GROUND SURFACE DEFORMATION USING THE FINITE ELEMENT METHOD, IN CONDITIONS OF THE LONGWALL MINING OF THE COAL LAYER NO. 3 - LIVEZENI MINE

Ilie ONICA, Eugen COZMA*, Dacian Paul MARIAN***

The Livezeni Mine is situated in eastern part of the Jiu Valley coal basin (Romania) and produces about 0.5 million tons of hard coal (presently, in totality from coal layers no.3). In the case of this thick and gentle coal layer, the mining methods are by use of the longwall mining technologies with roof control by rocks caving. In this paper, it is presented the analysis of the complex deformations of ground surface, as a consequence of superposed effect of three mining panels. Also, it is analysed the ground surface subsidence phenomenon using the 2D finite element method. The modelling is made in the elasticity and the elasto-plasticity behaviour hypothesis. The obtained results are compared with the in situ measurements data basis.
Keywords: subsidence, horizontal displacement, stress, finite elements.

Generalities

The Petroşani Hard Coal Basin, under the management of the Hard Coal Company of Petroşani, contains the most important hard coal deposit of Romania, with a balance reserve about on billion tons of coal. This coal deposit was known and mined since the year 1788, as far back as the Austro-Hungarian Empire [1]. But, the intensive coal mining of this deposit began in the same time with the Romania's industrialisation, after the Second World War, reaching after 1980 the over 9-10 millions tons of coal per year [1].
Due to Romanian industry reorganisation, after the year 1990, in conformity with the new demands of the market economy, the coal production of this basin was reduced to about 3.5 millions of tons per year, from which 0.5 million are obtained from the Livezeni mining field. From the beginning this coal deposit was split into 16 mining fields, from which following several successive reorganisation and closing stages, only 7 mining fields are left in activity.

The complicated deposit tectonics determines the delimitation in geological blocks of reduced extent (most of them varying between 200 and 300 m) and an equally technical difficulty in mining. Moreover, there occurs a methane gas emission (of over 10 to 15 methane m^3/coal ton) and there is a marked tendency of coal self-ignition [1], [2].

In this mining perimeter, through the geological research works, there was identified a number of 18 coal layers, of which the most economical importance having the coal layer no.3 (48%) and coal layer no.5 (12%). The sedimentary rocks complex, in which these coal layers are present, consists in rocks deposits which belong to Superior Cretaceous, Neocene and the Quaternary [12].

The subject of this study consists in the underground mining influence analysis on the ground surface of three adjacent mining panels (panel (3-4), panel 5 and panel 6), situated on the coal layer no.3, block VI A. Coal layer no.3, for these panels, was mined in inclined slices (about 2.5m thickness) with the longwall mining system, complexly-mechanized (powered support SMA-P2H, shearer 2K52-MY and armoured conveyer TR-7) and roof control by caving [2].

The underground excavations sizes results from the coal mining corresponding of these panels are presented into Table 1.

***Table 1** The average sizes of the mining panel of the coal layer no.3, block VI A*

Panel	Slices number	Mined total thickness (m)	Longwall face length (m)	Panel extent (m)
Panel (3-4)	4	10	119	346
Panel 5	5	12.5	87	440
Panel 6	1	2.5	137	362

**Prof. eng. Ph.D University of Petrosani*
*** Eng. Ph.D student University of Petrosani*

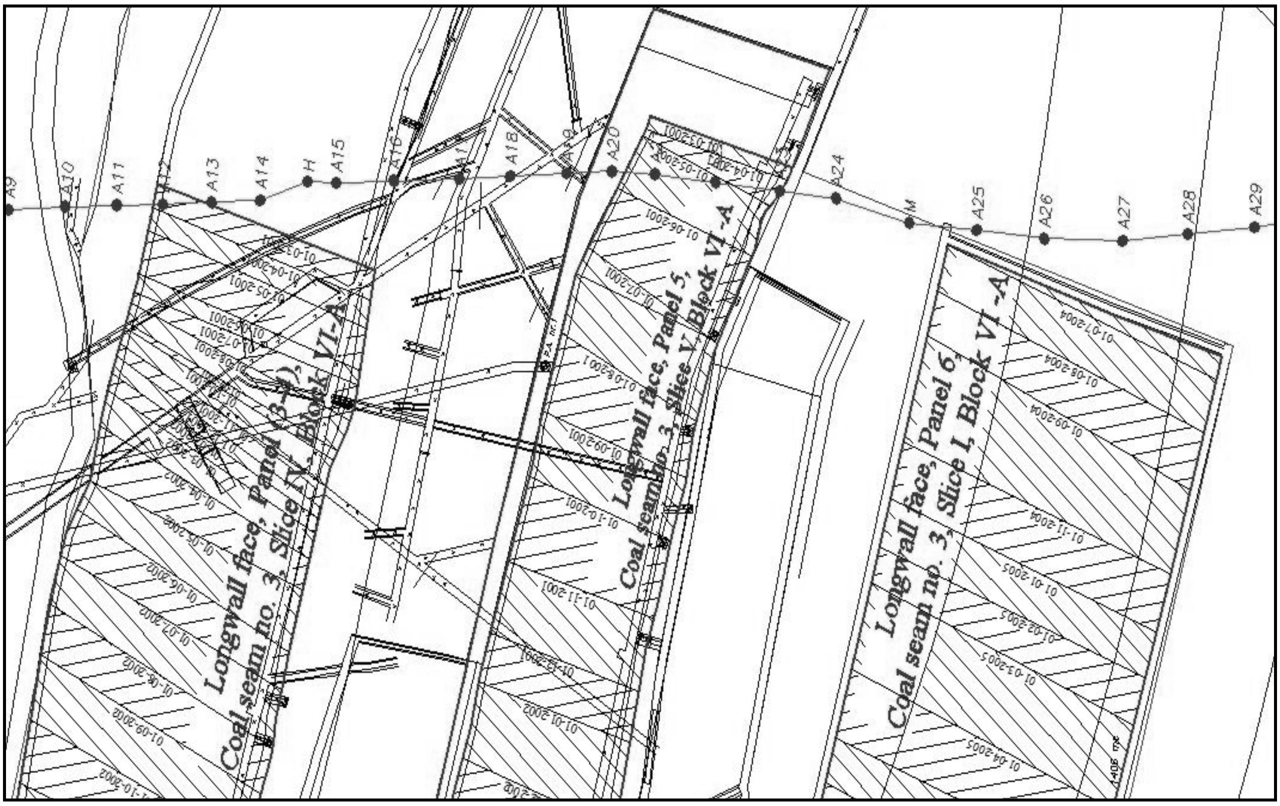


Figure 1 *The monitoring station of ground displacement and deformation of Livezeni Mine*

Geo-mechanical characterization

As the deposit genesis is sedimentary, the most frequent rocks in the basin are: limestones, marls, argillaceous or marly sandstones, conglomerates, etc., their strength ranging between 15–16 MPa up 50–60 MPa, sometimes even more. Mainly, they are rocks of relatively low stability [8]

The main factors that contribute at the definition of the stress and strain state surrounding the excavations generated by the coal layers mining with the roof rocks caving, in the Jiu Valley coal basin, are the following: the excavation sizes, the layer dip, the coal and surrounding geo-mechanics characteristics, the mining depth, the face supports characteristics, the face advancement speed, the distance from the adjacent panels, the distance from nearby coal layers, etc [4], [8].

The average values of the main mechanical and elastic characteristics of the rocks used in the ground surface deformation analysis, in the Livezeni Mine conditions, are shown in the Table 2 [3], [11].

Table 2 *The average values of the geo-mechanical characteristics of the roof and floor rocks of the coal layer no.3 [3], [11].*

Rocks characteristics	UM	Rocks		Coal layer no.3
		roof	floor	
Apparent specific weight, γ_a	kN/m^3	26.63	27.01	14.5
Module of elasticity, *E*	kN/m^2	5 035 000	5 268 000	1 035 000
Poisson ratio, ν	-	0,19	0,20	0,13
Compressive strength, σ_c	kN/m^2	43 500	46 000	12 500
Tensile strength, σ_t	kN/m^2	4 600	4 950	1 000
Cohesion , *C*	kN/m^2	6 130	6 630	1 300
Internal friction angle, φ	^{o}	55	56	50

As a result of the measurement analysis made on the ground surface under the underground mining influence, so as to find the optimum design parameters of the main safety pillars, the limit angles of subsidence have been set for the different coal mining fields of the Jiu Valley coal basin [9].

The values of the limit angles of influence (β, γ and δ), depending on the mining depth H (m), for the Livezeni mining field, in conformity with the instructions elaborated by the ICPMC Petroşani are expressed by the following relations:

$$\beta = 0{,}0309 \cdot H + 56{,}8;$$

$$\gamma = 0{,}0261 \cdot H + 56{,}133;$$

$$\delta = 0{,}146 \cdot H + 51{,}867$$

Also, in the same conditions, the average failure angles, recommended by ICPMC are the following:

$$\beta_{rupere} = 45 \div 55^o;$$

$$\gamma_{rupere} = 55 \div 60^o;$$

$$\delta_{rupere} = 75^o$$ [9].

Ground surface deformation monitoring

Now, the monitoring of the ground surface deformation parameters under the underground mining influence at the Livezeni Mine is made using a monitoring (surveying) station that consists in 50 benchmarks. The benchmarks' emplacement is along the access road toward the Parâng Mountains tourist area [10]. The topographical measurements were made every three months, beginning with the year 2001. This monitoring station provides data concerning the ground subsidence area affected by the mining of the coal layer no.3, block IV A, panel (3-4), 5 and 6. Taking into account the values of the measured parameters, with the aid of the known calculus relations, there were determined the main parameters of the subsidence basin, namely: subsidence or vertical displacement, horizontal displacement, horizontal strain and the slope [5], [6].

The subsidence basin from the Figure 2 is a composed basin, resulted from the superposition influence of the three panels. This subsidence basin has an irregular shape due the fact that the three individual basin are intersected, and also because the monitoring station is situated toward the mining boundaries of the panels (Fig.1), area where the transversal deviations are maximum.

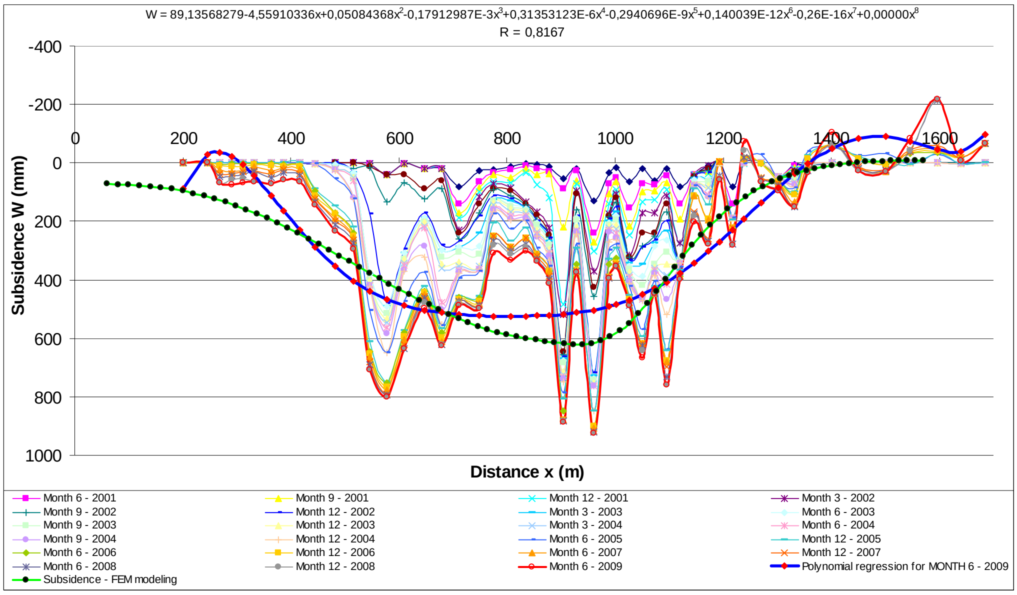


***Figure 2** The subsidence profiles at the Livezeni Mine*

In this case, the accuracy of the values that characterise the obtained subsidence basin is lower because the fact that, it is not only the result of the ground subsidence but also the result of the displacement of it, and the deviations were corrected in conformity with the following methodology. Even if the transversal deviations that act on this subsidence profile are approximately equal in all the points situated inside the goaf, the difference level between every point benchmark at the base measurement and the their level at the final measurement is not the same, because the ground surface elevation mark is different (Fig. 3).

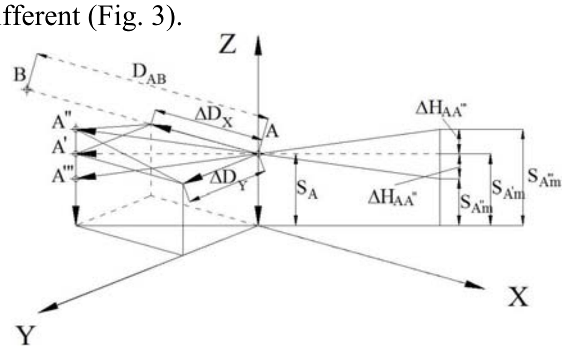


***Figure 3** The displacement and the subsidence of a point A*

In these conditions, we are considering the points A and B that belong to a displacement and subsidence monitoring profile and the following parameters are defined: D_{AB} –distance between the points A and B; ΔD_X – displacement following the X axis (horizontal displacement); ΔD_Y – displacement following the Y axis (transversal deviation); S_A – displacement following the Z axis (real subsidence of the point A); $S_{A`m}$ – the measured subsidence in the point A\`. $S_{A``m}$ – the measured subsidence in the point A\`\` ; $S_{A```m}$ – the measured subsidence in the point A\`\`\`;$\Delta H_{AA``}$ - initial level difference between the point A and the point A\`\`; $\Delta H_{AA```}$ - initial level difference between the point A and the point A\`\`\`.

Because the displacement is under few meters we can consider that the subsidence in the point A is equal to the subsidence in the point where that was displaced (the points A\`, A\`\`, A\`\`\`), that is $S_A = S_{A`} = S_{A``} = S_{A```}$.

The subsidence and the vertical displacements, previous mentioned, are calculated with the relation: $W_i = H^*_i - H_i$ (mm) (where: H^*_i is the level of the point "i" at the zero measurement; H_i – the level of the point "i" measured at a given moment).

Analysing the in situ measurements situation, we can conclude that, taking into account the ground surface subsidence and displacements there are three cases of the correction determination of the measured values, namely:

1) Case when the point A, with the level H_A, is displaced in the point A\`, having the initial level equal to the level of the point A. In this case, there is no correction because the ground slope is zero, and by consequence, the measured subsidence is equal to the real subsidence ($S_A = S_{A`m}$);

2) When the point A, having the level H_A, is displaced in the point A\`\`, having the level $H_{A``} > H_A$ . In this case the measured subsidence is less then the real subsidence ($S_{A``m} < S_A$) and, as a consequence, must be applied a correction equal to the initial difference level between the point A and the point A\`\` ($\Delta H_{AA``}$), namely: $S_A = S_{A``m} + H_{AA``}$;

3) When the point A, having the level H_A, is displaced in the point A\`\`\`, having the level $H_{A```} < H_A$, the measured subsidence is greater than the real subsidence ($S_{A```m} > S_A$) and, as a consequence, must be applied a correction equal to the initial difference level between the point A and the point A\`\`\` ($\Delta H_{AA```}$), namely: $S_A = S_{A```m} - \Delta H_{AA```}$.

These adjustments of the measured values are necessary only in the case when the horizontal displacement and (or) the transversal deviation are significant and when the ground surface is inclined.

In the case of this monitoring (surveying) station, the maximum measured subsidence is of W_{max} = 924mm and the horizontal displacement ranges between the value of U = + 3712mm and U = - 3625mm. The average of maximum subsidence is W_{max} = 524mm (the reference value in the case of numerical modelling).

Numerical modelling of the subsidence phenomenon

Models description

To build the 2D finite element calculus models the CESAR-LCPC finite element code was used. The CESAR software, development of which began in 1981, is the successor of the ROSALIE system developed by the Central Laboratory of Bridges and Roads of Paris, between 1963 and 1983. CESAR is a computational general code, based on the finite element method, addressed to the following areas: structures; soils and rocks mechanics; thermo-mechanics; hydrogeology. The CESAR-LCPC code, version 4, which involves the Cleo2D processor, completed with the C0 option (linear and non-linear static mechanics & diffusion) was used in this work, to perform the following models.

To determine the displacement and the ground surface deformation in the case of Livezeni Mine, where the ground is affected by the three panels, there were made two different models, in the plane strain hypothesis, namely: 1) the model "with mining voids" resulted as a consequence of underground coal mining; 2) the model "with caved zones" (on a height equal to eight times the mined height), due the roof rocks caving in the goaf (Figure 4).

The calculus for these two models was performed in two hypotheses: a) in the elastic behaviour of the rock massive and b) in the Mohr-Coulomb elasto-plastic without hardening behaviour. In view of finding the influence degree of every panel on the entire subsidence basin, generated by mining all of these three panels, maintaining the geo-mechanical conditions constant, there were made certain models where the coal layer mining was simulated with every independent panel.

In all of the modelling cases, both rocks and coal layer no.3 were supposed to be continuous, homogenous and isotropic and the geo-mechanical characteristics taken into the calculus having the average values (Tab.2).

The natural state of stresses was estimated being geostatic, characterized by the vertical stress $\sigma_v = \gamma \cdot H$ and horizontal stress $\sigma_h = \frac{\nu}{1-\nu} \cdot \sigma_v$ (because of the lack of the real values in situ measured).

To fit on the models in function of the measured values of the maximum vertical displacements and to correct the rocks and coal characteristics in laboratory obtained (Tab.2) toward the in situ values, the calculus of the models was made successively using the values reduced by 0%, 30%, 50% and 70% (respectively multiplied with a reducing coefficient K = 1; 0.7; 0.5; 0.3 - structural weakness coefficient). Because the numerical models were significantly sensitive only to the modulus of elasticity variation, only the reduction of this parameter was taken into analysis.

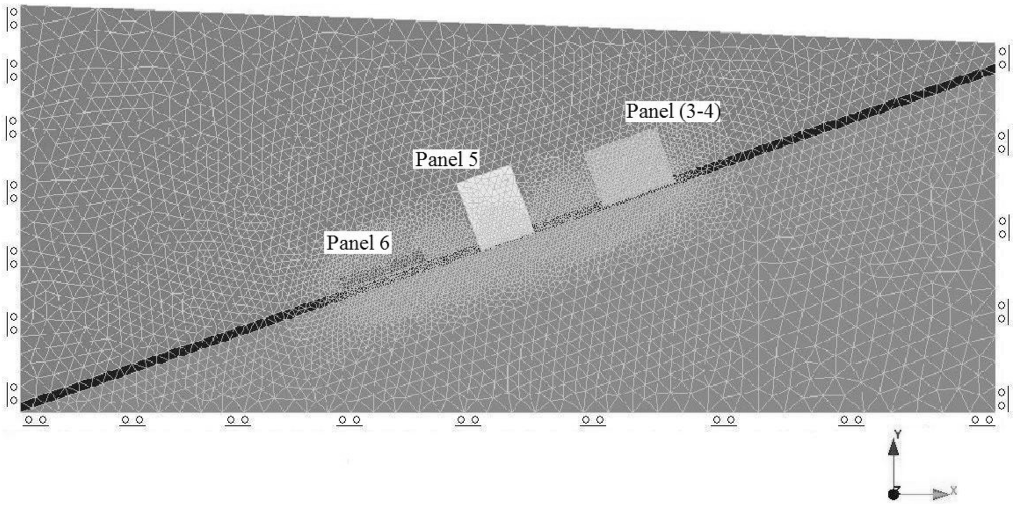


Figure 4 *The finite element model "with caved zones"*

Modelling achievement

2D modelling achievement, in the plane strain hypothesis, for every previous defined model the following steps were necessary: a) establishment of boundaries, interest zones and meshing of the model; b) determination of zones (regions) and computational hypothesis and the geo-mechanical characteristics input; c) boundaries conditions establishment; d) initial conditions and loading conditions establishment; e) achievement of calculus and stoking of results [5].

Establishment of boundaries, interest zones and meshing of the model

For a better precision of the calculus, the models were performed with sizes X=1500m and Y = 690m. Also, the sizes of the interest zone around underground excavations were established so as to involve the model surface where the stress and strain variation is maximum. Model meshing, respectively of every region, was made by triangle finite elements with quadratic interpolation. Respectively, the model meshing was performed with a total number of nodes of 23448 and surface elements of 11661.

Determination of regions and computational hypothesis and the geo-mechanical characteristics input

In order to make a qualitative description of the models, there were taken into consideration 3 regions with various geo-mechanical characteristics, in the case of the models "with mining voids", respectively 4 regions in the case of the models "with caved zones", adequate at the roof and floor rocks, coal layer and the caved rocks of the goaf.

The rocks characteristics, considered to be homogenous and isotropic, are presented in Table 2, and taken in the calculus in the elastic behavior hypothesis, respectively elasto- plastically without hardening behavior Mohr-Coulomb hypothesis, were reduced successively, taking into account the structural weakness coefficient.

The caved rocks of the goaf was considered being a very compressible elastic body, characterized by the elasticity modulus of 5000kN/m^2, Poisson ratio of 0.4 and specific density of 1800kg/m^3.

Boundaries conditions establishment

The superior side of the model is considered free and the lateral sides, blocked (for the inferior side the vertical displacements v = 0 and the horizontals $u \neq 0$ and for the lateral sides $v \neq 0$ şi u = 0).

Initial conditions and loading conditions establishment

Initial loading conditions of the model were considered as geostatic $[\sigma_o]$, corresponding to an average mining depth of H=337m, namely: the vertical geostatic stresses $\sigma_{oy} = \rho_s \cdot g \cdot H = 87819$ kN/m^2=87.8MPa and the horizontal geostatic stresses $\sigma_{ox} = \frac{\nu}{1-\nu} \cdot \sigma_{oy} = k_o \cdot \sigma_{oy} =$ 21076kN/m^2=21.076MPa (where: $k_o = \frac{\nu}{1-\nu} = 0.24$). The induced stress by the excavation presence was $[\sigma_e]$, respectively the stresses variation represented by the horizontal stress σ_{ex} = -21.076MPa and the vertical stress σ_{ey} =-87.8MPa. Thus, the loading of the model was performed in the total stresses: $[\sigma_T] = [\sigma_o] - [\sigma_e]$ [5].

Achievement of calculus and stoking of results

The calculus was made taking 60 iterations per increment and a tolerance of 1% of the results, using for the resolution the initial stress method with non-linear behaviour of geo-mechanical problem. The calculus results were stocked in the graphical form on the model surface (isovalue, vector and tensor representation) and in the predefined sections following the ground surface. The results obtained are corresponding to the subsidence W (mm) and horizontal displacement U (mm).

Analysis of the numerical modeling results

Analyzing the obtained results from the numerical modeling it is observed that the surface basin has a simple shape, different by report to the real basin, because of their emplacement toward the goaf boundaries. In contrary, in the case of FEM modeling, the profile is situated in the middle part of the subsidence basin.

The maximum subsidence and displacements values obtained from the numerical modeling, in elasticity and elasto- plasticity, previous presented, are shown in Table 3.

Table 3 *Maximum subsidence and displacements obtained from the numerical modelling for individual mining panel and for grouped mining panels*

ELASTICITY - Models “with mining voids”												
Coef.	Panel 6			Panel 5			Panel (3-4)			Panel (3-4) +5+6		
	W	U		W	U		W	U		W	U	
	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
K=1	132	39	-39	66	24	-19	110	41	-28	237	78	-71
K=0,7	189	56	-56	95	34	-27	157	58	-40	339	111	-101
K=0,5	264	78	-79	133	48	-37	219	82	-55	474	156	-142
K=0,3	440	130	-131	222	80	-62	365	136	-92	790	260	-237
ELASTO - PLASTICITY - Models “with mining voids”												
Coef.	Panel 6			Panel 5			Panel (3-4)			Panel (3-4) +5+6		
	W	U		W	U		W	U		W	U	
	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
K=1	134	40	-40	68	24	-19	110	41	-28	241	79	-72
K=0,7	192	57	-57	97	35	-27	157	58	-40	344	113	-103
K=0,5	269	80	-80	135	48	-38	220	82	-56	482	158	-144
K=0,3	448	133	-133	225	81	-63	367	136	-93	803	264	-240
ELASTICITY - Models “with caved zones”												
Coef.	Panel 6			Panel 5			Panel (3-4)			Panel (3-4) +5+6		
	W	U		W	U		W	U		W	U	
	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
K=1	133	39	-40	103	25	-41	146	42	-47	306	66	-120
K=0,7	184	53	-56	147	36	-57	207	59	-66	430	92	-169
K=0,5	248	72	-76	203	50	-80	286	82	-91	590	125	-231
K=0,3	380	110	-117	332	81	-129	463	132	-147	942	193	-370

ELASTO - PLASTICITY - Models "with caved zones"												
Coef.	Panel 6			Panel 5			Panel (3-4)			Panel (3-4) +5+6		
	W	*U*		*W*	*U*		*W*	*U*		*W*	*U*	
	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.	Max.	Max.	Min.
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
K=1	129	38	-39	103	25	-41	146	42	-47	307	67	-120
K=0,7	177	52	-53	147	36	-57	207	59	-66	431	93	-169
K=0,5	237	69	-72	203	50	-80	286	82	-91	592	125	-232
K=0,3	360	105	-110	332	81	-129	463	132	-147	943	193	-370

From the previous table it could be observed that, there are very small differences between the models computed in elasticity and the same ones in elasto-plasticity behaviour (the rocks having behaviour to the limits between these). The results more appropriate to the in situ measurement are for the "caved zones" models, in elasto-plasticity behaviour, for a structural weakness coefficient of $K = 0.5$.

In Figure 5 are represented the subsidence basins obtained for the models "with caved zones", in elasto-plasticity (for K=0.5), as result of three panels mining, as well as the subsidence basin generated by the every singular panel and various combinations between them, and the horizontal displacements curves are shown in Figure 6.

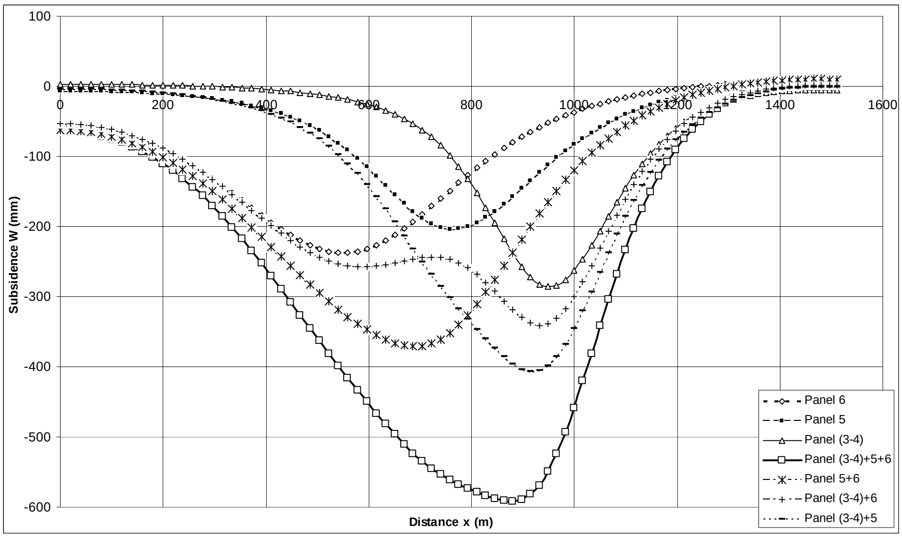


Figure 5 *The subsidence basins obtained from the numerical modelling*

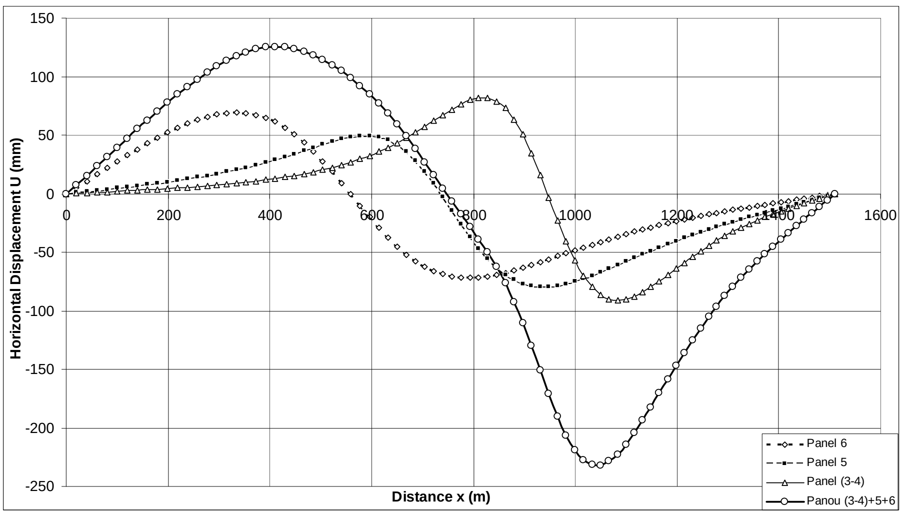


Figure 6 *The horizontal displacement graphics obtained from the numerical modelling*

The subsidence basins obtained from the numerical (FEM) modelling on the model “with mining voids” and on the model “with caving zones”, for all that three mining panels, in elasticity and elasto-plasticity, for a structural weakness coefficient of $K = 0.5$ are presented in the Figure 7 and the horizontal displacement curves in the Figure 8.

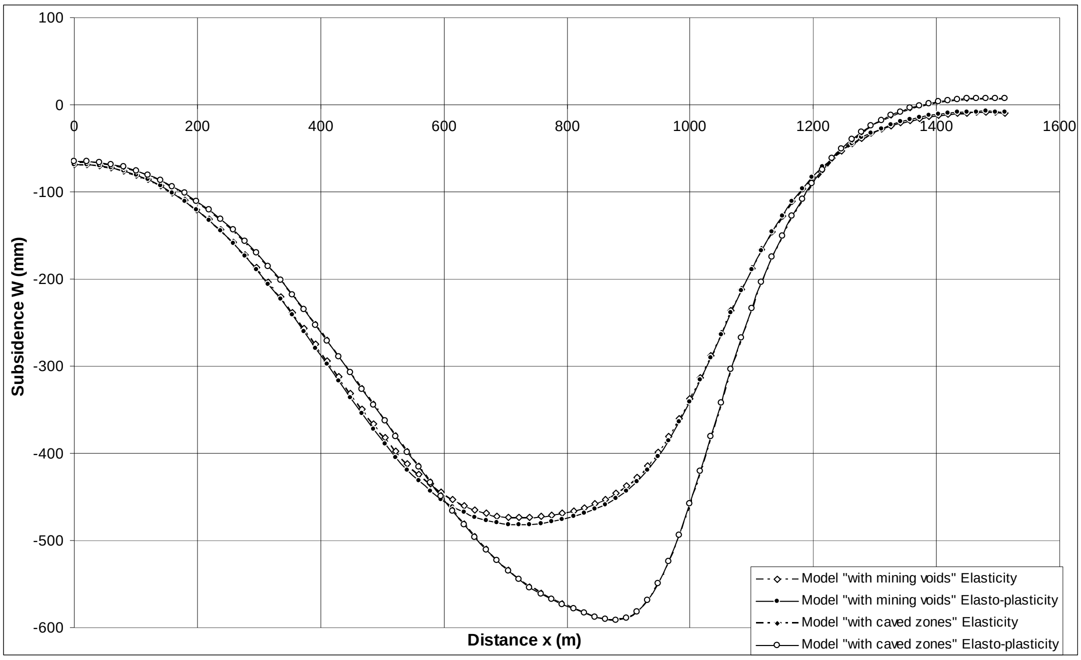


Figure 7 *The subsidence basins obtained from numerical modelling in elasticity and elasto-plasticity rocks behaviour*

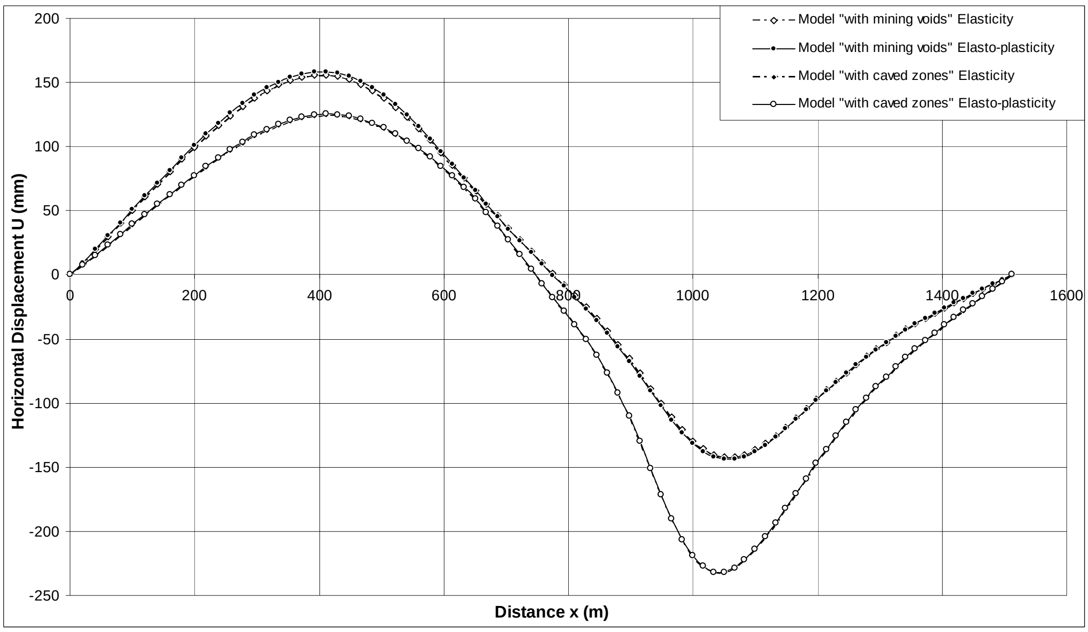


Figure 8 *The horizontal displacement graphics obtained from numerical modelling*

From the Figure 7 can be concluded the fact that between the model “with mining voids” and the model “with caved zones” there is a small difference, about of 200mm. Also, between the same type models, computed in elasticity and elasto-plasticity, the difference is very small (negligible).

The surface zones affected by the compressions (a), tractions (b) and shears (c), where there could appear the opening phenomenon of the natural fissures or the new ones arising by exceeding the strength limits of the rocks, are shown in the fig. 9. The general state of stresses, developed in the rock massive, represented by the maximum stress σ_1 (a) and minimum stress σ_2 (b), under the underground excavations influence, are represented in fig. 10.

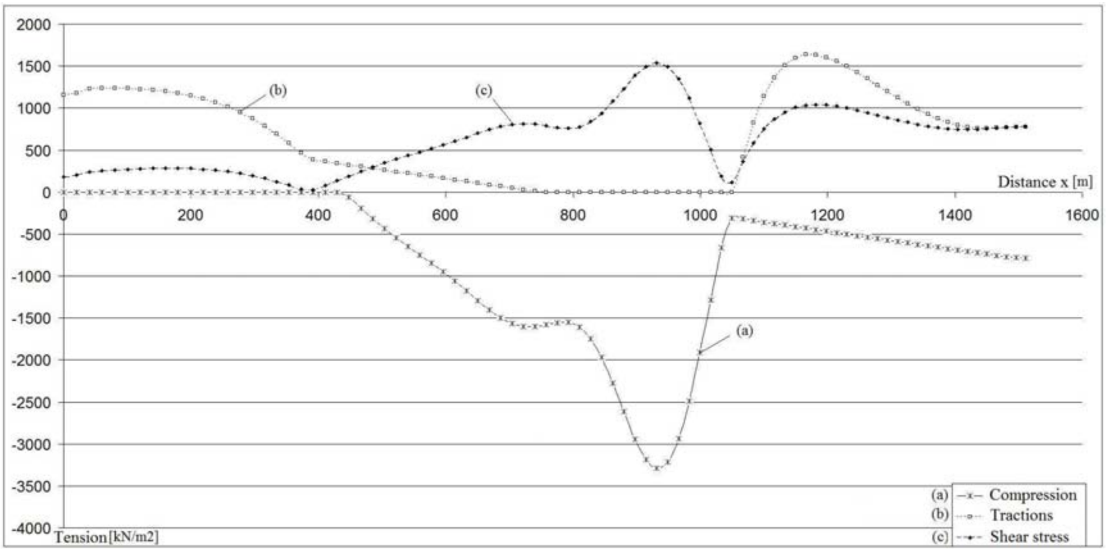
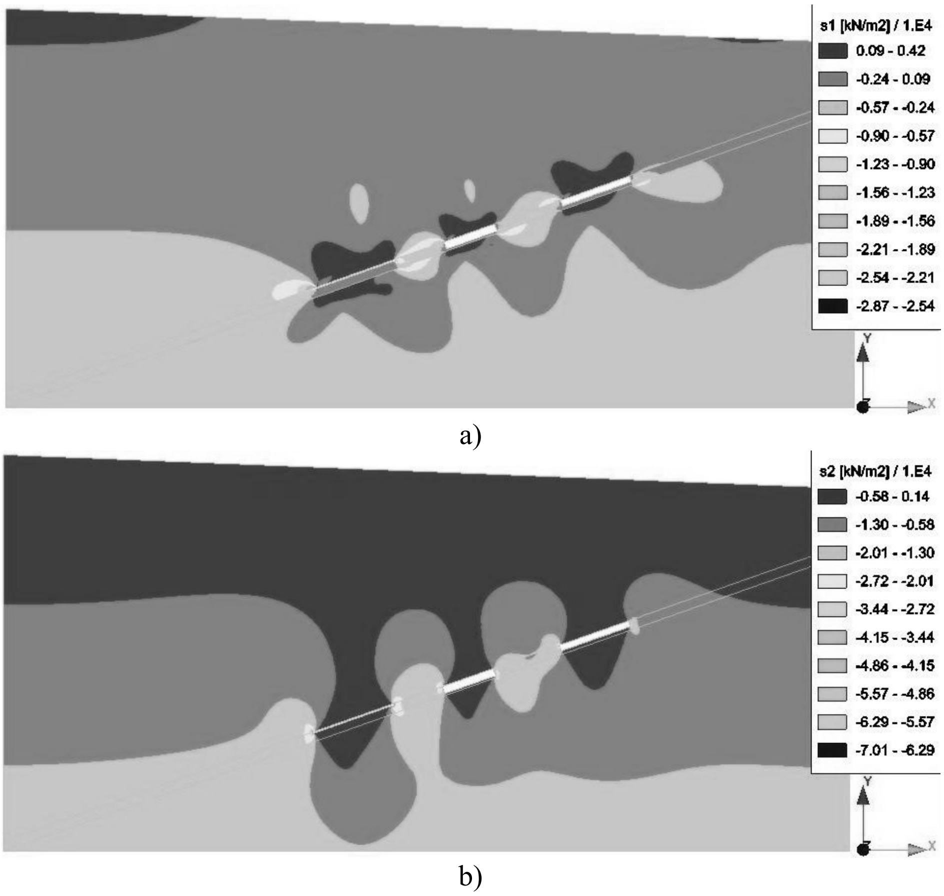


Figure 9 *Compressive stresses (a), tensile stresses (b) and shear stresses (c) at the ground surface calculated in the elasto-plasticity hypothesis*



b)

Figure 10 *Isovalue representation of the maximum stress* σ_1 *(a) and minimum stress* σ_2 *(b), in the rock massive, affected by the underground excavations*

Conclusions

The subsidence and displacement monitoring (surveying) station, in the case of Livezeni Hard Coal Mine, that consists of 50 benchmarks, where there are measured the ground surface subsidence and displacement every three months. This ground surface is affected by the coal underground mining of three panels, mined with longwall faces and roof control by total caving. Thus were determined the main parameters of the subsidence basin (subsidence or vertical displacement, horizontal displacement, horizontal strain, slope and the curvature).

The subsidence basin has a very complicated shape, being the result of coal layer no.3 mining with three neighbouring panels, and the monitoring (surveying) station is situated towards the boundaries of these three mining panels (where the deviations are considerable).

In this case, for a better understanding of the subsidence phenomenon, the 2D modelling with finite element method was used. Thus, with the aid of CESAR-LCPC code was generated two models groups, namely: "with mining voids" and "with caved zones". The calculus was performed in the elasticity rock behaviour and in the elasto-plasticity behaviour Mohr-Coulomb hypothesis.

After the analysis of the obtained results we can conclude the fact that the model with the more appropriate values by the in situ reality is the one "with caved zones", computed in the elasto-plasticity Mohr-Coulomb hypothesis, for a structural weakness coefficient K=0.5 (the maximum obtained subsidence is of W_{max} = -592mm and the horizontal displacements ranging between of U = + 125mm and of U= - 232mm).

References

1. **Almăşan, B.**
Exploatarea zăcămintelor minerale din România, Volumul I, Editura Tehnică, Bucureşti, 1984, pag. 70-291.

2. **Covaci, St.**
Exploatări miniere subterane, Vol.I, Editura Didactică şi Pedagogică, Bucureşti, 1983, pag.424.

3. **Hirian, C.**
Mecanica rocilor, Editura Didactică şi Pedagogică, Bucureşti, 1981, pag. 322

4. **Oncioiu, G., Onica, I.**
Ground Deformation in the Case of Underground Mining of Thick and Dip Coal Seams in Jiu Valley Basin (Romania), Procedeengs of 18th International Conference on Ground Control in Mining, 3-5 August, 1999, Morgantown, WV, USA, 1999, pag.330-336.

5. **Onica, I.**
Introducere în metode numerice utilizate în analiza stabilităţii excavaţiilor miniere, Editura Universitas, Petroşani, 2001, pag. 156.

6. **Onica, I.**
Impactul exploatării zăcămintelor de s.m.u. asupra mediului, Editura Universitas, Petroşani, 2001, pag.173-198.

7. **Onica, I., Cozma, E., Goldan, T.**
Degradarea terenului de la suprafaţă sub influenţa exploatării subterane, Buletinul AGIR, anul XI, nr.3, 2006, pag.14-27.

8. **Onica, I., Cozma, E.**
Stress and Strain State Developed Around the Longwall Faces in the Jiu Valley Coal Basin, Proceedings of the 21 World Mining Congress & Expo –Session 6: Coal Mining – Chances and Challenges, Krakow, 2008, pp.153-163.

9. **Ortelecan, M.**
Studiul deplasării suprafeţei sub influenţa exploatării subterane a zăcămintelor din Valea Jiului, zona estică, Teză de doctorat, Universitatea din Petroşani, 1997, pag.195

10. **Ortelecan, M., Pop, N.**
Metode topografice de urmărire a comportării construcţiilor şi terenurilor înconjurătoare, AcademicPres, Cluj-Napoca, 2005, pag. 256

11. **Todorescu, A.**
Proprietăţile rocilor, Editura Tehnică, Bucureşti, 1984, pag. 676

12. **Petrescu, I.** ş.a.
Geologia zăcămintelor de cărbuni. Zăcăminte din România, Vol.2 Editura Tehnică, Bucureşti, 1987, pag.81-106.