# NEW PROFILE FUNCTION FOR GROUND SUBSIDENCE ASSESSMENT IN THE CASE OF UNDERGROUND COAL MINING

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

*The Petroşani Hard Coal Basin of Romania contains a balance reserve of about one billion tonnes of coal. 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 million tonnes per year. In these conditions has arisen the necessity of revaluation of the impact produced by the underground mining on the ground surface; to determine the development of the subsidence phenomenon in view to elaborate some of the prevention methodologies and the design of the safety pillars for some objectives situated on the surface and underground. Therefore, besides starting the new subsidence and displacement measurements, in the first stage, we proceeded to analyse the old measurements achieved at the Hard Coal Company level, along the time, in different mining fields. Having in view the great diversity of the geo-mining conditions of the mined zones (thick coal seams with gentle and great dip, situated at the variable depths), the most significant cases were taken in study. After the analysis of these measurements, it was elaborated a special time dependent profile function for the conditions of gentle and medium dip seams, as Uricani mine, and generalized for the great dip mines, as Vulcan, Lonea, Petrila, Dâlja mines, with a very good precision of the results. Also, for all these mines, was modified the profile function elaborated by Peng and Chen [22] for Northern Appalachian Coalfield, taking into account the time factor.*

**Keywords:** subsidence, displacement, profile function, finite element method

## Jiu Valley hard coal basin

The Petroşani Hard Coal Basin contains the most important hard coal deposit of Romania, with a balance reserve of about one billion tonnes 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 at the same time with Romania's industrialisation, after the Second World War, reaching after 1980 over 9-10 millions tonnes of coal per year [1], [23].

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 million tonnes per year.

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 tonne) and there is a marked tendency of coal self-ignition [1], [23].

In this coal basin, through the geological research works, there was identified a number of 18 coal seams, of which the most economical importance having the coal seam no.3 (48%) and coal seam no.5 (12%).

The sedimentary rocks complex, in which these coal seams are present, consists in rocks deposits which belong to Superior Cretaceous, Neocene and the Quaternary [23].

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 [4], [16], [25].

The subject of this study consists in the underground mining influence analysis on the ground surface of the coal seam no.3 in the case Uricani, Vulcan, Lonea, Petrila and Dâlja mines, by using a newly developed profile function.

## Profile functions

Subsidence is an inevitable consequence of underground mining – it may be small and localized or extend over large area, it may be immediate or delayed for many years. Mine subsidence may be defined as ground movements that occur due to the collapse of the overlying strata into mine voids [24].

The subsidence consists of following major components: subsidence, displacement, slope, curvature and horizontal strain. Also, there are several terminologies that used to define the characteristics of a subsidence profile in a major cross section: angle of draw, angle of critical deformation, angle of break, inflection point and radius of major influence [21].

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The factors controlling the final surface deformations are the following: physical properties of the overburden strata, size of opening or gob, mining depth (mining depth and mining height, mining depth and mining width), multiple panel mining, surface topography, time elapse [21], near-surface geology, geologic discontinuities, fractures and lineaments, groundwater, water level elevation and fluctuations, method of working, rate of face advance, backfilling of the gob, etc [24].

The major objectives of the subsidence engineering are: 1) prediction of the ground movements; 2) determining the effects of such movements on structures and renewable resources; 3) minimizing damage due to subsidence [24].

Existing subsidence prediction techniques fall under two basic categories, empirical and phenomenological. Promising empirical methods for prediction of the subsidence over underground mines consist of the following: 1) graphical; 2) profile functions; 3) influence functions. Profile functions involve the derivation of a mathematical function that can be used to plot a complete profile of the subsidence trough at the surface. It differs from a phenomenological approach in that the constraints employed in the profile function are empirically derived from observed data [24].

This method can be readily applied to geologically dissimilar conditions by modifying the constant values. Profile functions nave been successfully applied in several countries such: Poland, Hungary, Soviet Union, and United State etc. [24] and actually in Romania. The example of profile functions are the following [24]:

**A) Critical extraction**:

-*Hyperbolic profile function*: UK [6], [27]

$$W(x)=\frac{1}{2}\cdot W_{\max}\cdot\left[1-\tanh\left(\frac{c\cdot x}{B}\right)\right] \quad (1)$$

-*Error profile function*: Poland/Upper Silesia [7]

$$W(x)=\frac{1}{2}\cdot W_{\max}\cdot\left\{1-\left[\frac{2}{\pi^{1/2}}\int_0^{\ln x/B}\exp\left(-u^2\right)\cdot du\right]\right\} \quad (2)$$

-*Exponential profile function*:
Hungary [10], [11]

$$W(x)=W_{\max}\cdot\exp\left[-\left(\frac{1}{2}\right)\cdot\frac{(x+B)^2}{B^2}\right] \quad (3)$$

US/Appalachia [22]

$$W(x)=W_{\max}\cdot\exp\left[-\left(\frac{c\cdot x}{B}\right)^d\right] \quad (4)$$

-*Trigonometric profile function*:
USSR/Donets, General Institute of Mine Surveying [2]

$$W(x)=\frac{1}{2}\cdot W_{\max}\cdot\left[1-\left(\frac{x}{B}\right)-\left(\frac{1}{\pi}\right)\cdot\sin\left(\frac{\pi\cdot x}{B}\right)\right] \quad (5)$$

Hoffman [5]

$$W(x)=W_{\max}\cdot\sin^2\left[\left(\frac{\pi}{4}\right)\cdot\left(\frac{x}{B}-1\right)\right] \quad (6)$$

**B) Subcritical extraction**:
-*Trigonometric profile function*:
USSR/Donets, General Institute of Mine Surveying [2]

$$W(x)=W_{\max}(n_1,n_2)^{1/2}\cdot\left[n^2\cdot A+\frac{1-n^2}{4}\cdot B^2\right] \quad (7)$$

where:

$$A=\left(1-x+\frac{\sin 2\cdot\pi\cdot x}{2\cdot\pi}\right)$$

$$B=(1+\cos\pi\cdot x)$$

-*Hyperbolic profile function*:
Poland/Upper Silesia [8], [26]

$$W(x)=\frac{1}{2}\cdot W_{\max}\cdot\left[\tanh\frac{2\cdot(x+w)}{B}-\tanh\frac{2\cdot x}{B}\right] \quad (8)$$

Where: $x$ is horizontal distance; $c$ - arbitrary constant; $B$ - radius of critical area of excavation; $u$ - integration variable; $w$ - panel width; $W(x)$ – profile function; $W_{\max}$ - maximum possible subsidence; $n_1$, $n_2$ – coefficients related to width/depth; $n$ – $n_1$ or $n_2$ depending on side of panel.

**Subsidence analysis in the case of the coal seam no.3, block v, panel 1, Uricani mine**

The ground surface displacement and deformation monitoring under the underground mining influence at the Uricani Mine is achieved by the medium of the monitoring station composed of 10 observation benchmarks (the station length is of 563.6m).

The topographical measurements were three in three months, beginning with October 2007. This monitoring station provides data concerning the ground surface displacements and deformations by consequence of the underground mining of the coal seam no.3, block V, panel 1 (Fig.1).

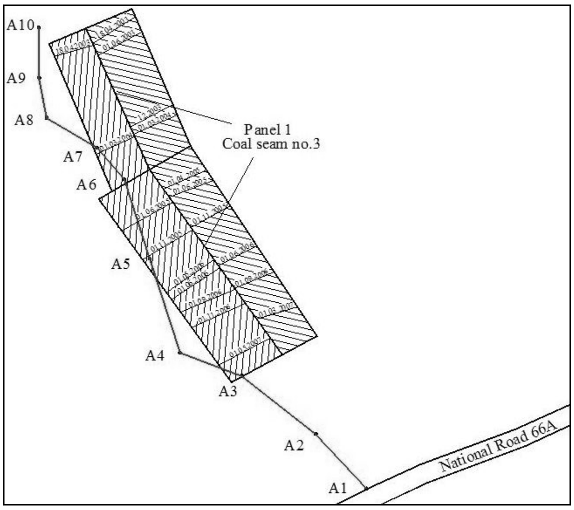


*Fig.1. Monitoring station for the ground surface subsidence at the Uricani Mine*

The mining of the thick and gentle inclined coal seam (of under $10^{o}$) was achieved with top coal caving longwall mining (with a length of 90m) on the entire seam thickness and on the panel length of 354m. This panel mining began in 2003 and was completed in the second half of the year 2007.

Besides the horizontal displacement *U*, in mm, and the horizontal strain $\varepsilon$, in mm/m, other important parameters which define the subsidence basin are: the subsidence or the vertical displacement, *W*, in mm; slope, *T*, in mm/m; curvature, *K*, in $m^{-1}$ [14].

Studying these parameters, we found that between them there exist some dependencies, namely: the vertical displacements are maximum when the slope is zero and presents an inflexion point for a maximum value of the slope (in the point where the curvature of the subsidence basin vanishes).

For a mathematical expression of these dependencies, the following functions will be defined: *W*(*x*) is the vertical displacements function; *T*(*x*) – slope function; *K*(*x*) – curvature function.

Thus, the measured subsidence basins were statistically analysed [12], [15] with the aid of a new developed profile function which has the following form [9]:

$$W(x) = a \cdot x^{b} \cdot e^{-c \cdot x} \quad (9)$$

Where: *a*, *b* and *c* are the regression coefficients.

Between these functions exists the followings mathematical correlations, namely [14]:

$$T(x) = \frac{dW}{dx}; \quad K(x) = \frac{d^2W}{dx^2} \quad (10)$$

Taking into account the previous correlations, depending on the regression parameters, there could be established the other parameters' equations of the subsidence basin.

$$T(x) = \frac{dW(x)}{dx} = \frac{a \cdot x^{(b-1)}}{e^{c \cdot x}} \cdot (b - c \cdot x) \quad (11)$$

For $T(x) = \frac{dW(x)}{dx} = 0$, respectively at the distance $x = \frac{b}{c}$ results the maximum subsidence:

$$W_{\max} = a \cdot \left(\frac{b}{c}\right)^{b} \cdot e^{-b} \quad (12)$$

Also, the curvature function of the subsidence basin is:

$$K(x) = \frac{d^2W(x)}{dx^2} = a \cdot x^{(b-2)} \cdot e^{-c \cdot x} \cdot A \quad (13)$$

Where: $A = \left[ c^2 \cdot \left(x - \frac{b}{c}\right)^2 - b \right]$

The inflexion points $x_1$ and $x_2$ of the vertical displacement curve (for $K(x) = 0$) are:

$$x_{1,2} = \frac{b \mp \sqrt{b}}{c}$$

In the case of the coal seam no.3, block V, panel 1, Uricani Mine, the coefficients *a*, *b* and *c* obtained for every partial subsidence profile and the square of the coefficient of determination $R^2$ of every equation (9) are presented in Table 1.

*Tab. 1. Regression coefficients a, b and c and the coefficient of determination $R^2$*

| Data | Time – *t* [month] | *a* | *b* | *c* | $R^2$ |
|---|---|---|---|---|---|
| 03.12.2007 | 1.25 | $4.201 \cdot 10^{-30}$ | 14.784333 | 0.041864 | 0.984 |
| 15.03.2008 | 4.6 | $6.279 \cdot 10^{-23}$ | 11.414900 | 0.032404 | 0.986 |
| 16.06.2008 | 7.7 | $2.494 \cdot 10^{-19}$ | 9.696927 | 0.026632 | 0.985 |
| 05.09.2008 | 10.3 | $1.858 \cdot 10^{-15}$ | 7.950222 | 0.022357 | 0.985 |
| 15.11.2008 | 12.7 | $1.152 \cdot 10^{-14}$ | 7.592713 | 0.021372 | 0.983 |
| 12.03.2009 | 16.5 | $1.041 \cdot 10^{-14}$ | 7.637613 | 0.021582 | 0.968 |
| 12.06.2009 | 19.5 | $2.522 \cdot 10^{-14}$ | 7.460140 | 0.020980 | 0.961 |
| 15.09.2009 | 22.7 | $7.914 \cdot 10^{-14}$ | 7.247970 | 0.020503 | 0.956 |

To introduce the time variable into this profile function, the regression operation of the all regression coefficients, shown in the Table 1, was made, depending on the time *t*. Thus, there resulted a new generalized profile function, time dependent, which has the form [9]:

$$W(x,t) = a_1 \cdot t^{a_2} \cdot x^{b_1 \cdot \ln(t) + b_2} \cdot e^{-(c_1 \cdot \ln(t) + c_2) \cdot x} \quad (14)$$

where: *x* is the distance measured from the limit of the subsidence basin; *t*–time;

$a_1 = 2 \cdot 10^{-31}; b_1 = -2.593; c_1 = -0.0074$;

$a_2 = 12.936; b_2 = 15.365; c_2 = 0.0435$ ($R^2$=0.971)

are the regression coefficients of the generalized profile function.

The real subsidence curves, depending on the time, and the results of the time dependent profile function are presented in Figure 2.

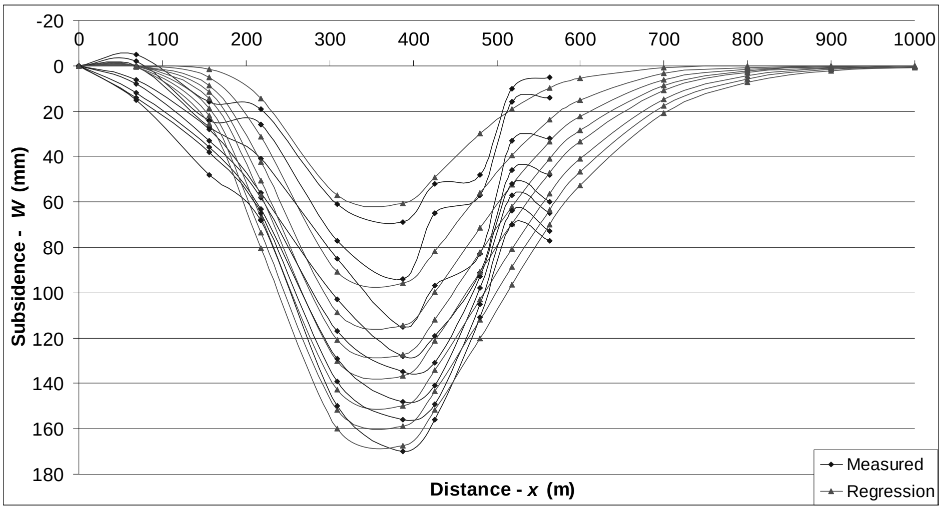


*Fig. 2. Real curves of the ground subsidence and the corresponding profile functions, in the case of the coal seam no.3, block V, panel 1, Uricani Mine*

In the year 1981, Peng and Chen [21], [22] developed the following negative exponential function of the subsidence profile on the major cross section of the subsidence basin:

$$W(x) = W_{\max} \cdot A \quad (15)$$

Where: $A = e^{-a \cdot z^b}$; $W_{max}$ is the maximum subsidence; *a*, *b* are constants; $z = \frac{x}{s}$; *x* is the horizontal distance from the origin (which is located at the centre of the subsidence profile); *s* is the half-width of the subsidence basin.

Also, for the calculus of the horizontal displacement, the following relation is proposed:

$$U(x) = U_{\max} \cdot A' \quad (16)$$

where: $A' = -a \cdot b \cdot z^{(b-1)} \cdot A$.

In our cases (when the subsidence profiles are asymmetrical), in order to obtain the complete subsidence profile, the relation (15) must be applied twice, for the left side and for the right side of the measured subsidence profile. If this relation is applied for every time profile, there will be obtained the corresponding regression coefficients $a_s$ and $b_s$, for the left side profile, and $a_d$ and $b_d$ for the right side profile. Similar to the profile function (14), so as to introduce the time variable in the Peng & Chen function, the regression of the regression coefficients was made, depending on the time. Thus, the following relations were obtained:

a) – for the left side of the subsidence profile [9]:

$$W_s(x,t) = W_{\max} \cdot e^{-m_s \cdot z^{n_s}} \quad (17)$$

where: $m_s = a_{s1} \cdot \ln(t) + a_{s2}$ and $n_s = b_{s1} \cdot \ln(t) + b_{s2}$

The obtained regression coefficients are the following:

$a_{s1} = -0.936; a_{s2} = 6.642; b_{s1} = -0.074; b_{s2} = 2.139$ ($R^2$=0.994)

b)– for the right side of the subsidence profile [9]:

$$W_d(x,t) = W_{\max} \cdot e^{-m_d \cdot z^{n_d}} \quad (18)$$

where: $m_d = a_{d1} \cdot t^{a_{d2}}$ and $n_d = b_{d1} \cdot t^{b_{d2}}$

For the geo-mining conditions of the Uricani mine, the regression coefficients have the following values:

$a_{d1} = 6.964; a_{d2} = -0.693;$

$b_{d1} = 4.085; b_{d2} = -0.401$ ($R^2$=0.983)

The real subsidence curves, depending on the time, and the approximation results of the modified Peng & Chen time dependent profile function are presented in Figure 3.

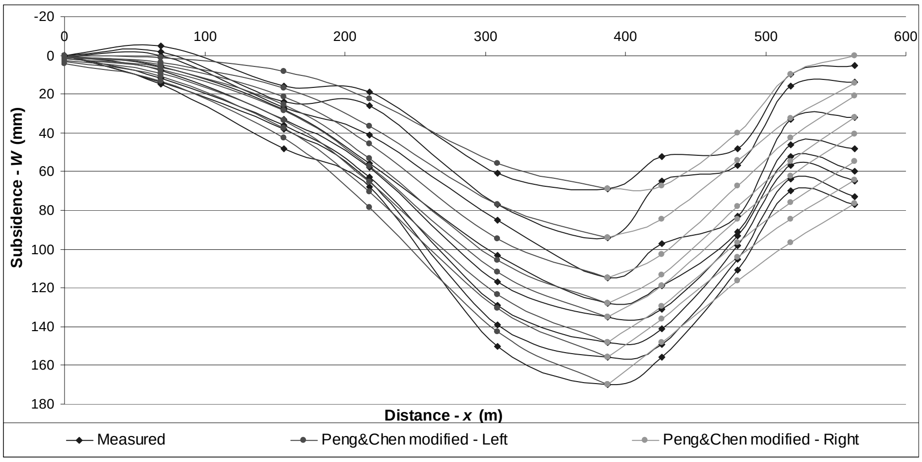


*Fig.3. Real subsidence curves and the curves of the Peng & Chen modified profile function*

In the previous figure, there could be observed that the Peng & Chen modified relation offers a very good fit of the measured data. The main advantage of this profile function is that it takes into consideration both the maximum subsidence and the time. In the case of deficiencies, it may be mentioned that: if the monitoring station didn't cover the entire profile of the subsidence basin, the function couldn't predict the behaviour of the entire subsidence profile; the connexion between every time dependent left and right profiles is through an angular point.

The subsidence basin of the 2D finite element numerical model [9], [13], [17], [18], [19] in the Mohr-Coulomb elasto-plastic behaviour hypothesis, was compared with measured subsidence (Fig.4), resulting an equal maximum subsidence but with certain deviation from the general subsidence profile.

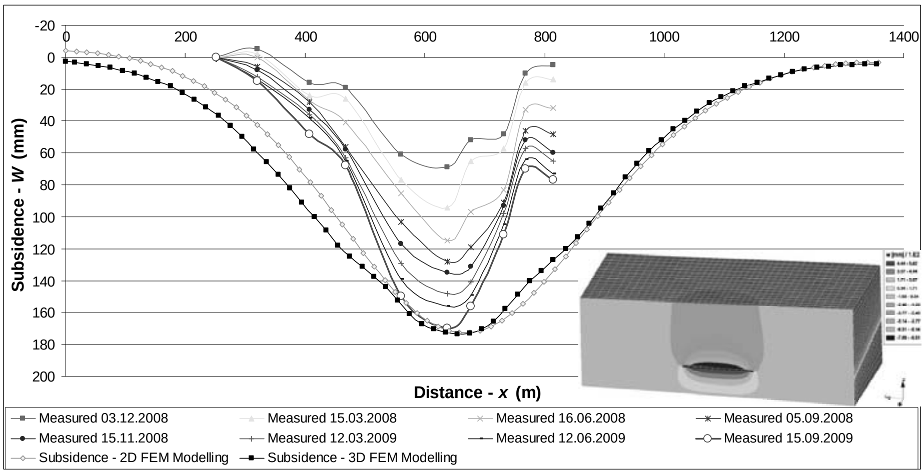


*Fig. 4. Subsidence basin obtained from the numerical modelling compared with the real measured subsidence profiles*

For to achieve the 2D and 3D analysis of the ground surface stability, affected by the underground mining of thick coal seam no.3, panel 1, block V, at the Uricani Mine, was used CESAR-LCPC computational code [9], [13], [17], [18], [19]. Thus, for 3D analysis a single model was created, with "mining voids", in the hypothesis of the elastic behaviour of the rock massive [9].

The subsidence basin obtained by the numerical modelling, in elasticity, with 3D finite elements, following the ground surface monitoring station trail (Fig.1) is shown in figure 4, in comparison with the measured subsidence and the results from the 2D numerical modelling (in the principal profile).

Also, in figure 5 is represented the variation of the horizontal displacements after X axis and in figure 6, after Y axis (transversal on the monitoring station).

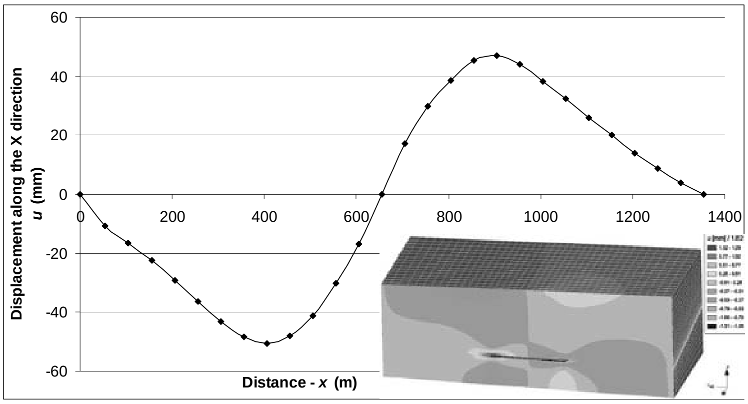


*Fig.5. Horizontal displacements after X axis, obtained from 3D numerical modelling*

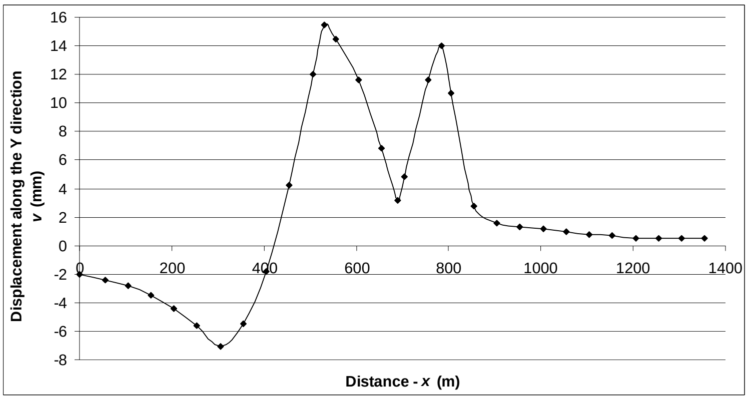


*Fig.6. Horizontal displacements after Y axis, obtained from 3D finite element numerical modelling (transversal on the monitoring station)*

**Subsidence analysis in the case of the coal seam no.3, block VII-VIII, face no. 366 and 376, Vulcan Mine**

The monitoring of the ground surface subsidence under the influence of underground mining at the Vulcan Mine is made by aid of the monitoring station composed of 16 benchmarks (the total length of the monitoring station being of 620.8m). The topographical observations were executed in a number of three in three months, beginning with October 2008. This monitoring station provides the data concerning the ground surface subsidence and deformation data as a consequence of the underground mining of coal seam no.3, block VII-VIII, faces no. 366 and 376 (Fig.7).

Coal seam no.3 (with an average thickness of about 50m) is mined in horizontal slices with top coal caving mining method, related with these two coal faces. The mining began in 1964, when the roof control by rocks caving was used.

After the statistical analysis of the measurements and the approximation of these with the aid of the profile function (9), then after the regression operation of the regression coefficients of every measurement stage, the generalized profile function (14) was obtained, time dependent, with the following regression coefficients:

$a_1 = 7 \cdot 10^{-132}; b_1 = -4.1863; c_1 = -0.0113;$

$a_2 = 21.23; b_2 = 60.35; c_2 = 0.1363$ ($R^2$=0.950).

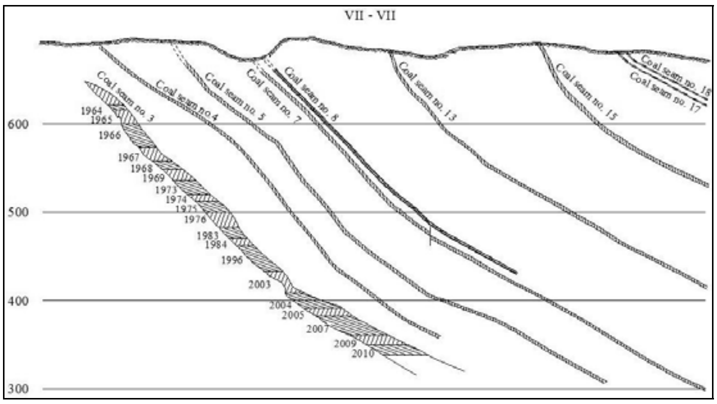


*Fig.7. Vertical cross - section, Vulcan Mine*

The subsidence curves, periodically measured, as well as the approximation curves of the time dependent profile function is graphically represented in Figure 8, where it is shown a very good fit of the in situ measurements.

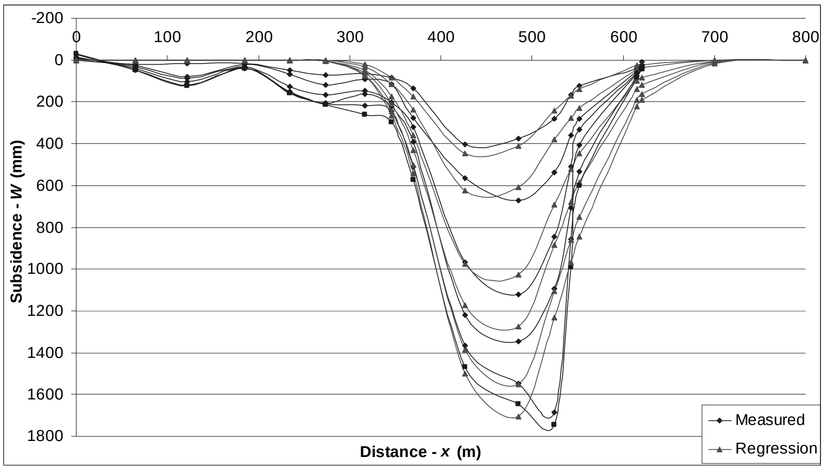


*Fig.8. Real subsidence curves and the curves of the time dependent profile function, in the case of coal seam no.3, block VII-VIII, face no.336 and 376, Vulcan Mine*

**Subsidence analysis in the case of the coal seam no.3 and 5, block VI, Lonea Mine**

Hereinafter, the measurement achieved on an old monitoring station will be analysed, materialized in the year 1985 by the Mining Faculty of Petroşani. This station is composed of two alignments: one strike alignment with a single stable end composed of 14 benchmarks (with a total length about 380m) and one transversal alignment with a single stable end, composed of 35 benchmarks (with a total length about 558m). The strike alignment was monitored until the year 1987, when the stable benchmark was lost and on the strike alignment the observation was made until the year 1996.

This monitoring station provides the data concerning the ground subsidence as effect of the mining of coal seam no.3 and 5, block VI (Fig. 9). The average dip of the coal seams is of about 30$^o$ and the thickness is 28-42m, for the coal seam no.3 and 4-5m, for coal seam no.5. The applied mining method is in horizontal slices, with roof control by integral rocks caving [3].

Similarly with the previous cases, the regression coefficients of the generalized time dependent profile function (14) are the following:

$a_1 = 3 \cdot 10^{-123}; b_1 = -8.527; c_1 = -0.013716;$

$a_2 = 46.949; b_2 = 54.017; c_2 = 0.095607$

($R^2$=0.970).

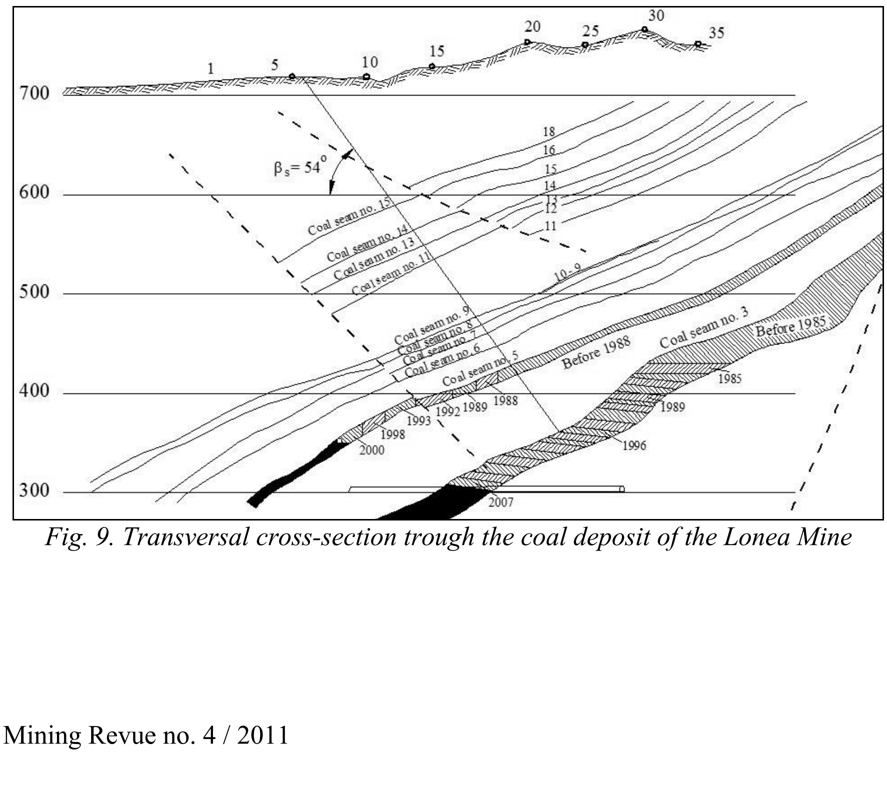


*Fig. 9. Transversal cross-section trough the coal deposit of the Lonea Mine*

Also in this case, it is observed a good statistical approximation of the real measurements with this profile function.

The subsidence curves, in time measured, as well as the statistical approximation with the generalized profile function (14) are graphically represented in Figure 10.

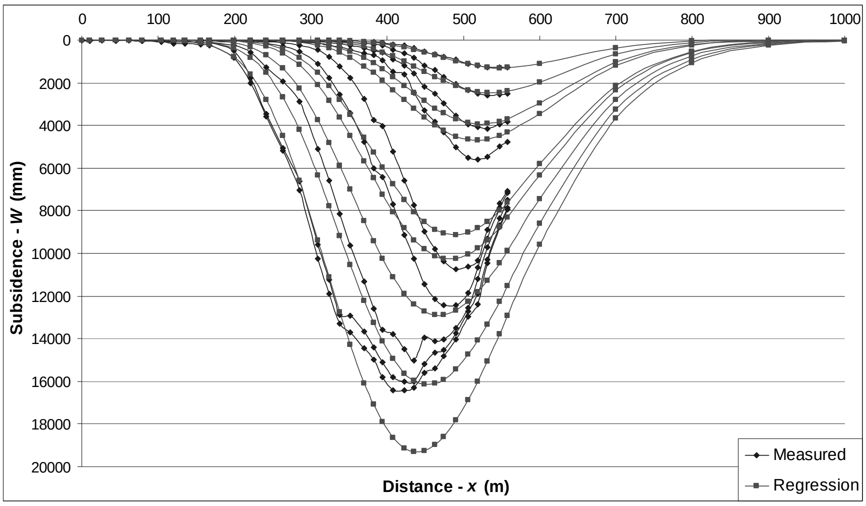


*Fig. 10. Subsidence curves, time dependent, measured and approximated with the profile function, for the case of coal seam no.3 and 5, block VI, Lonea Mine*

As it is shown in Figure 10, because of the advancement in the deep of the mining of coal deposit, the position of the point, corresponding to the maximum subsidence, for every intermediary subsidence profile, is modified and the subsidence basin develops asymmetrically, and more laterally.

**Subsidence analysis in the case of the coal seam no.3, face no. 138 and 139, Petrila Mine**

The measurements made along the alignment 200, materialized in year 1981, are composed of 16 monitoring benchmarks, disposed on the distance of 250m. Since 1978, the coal seam no.3 mining, under the level +300m, was practiced by slices, using the roof control by caving at the area of face no. 138 and 139. During the year 1991, in the face no.139 was achieved the total filling at the level +200m [20].

Similar with the previous cases, the statistical analysis of the measurements was made by profile function (9) and the generalized time dependent function (14) which led to the following regression coefficients:

$a_1 = 2,686 \cdot 10^{-4}; b_1 = -0,364; c_1 = -0,002496;$

$a_2 = 2,414; b_2 = 2,828; c_2 = 0,019876$ ($R^2$=0.981).

The subsidence curves of the real data and the results of the profile function, defined by the previous coefficients, are represented in Figure 11.

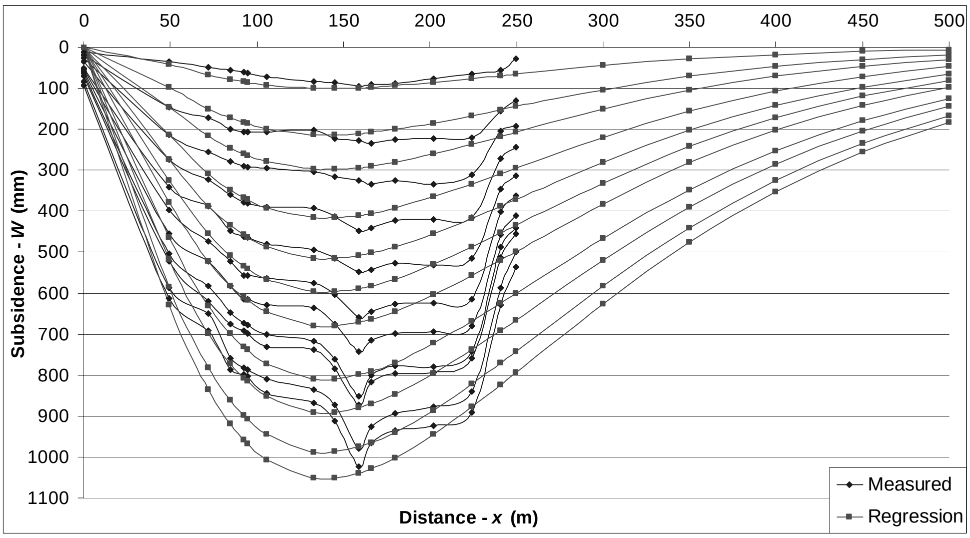


*Fig.11. Subsidence curves of the measured and approximated values, for the case of coal seam no.3, face no. 138 and 139, Petrila Mine*

**Subsidence analysis in the case of the coal seam no.3, block III, Dâlja Mine**

In this case it will be analysed the measurement achieved on a monitoring station that was materialized in the year 1975, composed of a transversal alignment with two stable ends, involving 33 benchmarks, along a distance of 841.8m.

The observations, on this monitoring station, were made biannually, until 1981. This station had the role of observing the ground subsidence and displacements caused by the underground mining of coal seam no.3, block III, mined in horizontal slices and roof control by rocks caving [3]. In this block the coal seam no.3 has the thickness ranging between 2 and 11m and the dip of about 60 – 68$^o$ [20].

As in the cases previous presented, the statistical analysis led to the profile function (14), explicit in function of the time, with the aid of the following regression coefficients:

$a_1 = 3.860 \cdot 10^{-140}; b_1 = -11.879; c_1 = -0.024739;$

$a_2 = 62.418; b_2 = 63.180; c_2 = 0.135407;$

($R^2$=0.865).

The subsidence curves, measured and approximated, are shown in Figure 12.

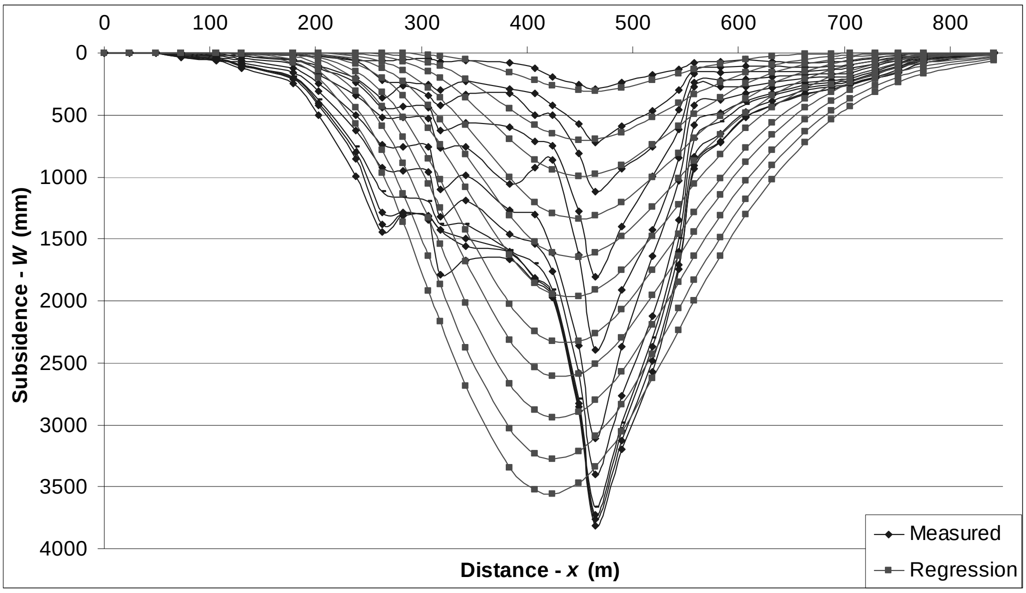


*Fig. 12. Subsidence curves, depending on the time, in the case of coal seam no.3, block III, Dâlja Mine*

**Conclusions**

At the same time with the reconsideration of the mining of Jiu Valley hard coal deposit, because of the closing programme of several mines and the beginning of a new panels' mining and the need for the revalorization of the surface lands and the assessment of the constructions' integrity, the requirement of assessment of the ground surface stability has arisen, in the mining fields influence areas.

Therefore, an immediate assessment of the measurements provided over time was tried, in the different Jiu Valley mining fields and the analysis of this data base, stored by the Hard Coal Company of Petroşani (some significant case studies are presented in this paper).

We mention that the data analysis was difficult because the ground surface monitoring was made following the alignments that were not always relevant from a scientific point of view. Over time, the purpose of this monitoring was to observe the stability of certain roads, land areas and other targets of immediate interest.

By consequence, a time dependent profile function was elaborated, which predicts very well the development in time of the subsidence basins produced as an effect of the underground mining of the thick coal seams of the Jiu Valley coal basin. Also, with the encouraging results, we tried to adapt, at the Jiu Valley conditions, the profile function made by Peng and Chen for the Northern Appalachian Coalfield.

The subsidence phenomenon analysis by the profile functions methods, by numerical modelling and other researches tools will be further developed, at the entire coal basin level. These are the prediction and control methods, necessary for the new panels mining design and the measures required to mitigate the degradation phenomenon of the lands situated under the influence areas of the underground mining fields.

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