SURFACE DEFORMATION PROGNOSIS IN THE CASE OF PAROȘENI MINE USING THE PROFILE FUNCTION AND THE 3D FINITE ELEMENT METHOD

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Abstract: *The paper refers to the analysis of the measurements from the surface terrain deformation at Paroseni Mine and data approximation with a profile function – of predictive and comparative analysis with the results obtained from finite element modeling in 3D.*
Key words: *subsidence, horizontal displacement, coal seam, underground mining, profile function, numerical modelling, finite element*

1. Monitorring the surface terrain deformation in the case of Paroșeni Mine

The monitoring of the land deformation phenomenon, as a result of the underground mining at Paroșeni Mine, is accomplished by an alignment consisting of a total of 63 points, with a total length of 1,600 m, the purpose of which is to monitor the access road to the return station of the waste dump funicular.

In the above mentioned area, seam 3 and 5 were extracted; seam no. 3, in the panels 1, 2 and 3, from block V and panels 1, 2, 3, and 4 from block VI, and seam no. 5, in the panel 6, block III and panel 6 and 7, in block V (figure 1).

The monitoring period ran from June 2011 to May 2015, and, due to the fact that part of the initial points had disappeared during this period, in the graphic representation of the subsidence trough, only the points existing over the entire duration of monitoring of the surface subsidence phenomenon have been taken into account.

The development of the subsidence trough over time, based on the measurements carried out, is shown in figure 2. Also, the time evolution of the maximum subsidence, resulting from the processing of the data collected from the field, is shown in figure 3.

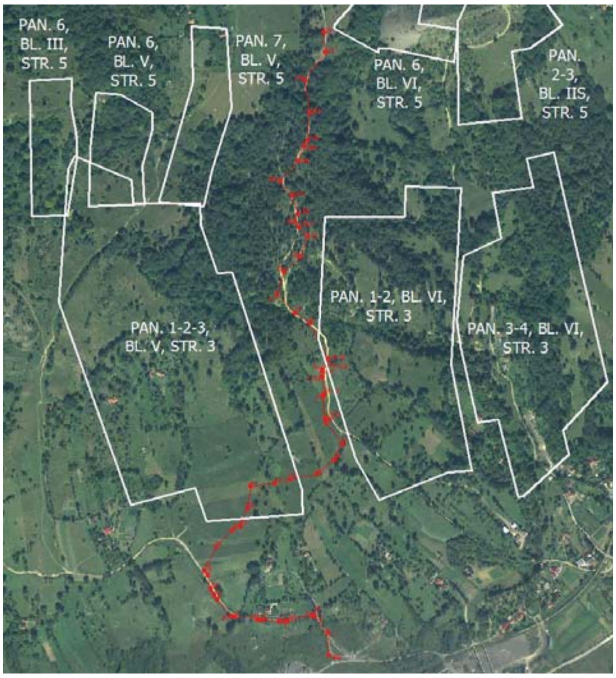

Fig.1 *Alignment of subsidence monitoring at Paroșeni Mine*

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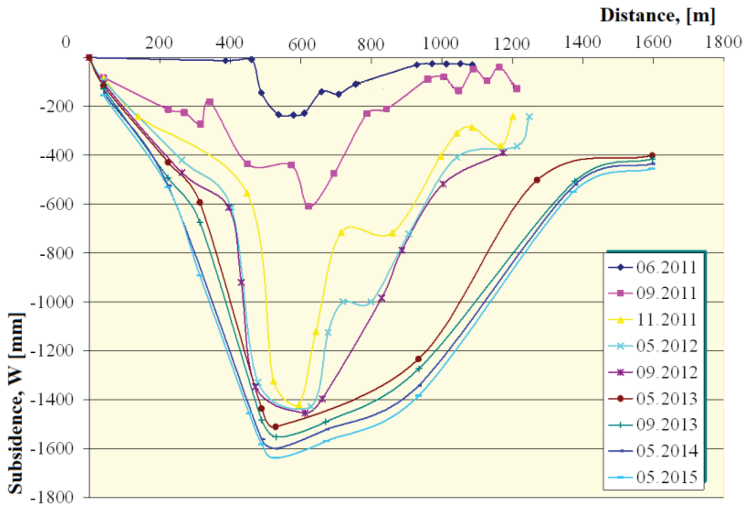


Fig.2. *Subsidence graph resulted from measurements at Paroseni Mine [1], [2]*

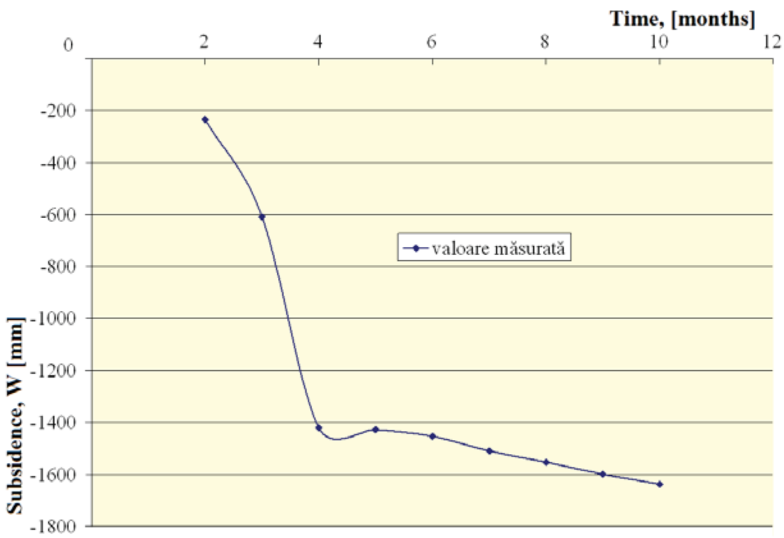


Fig.3. *The evolution in time of the maximum subsidence measured at Paroseni Mine [1], [2]*

For the statistical approximation of subsidence trough produced by the underground mining of the coal seams 3 and 5, in the mentioned panels, the profile function (1) was used for the prediction of subsidence:

$$W(x) = a \cdot x^b \cdot e^{-c \cdot x} \quad (1)$$

where: x is the distance measured from the limit or the subsidence trough to the reference point.

The value of the regression coefficients a, b and c, of the function (1) in the case of maximum subsidence, from the Paroseni Mine, is the following: $a = -1.777 \cdot 10^{-3}$; $b = 2.517$; $c = 3.974 \cdot 10^{-3}$; and the determination coefficient is $R^2 = 0.995$.

Using this profile function the maximum calculated subsidence is 1,614mm, in relation to the one measured, of 1,638 mm (resulting in a very good estimate of the measurements).

Figure 4 shows the graph of this function compared to the maximum subsidence resulted from the processing of the data collected from the field.

The time evolution of the maximum subsidence resulting from the processing of the data collected from the field, compared to the maximum subsidence resulting from the use of the profile function is shown in figure 5.

During this period, the surface subsidence speed is between 124 mm/month in the first monitoring period and 3 mm/month in the last period. It can also be noticed that during the winter period – November 2011 – May 2012 (the period between the 23rd month and the 32nd month of monitoring), September 2013 – May 2014 (month 48 to month 56 of monitoring period), subsidence speed is significantly reduced from 124 mm/month in the first monitoring period to 6 mm/month, which may lead to the wrong conclusion that the phenomenon has entered in the final phase (the extinguishing phase).

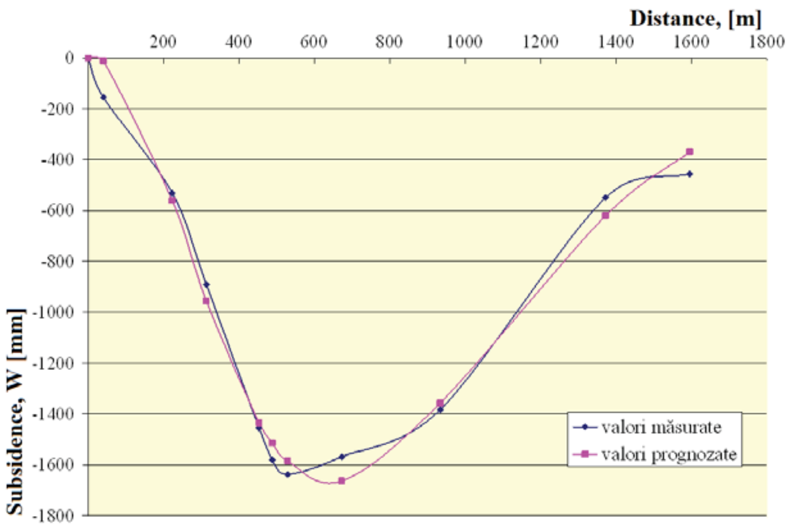


Fig.4. *Maximum measured subsidence and maximum predicted subsidence at Paroseni Mine [1], [2]*

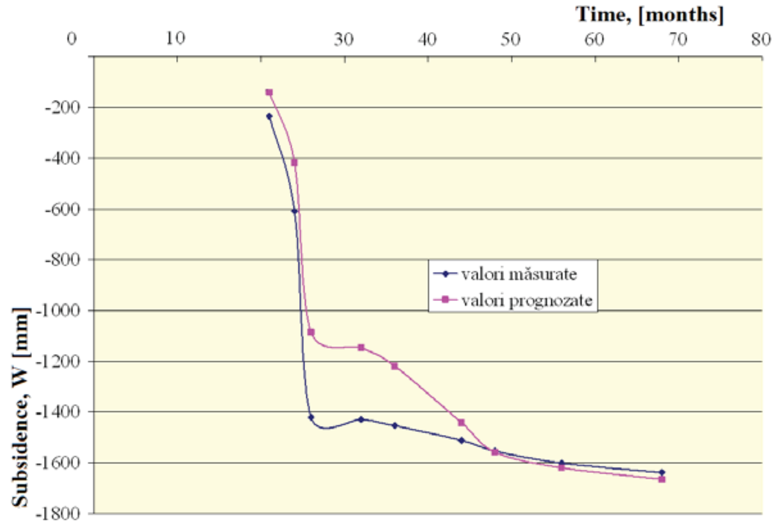


Fig.5. *The evolution in time of the maximum measured and predicted subsidence at Paroseni Mine [1], [2]*

2. The influence of the time factor on the surface subsidence in the case of Paroşeni Mine

After the determination of the coefficients *a*, *b* and *c* of the prognosis function (1), the graphical representation of these coefficients was made (fig. 6) resulting a number of issues, namely:

- The evolution of the three coefficients is nonlinear over time;
- The approximation functions whose regression coefficients are closer to 1 are the linear ones and have the expressions:

$$a_{(t)} = -a_1 \cdot t + a_2 \quad (2)$$

$$b_{(t)} = -b_1 \cdot t + b_2 \quad (3)$$

$$c_{(t)} = -c_1 \cdot t + c_2 \quad (4)$$

where: t is time;

a_1, a_2,…, c_2 – regression coefficients of linear functions (2), (3) and (4).

- From the new regression function of coefficients *a*, *b* and *c*, which are dependent parameters, explained, are part of it the pairs of regression coefficients (a_1, a_2), (b_1, b_2), and (c, c_2); the value of these regression coefficients for function (5), in the case of Paroseni Mine, is shown in the table 1.

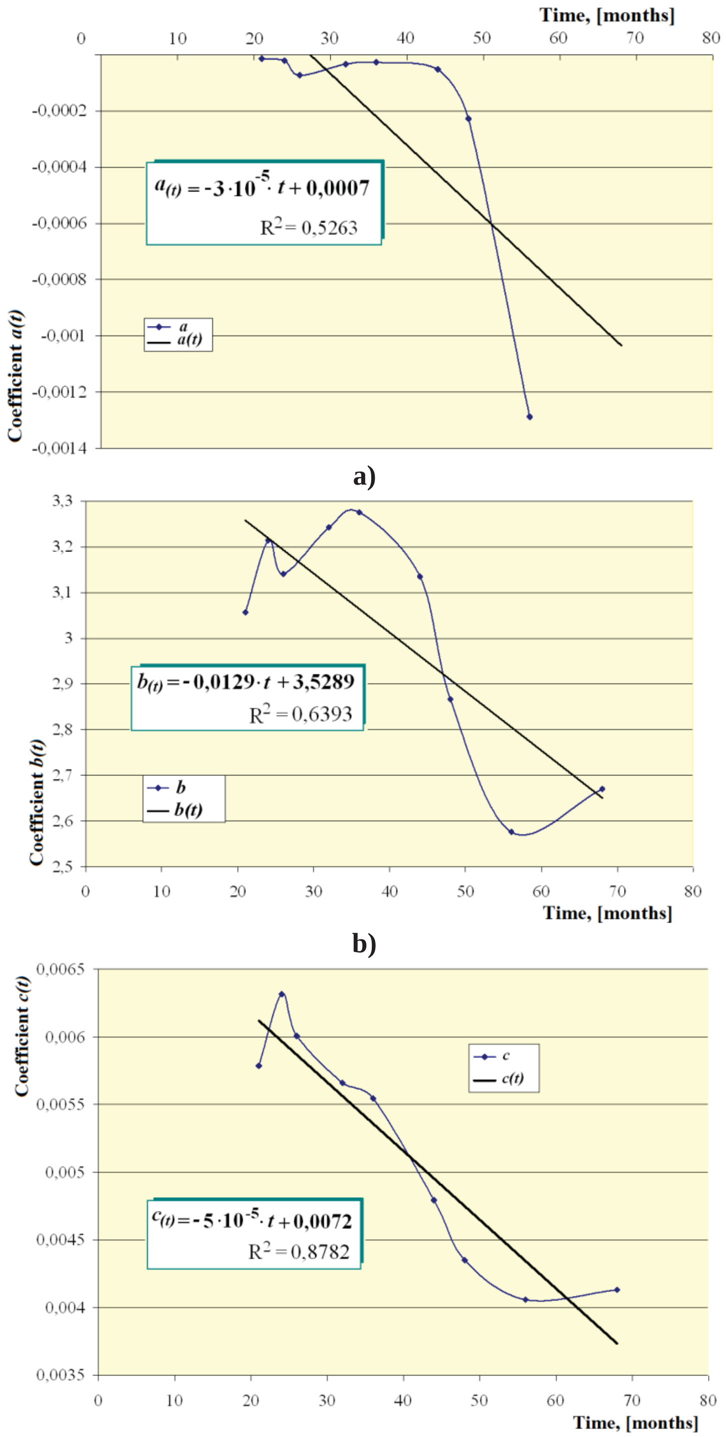
Consequently, the new subsidence prognosis function obtained for the Paroseni Mine, which takes into account both the distance measured from the limit of the subsidence trough and time, has the form:

$$W(x,t) = \left(-a_1 \cdot t + a_2\right) \cdot x^{-b_1 \cdot t + b_2} \cdot e^{\left(-c_1 \cdot t + c_2\right) \cdot x} \quad (5)$$

where: is the distance measured from the limit of the subsidence trough to the reference point; t – time.

The value of the average determining factor of the function (5) is $R^2_{med} = 0{,}897$.

The comparative graphical representation of the subsidence curves predicted with function (5) and the measured subsidence curves, in time, is shown in figure 7.



c)

Fig. 6. *Evolution over time of the regression coefficients a, b and c and the regression functions of the regression coefficients* $a_{(t)}$, $b_{(t)}$ *and* $c_{(t)}$

Table 1. *The values of regression coefficients for function (5) [1], [2]*

Coefficient	Value	Coefficient	Value	Coefficient	Value
a_1	$3\cdot10^{-5}$	b_1	0,0129	c_1	$5\cdot10^{-5}$
a_2	0,0007	b_2	3,5289	c_2	0,0072
R^2	0,5263	R^2	0,6393	R^2	0,8782

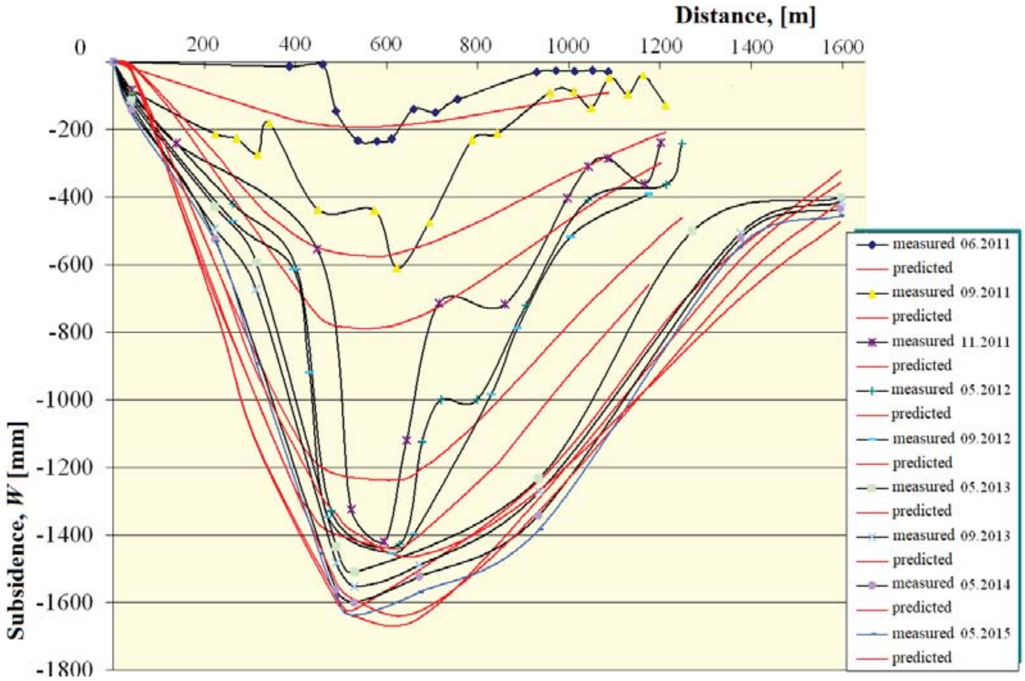


Fig.7. *The comparative chart of the measured subsidence with those predicted with the new profile function [1], [2]*

Using the new profile function, the maximum calculated subsidence is 1,647 mm, against the measured one, which is 1,638 mm – resulting a very good estimation of the profile function, for the subsidence prognosis in the case of Paroseni Mine.

3. Numerical modeling of the surface subsidence phenomenon at Paroșeni Mine

Owing to the fact that the alignment used to monitor the subsidence phenomenon at Paroseni Mine is situated largely outside the excavated fields (fig. 1), they considered as necessary and very important issues to carry out a three-dimensional modelling of the area to capture the development of this phenomenon as close as possible to reality.

For the numerical modelling of the situation presented in figure 1, from Paroseni Mine, they used the CESAR-LCPC finite element software, with the CLEO3D processor [8].

Numerical modelling with the finite element method involves the passage of certain stages, namely [7], [8], [9]:

- Building the model;
- Initializing the model and editing the geo-mechanical features;
- Imposing boundary conditions and editing the characteristics to load the model;
- Launching in calculations and getting results.

In order to determine the land surface displacement, in the area of the monitoring emplacement where the land is affected by the underground mining of the coal seam no. 3 and 5, a 3D model with "mining voids" was designed, whose rocks are considered homogeneous and isotropic, taking into account the hypothesis of elastic behaviour of the massif [3].

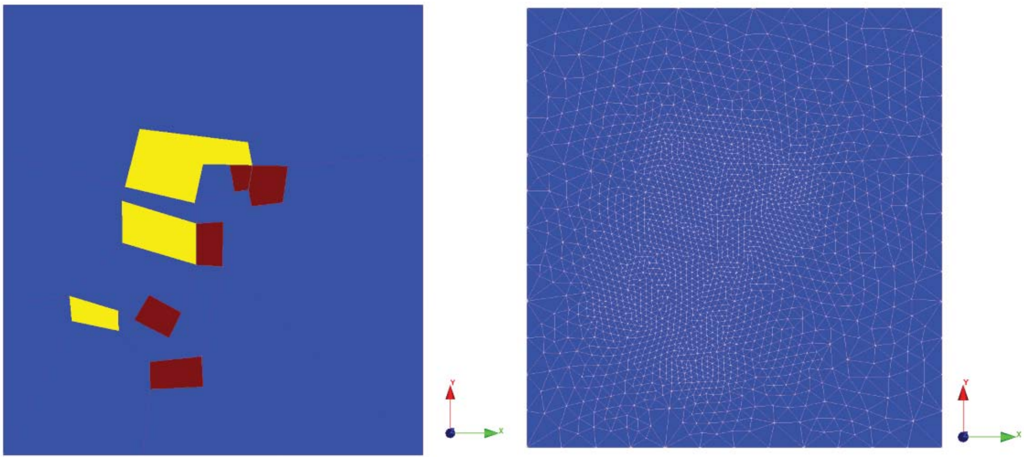
This stage of model designing required the following phases: a) building the geometry of the model; b) establishing the areas of interest; c) meshing of the model [7], [8], [9].

At this stage, in order that the boundaries of the model would not affect the results, a very large model was created (Fig. 8), taking into account a distance of 500 m, measured from the ends of the model to the edge of the panels (extracted spaces). Thus, a model with the following dimensions resulted: X=3,169 m; Y=3,426 m; Z=580m.

Following the meshing of the model with triangular finite elements, using a linear interpolation function, a number of 38,095 nodes and 71,262 volume elements were obtained. This simplified mod of modelling has been chosen, because of the very large dimensions, which also required (although simplified) the generation of a large number of elements, with consequences on computing resources.

In this stage, the initial conditions of the model were settled, which refer to: a) the geo-mechanical characteristics of the different groups of elements; whether those elements are active or not in the initial situation of the model; c) model load mode [8].

The geo-mechanical characteristics taken into account are summarized in table 2.



a) **b)**

Fig. 8. *Construction of the model with finite elements, under the conditions of Paroseni Mine [1], [2]*
a) Establishing the areas of interest (regions); b) Meshing with finite element

Table 2. *The values of the geo-mechanical characteristics of rocks and coal [6], [10]*

Rock characteristic	Symbol	UM	Rock	Coal
Apparent specific weight	ρ_a	kg/m^3	2 663	1 450
Young modulus of elasticity	E	kN/m^2	5 035 000	1 035 000
Poisson ratio	ν	adim.	0,19	0,13
Cohesion	C	kN/m^2	6 130	1 300
Internal friction angle	φ	^{o}	55	50

In this model, the load of the model was considered to be geostatic, for mining depth of the coal seam no. 3 of 480 m and seam no. 5, 410 m.

Regarding the limit conditions of the model (Fig. 9): the upper part of the model was considered to be free, without constraint; as for the lower limit, the condition has been set that the model is locked vertically (vertical displacement $w=0$), and on the horizontal to be free (horizontal displacement after the two axes $u \neq 0$; $v \neq 0$); for the sides of the model, the vertical movement was made free ($w \neq 0$) and the horizontal locked ($u=0$; $v=0$)

In order to perform the calculation related to this model (Fig. 8), a number of general calculation parameters have been established, such as: a) the number of increments; b) the maximum number of iterations per increment (50 iterations/increment); c) permitted tolerance (1%); d) method of calculation (initial strain method) [8].

After calculation, the results were displayed in a graphical form both on the surface of the model and on certain predefined sections of the model or on certain routes imposed by the user (Fig. 10). The results obtained refer to both displacements – vertical displacements, or subsidence (*w*), and horizontal displacements (*u* and *v*) – as well as to the state of tensions developed in the massive, from the mining void to the surface.

From the analysis of the obtained results (shown graphically in Figure 11), one may notice that, as far as the 3D numerical modelling is concerned, the subsidence trough appeared on the surface has a similar shape to that measured in the monitoring station, the maximum subsidence being 1,730 mm, a value relatively close to the maximum measured subsidence, whose absolute value is 1,638 mm. Also, the maximum subsidence obtained from 3D modelling is slightly higher than the maximum subsidence calculated with the profile function (5) of 1,663 mm.

Analysing the time evolution of the maximum subsidence measured at Paroseni Mine, (figure 5), and the maximum subsidence represented in figure 11, one may conclude that the subsidence phenomenon is in the extinguishing phase, and the final subsidence on the studied route according to the prognosis will be around 1,730 mm.

The horizontal displacement *U*, along the *x*-axis, obtained from the finite element model at Paroseni Mine, is in the range of -400 mm +500 mm (figure 12) and the horizontal displacement *V* along the *y*-axis is maximum 226 mm (figure 13).

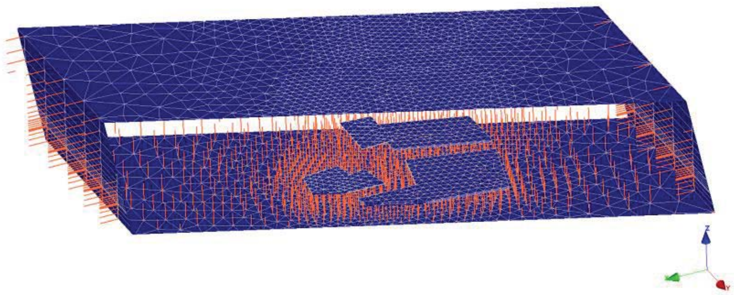


Fig. 9. *Imposing boundary conditions, for the model of Paroseni Mine*

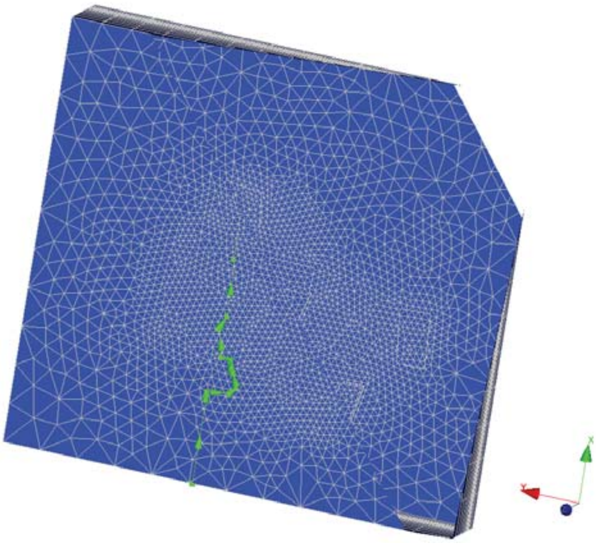


Fig. 10. *Drawing on the model the subsidence monitoring station from surface [1], [2]*

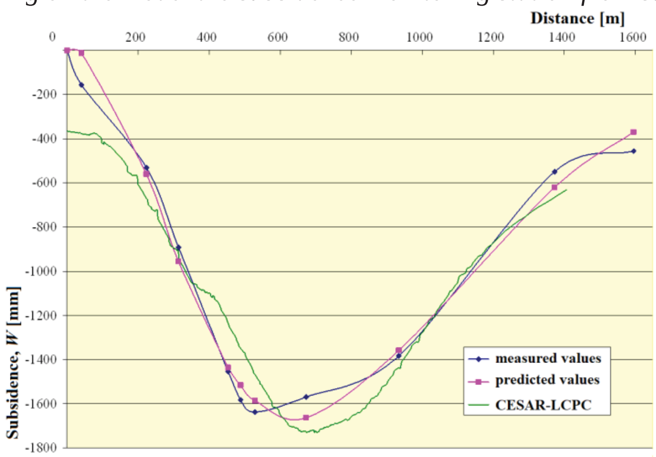


Fig. 11. *Comparative graphical representation of the measured maximum subsidence, predicted with the profile function and predicted by numerical modelling [1], [2]*

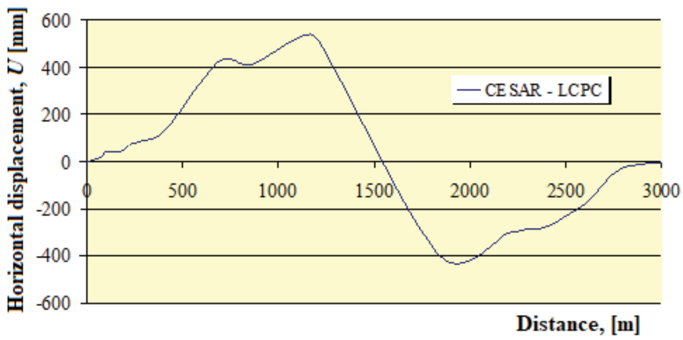


Fig. 12. *Horizontal displacement U in the 3D model with finite elements, along the monitoring alignment [1], [2]*

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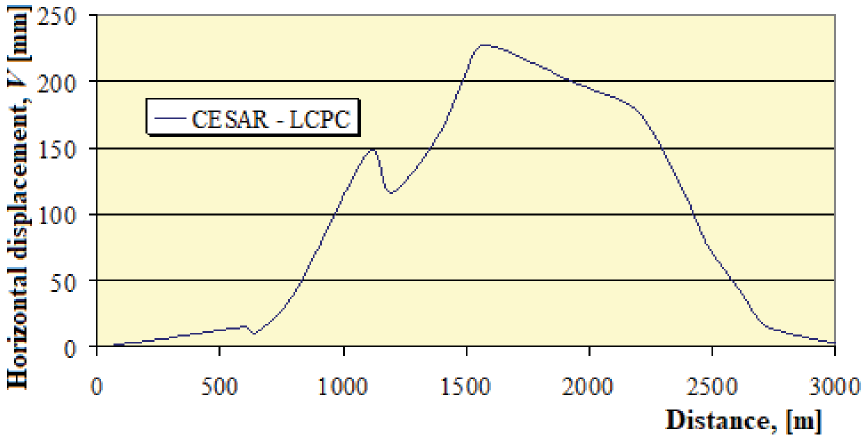

Fig. 13. *Horizontal displacement V in the 3D model with finite elements, along the monitoring alignment [1], [2]*

4. Conclusions

Monitoring the surface deformation phenomenon in the case of Paroşeni Mine, was performed on certain routes (determined by the interest of the mine), by topographical methods (middle geometric levelling and/or trigonometric levelling). The maximum measured subsidence represents 1,638 mm in the case of Paroşeni Mine.

The statistical and mathematical approximation of the measurements carried out at Paroşeni Mine, over a period of time, was accomplished through a profile function of the subsidence prognosis, specific to the Jiu Valley Mining Basin, which well estimated the measurements made over time, namely 1,614 mm.

For the mining conditions of Paroşeni Mine, a 3D modelling with finite elements was carried out using the CESAR-LCPC software. The maximum subsidence value obtained on the occasion of the measurement alignment was 1,730 mm, which well estimates the field measurements. Also, the value of the horizontal displacements resulting from the numerical modelling was: $U = -400 \div +500$ mm along the *x* axis; $V = +226$ mm along the *y* axis.

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