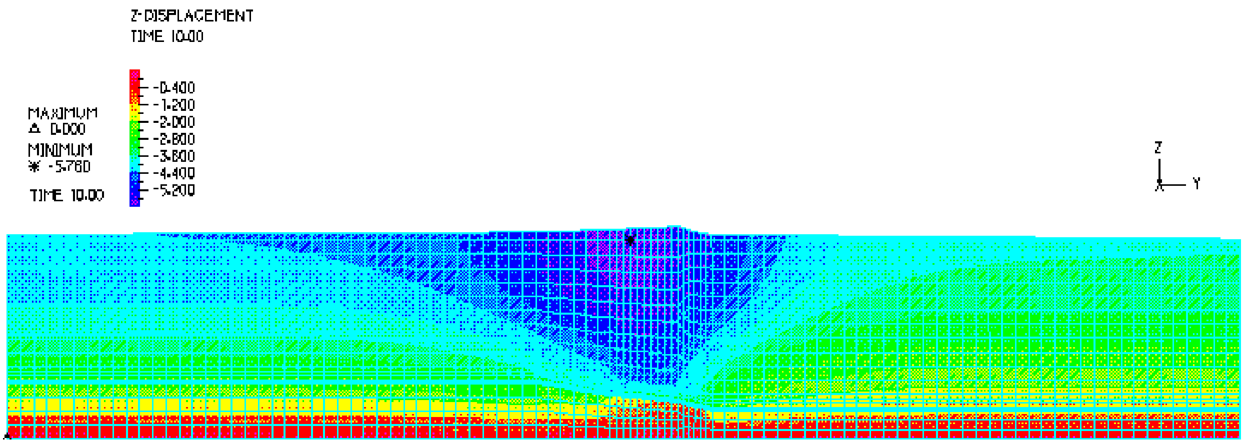

Fig. 2 Distribution of displacements for the profile 200 in step 10

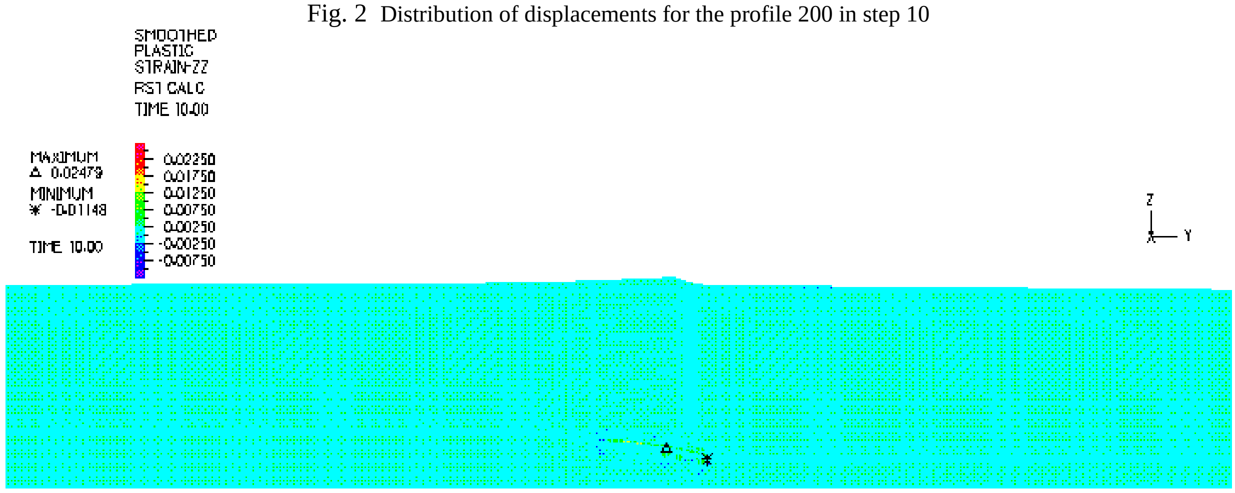

Fig. 3 Distribution of plastic zone for the profile 200 in step 10

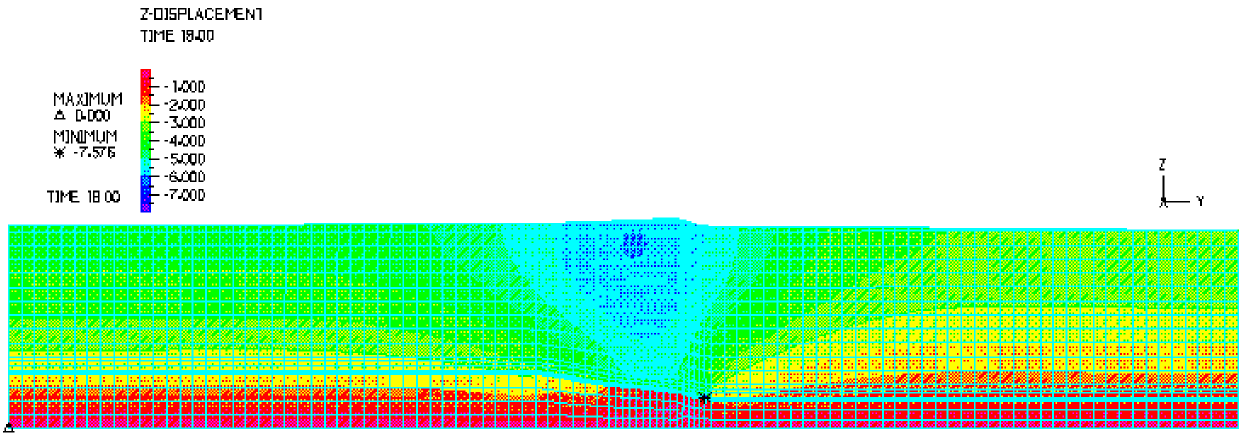

Fig. 4 Distribution of displacements for the profile 200 in step 18

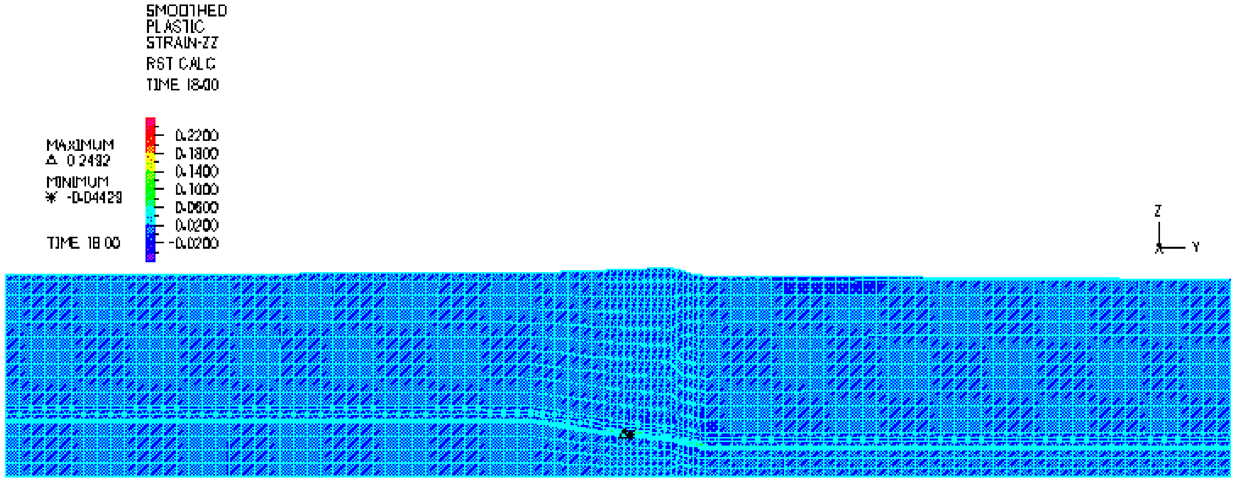

Fig. 5 Distribution of plastic zone for the profile 200 in step 18

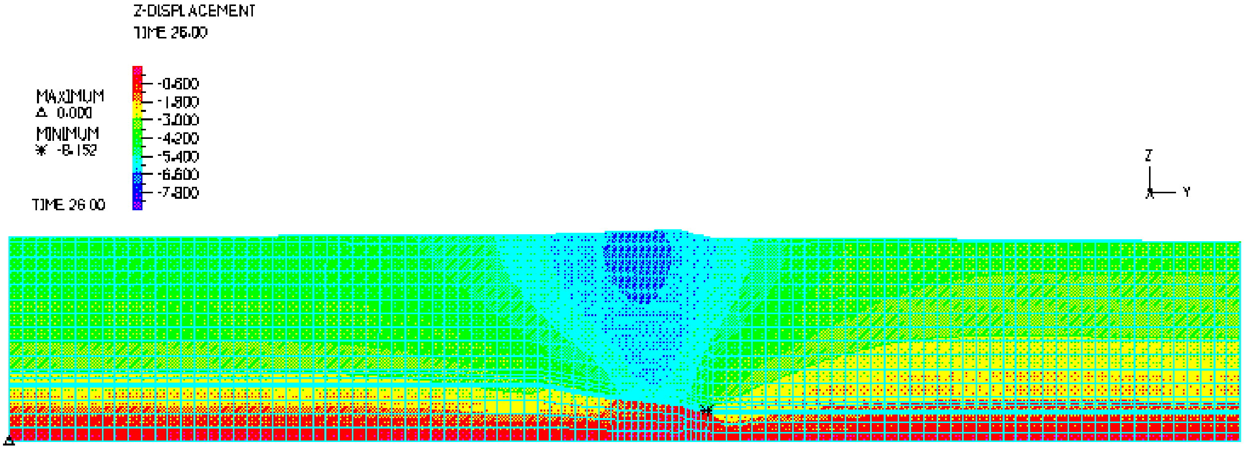

Fig. 6 Distribution of displacements for the profile 200 in step 25

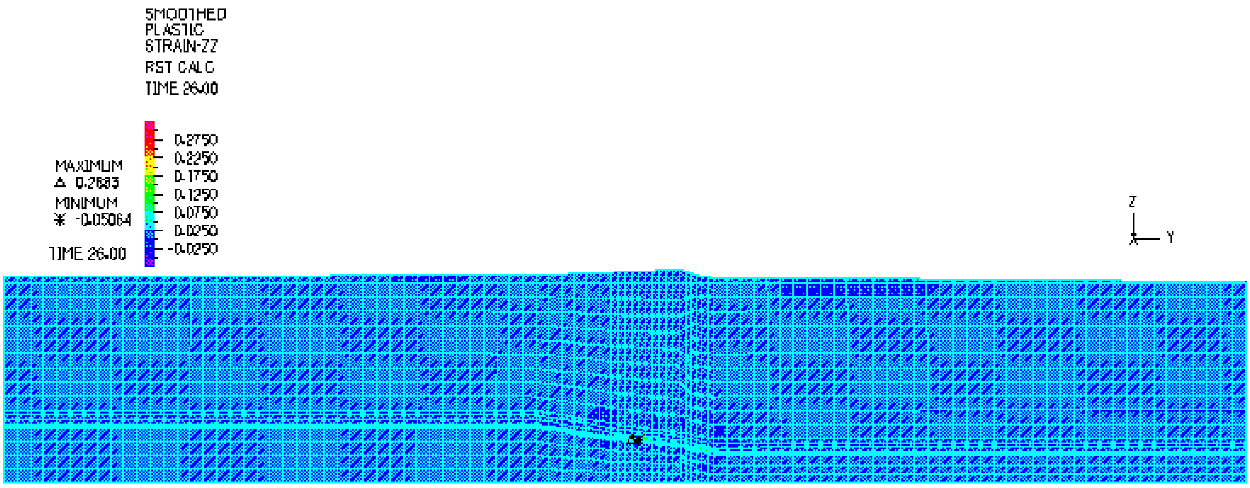

Fig. 7 Distribution of plastic zone for the profile 200 in step 25

V. Discussion of Results Estimations

Maximal value of vertical displacement on the surface is of -1.25 m in the case of simulation subsidence for profile 200 with excavated 4 m tick of coal seam. (Note: The simulations were performed with initial stresses and displacements what can be seen on figures.) Values of displacement are significant in elements of long wall roof. Taking into consideration that real environment is rock mass with macro and micro cracks this is fact that there is a seriously possibility of falling roof. Displacements of floor indicate that come to swelling due to distribution of stress-strain conditions. Plasticity of elements around excavation and in the roof is indicating capability breaks of rock mass. Irregular arch is formed and plasticity elements on surface are obvious. Maximal value tangential stress (5.08 MN/m^2) is in a corner of finished excavation, what presents critical point. Tension stress has maximal value 53.6 MN/m^2.

Maximal sinking of the surface obtained in-situ measurements was 1.344 m when is accomplished excavation 4 m tick of coal seam and it is reading in point that is concur with point on simulation model.

Maximal subsidence at surface is of -1.5 m in the case of excavating a 9 m coal seam which is positioned at the end of the last excavated part. Plasticity of elements has the lager values than in time step 10, so it is possible to make appear more significant cracks and caves in the roof of underground room. At the surface cracks and cascade trough can be formed. Tangential stress has maximal value 5.46 MN/m^2 and tension stress has 31.88 MN/m^2.

At last, in circumstance for 14 m excavated coal seam maximal displacement of surface is of -2.2 m. Finite element mesh is extremely deformed. Tangential stress has maximal value 6.08 MN/m^2 and tension stress has 35.13 MN/m^2. All values of surface displacements on profile 200 are presented on Fig. 8.

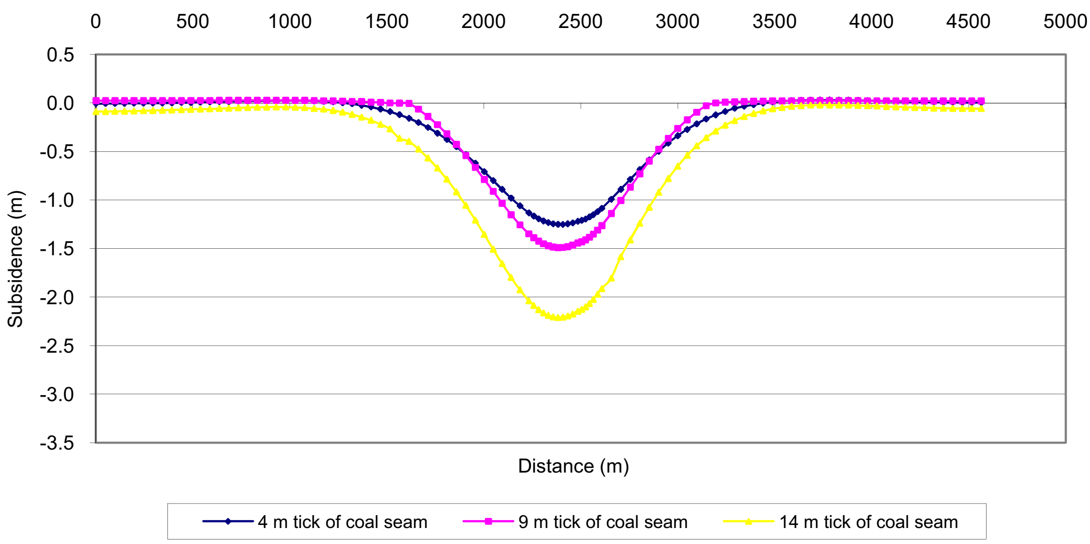

Fig. 8 Diagram of subsidence for profile 200

Obtained results differ from measured data for 7%. Comparative analysis is made only for situation excavation of 4 m tick of coal seam. Observed deviations can be explained trough following facts: irregularity of initial in-situ measurements, inaccurate input of geo-mechanical data, unknown dynamic of excavation and collapsed of masses, time of consolidation etc. All these factors are associated with uncertainties discussed in Chapter II. Future research foresees two phases, which include simulations and predications of ground movements for 9 and 14 m thick coal seams. Considering these results which are compared with measured data, it can be concluded that the model is accurate and well calibrated and can be applied for the simulation in different conditions, i.e. for other mines, and it can get its generally reusability.

The emphasis of this work was on predicting the shape of the normalized profile of subsidence. The nonlinear model predict much closer to the field subsidence profile. In order to match the predicted maximum subsidence with the field value, the elastic modulus of the region under yield state needs to be reduced by factor 1/10.

VI. Conclusion

This paper presents a wide potentiality numerical modeling and simulation system on example of subsidence. Simulation of surface subsidence above underground mine is performed with software ADINA based on the finite element method. Geometry model is associated with geological, geo-mechanical and technological characteristics of the system. Obtained results of estimation are compared with measured data in certain points of the profile. After that, correction complexity of model and reduction of input parameters was performed. The accuracy of 7% is very good, and as such, this model may be used in future prediction with regard to surface behavior. Two-dimensional analysis process of subsidence terrain above the underground mine has showed only part of wide possibility modeling and simulation with the computer. Crucial parameters are correct input data, correct create model and selected type of analysis as well as adequate used all options of the software ADINA.

Future research in this field would be related to the possibility of elasto-plastic and visco-plastic 3D analysis. To do would been necessary additional in-situ and laboratory investigations the characteristics of materials (geo-mechanical and geo-physical).

Of course this includes the introduction of new options that provide the software for the simulation. Progress can be reflected through the reduction of uncertainty of input data (their in-situ investigations, laboratory tests, processing the obtained this way data), modeling (properly chosen constitutive model, the type of analysis, numerical methods, i.e., changing the load with time functions and time steps, etc.), simulation (2D or 3D simulations with predefined elements, the type and number of integration points, the inclusion of additional options for the simulation), interpretation (sufficient training of engineers for the analysis of these results).

Finite element method and computer simulation is powerful tool that helps the management of mining companies and engineers to make reasonable decision and steps towards improving the quality of work and safety all employees as well as complete environment in the zone of subsidence. It is possible to predict behavior of the rock as well as soil masses during excavation process of coal and to make the relevant decisions in process of organization of technology work.

References

[1] *ADINA- Theory and Modelling Guide*. ADINA R&D. Inc, 2000
[2] Friedel Hartmann and Casimir Katz, *Structural Analysis with Finite Elements.* Springer-Verlag Berlin, Heidelberg, 2007
[3] D.T. Nguyen, *Finite Element methods: Parallel-sprase static and eigen-solutions.* Springer Science+Business Media, Inc., New York, 2006
[4] M.J. DeMarco, *Numerical modelling simulation of old works stability: new technologies and practical considerations*. Central federal lands highway division – FHWA Lakewood. CO, www.fhwa.dot.gov/mine/demarco.htm
[5] H. Kratzsch, *Mining Subsidence Engineering.* Springer-Verlag, Berlin, 1983
[6] A. Nuric, *Numeričko modelovanje i kompjuterska simulacija procesa slijeganja terena.* doctoral thesis, Faculty of Mining, Geology and Civil Engineering, Tuzla, 2004
[7] S.S. Peng, *Surface Subsidence Engineering*. Society for Mining, Metallurgy and Exploration, Inc., Littleton, Colorado, 1992
[8] J.R. Sturgul, Z. Li, *New developments in simulation technology and applications in the minerals industry*. International Journal of Surface Mining, Reclamation and Environment 11, A.A. Balkema, Rotterdam, pp. 159-16, 1999
[9] O.C. Zienkiewich, R.L. Taylor, *The Finite Element Method Fifth edition Volume 1: The Basis.* Butterworth-Heinemann, Oxford, 2000
[10] N.E. Yasitli and B. Unver, *3-D numerical modelling of stresses around a longwall panel with top coal caving.* The Journal of The South African Institute of Mining and Metallurgy Vol. 105, pp. 287-300, 2005
[11] G. Gambolati, M. Ferronato, P. Teatini, R. Deidda, G. Lecca, *Finite element analysis of land subsidence above depleted reservoirs with pore pressure gradient and total stress formulations*, International journal for numerical and analytical methods in geomechanics, John Wiley & Sons Ltd., 2001
[12] J. Trcková, *Experimental 3-D modelling of surface subsidence affected by underground mining activities.* The Journal of The Southern African Institute of Mining and Metallurgy volume 109, pp. 739-744, 2009
[13] N.E.Yaşıth, B.Ünver, M.M.Ceyhan, *Investigation of Rib Pillar Stability at Ömerler Underground Mine by Numerical Modelling*. The 19th International Mining Conferes and Fair of Turkey, IMCET2005, Izmir, Turkey, pp. 153-159, 2005
[14] A. P. E. Dirige, J. F. Archibald, *Numerical modeling simulations of spray-on liners support potential in highly stressed and rockburst prone rock conditions.* ROCKENG09: Proceedings of the 3rd CANUS Rock Mechanics Symposium, Toronto, 2009
[15] N. Sivakugan, R.M. Rankine, K.J. Rankine, K.S. Rankine, *Geotechnical considerations in mine backfilling in Australia*. Journal of Cleaner Production 14, Elsevier Ltd., pp. 1168-1175, 2005, www.elsevier.com/locate/jclepro
[16] V. R. Sastry and R. Nair, *Analysis of stress distribution in longwall barrier: a case study*. International Journal of Mining and Mineral Engineering, Vol. 2, No. 1, Inderscience Enterprises Ltd., 2010
[17] Z. Li, L. Xi-liang, W. Lai, *Finite element numerical simulation of ground subsidence in Liangjia colliery*. Transactions of Tianjin University Vol.8 No. 3, pp. 200-202, 2002
[18] G.M. Swift, D.J. Reddish, P.W. Lloyd, R.K. Dunham, *Numerical modelling of time-dependent deformation around an underground mine in rock salt.* Transactions of the Institution of Mining and Metallurgy Section A: Mining Technology, 110 (2), pp. 107-113, 2001, http://www.ingentaconnect.com/content/maney/mint/2... Modified: 27 Sep 2011 12:30
[19] M. J. DeMarco, *Numerical Modeling Simulation of Old Works Stability New Technologies and Practical Considerations*. Interstate Technical Group on Abandoned Underground Mines Fourth Biennial Abandoned Underground Mine Workshop, Updated: 04/07/2011

[20] R.Goodfellow, H. S. Mitri, N. Bedard, E. Lecomte, *3-Dimensional Numerical Modelling of Stope Sequencing For Mine Planning*. 43rd U.S. Rock Mechanics Symposium & 4th U.S. - Canada Rock Mechanics Symposium, 2009, Asheville, North Carolina, 2009 American Rock Mechanics Association, www.onepetro.org/mslib/servlet

[21] T. Belem and M. Benzaazoua, *Design and Application of Underground Mine Paste Backfill Technology*. Geotechnical and Geological Engineering , Vol. 26, No. 2, 147-174, DOI: 10.1007/s10706-007-9154-3

[22] R. P. Singh, R. N. Yadav, *Subsidence due to coal mining in India*. Land Subsidence, Proceedings of the Fifth International Symposium on Land Subsidence, The HagueIAHS Publ. no. 234, 1995

[23] M.A. Coulthard, *Applications of numerical modelling in underground mining and construction*. Geotechnical and Geological Engineering Volume 17, Numbers 3-4, 373-385, DOI: 10.1023/A:1008951216602

[24] Kumamoto, H., (2007), *Satisfying Safety Goals by Probabilistic Risk Assessment,* Springer Series in Reliability Engineering. Springer-Verlag London Limited.

[25] U.S. NRC, (2009), *NUREG-1855, vol. 1, Guidance on the Treatment of Uncertainties Associated with PRAs in Risk-Informed Decision Making*, Washington D.C.

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