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Predictive modelling of surface subsidence above an underground coal mine at Máza-Váralja-South (Northeast Mecsek, Hungary)

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Abstract

Today the number of the environmental hazards multiplied - mostly due of human impact. The anthropogenic landforms can be predicted by engineering methods in a mining area. These methods became the instruments of Environmental Impact Assessment (EIA). In this paper, such calculation method was applied, but it was combined with GIS. The vertical and horizontal spatial extent of a negative montanogenic landform was modelled. The results of this combined method estimate the locations of the expected major subsidences, thus it would be the basis of monitoring by surveying.

Keywords: subsidence sag and trough, Somosvári's modell, GIS, anthropogenic and environmental geomorphology

Introduction

The environmental problems of coal mining have been studied since it was industrialized. The number of scientific papers related to environmental impacts of the mining has increased since 1972 when the UN Conference on the Human Environment was held in Stockholm (Bian, Z. *et al.* 2010). However, the 1st International Symposium on Land Subsidence was organized by UNESCO in Tokyo as early as 1969 (Carreón-Freyre, D.C. 2010).

Surface subsidence is an inevitable corollary of underground mining. This phenomenon brings changes to surface landforms and to all natural factors (e.g. Blodgett, S. *et al.* 2002). The sag- to trough-shaped subsidence (Marino, G.G. 1993) was redefined and combined with definitions of Erdősi, F. (1987) after the geological and mining properties. The sag extends to only one level of the mining block, but the subsidence trough is the cummulative subsidence landform from different levels above a structural block. According

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to theory of Lehmann, K. (1919) the subsidence trough is found where the vertical and horizontal movements take place. Niemczyk, O. (1949) distinguished three further components of vertical and horizontal movement: inclination or tilt, curvature and strain (tension or compression), necessary to asses possible surface damage, because the buildings, the electrical poles, the trees are affected by them (Hoványi, L. 1968; Bahuguna, P.P. *et al.* 1991; Singh, M.M. 1991).

The maximum value of the mining subsidences could reach in some places -20 to -35 m e.g. in Ostrava-Karviná Region in Czech (Martinec, P. and Schejbalová, B. 2004; Brázdil, R. and Kirhcner, K. 2007), in Katowice Region or Rybnik Region in Poland (Liszkowski, J. 1991; Dulias, R. 2011) and in Ruhr Coal Basin in Germany (Drecker, P. *et al.* 1995).

Mining subsidence in Hungary was investigaed by Martos, F. (1956), Richter, R. (1965), Hoványi, L. (1968), Somosvári, Zs. (1989) at the Faculty of Mining Engineering University of Miskolc. The research program on the "determination of moving field of the cover layer above underground mining" took place between 1969 and 1984 in Mecsek Coal Basin (Somosvári, Zs. 2009). The mines closing inferred the subsidence calculation of time dependence after the change of political regime (Turza, I. 1990; Ládai, J.T. 2003). Because it is important when would stop the subsidence and its impacts.

The Calamites Ltd. plans to open an underground black coal mine at Máza-Váralja-South in the near future and therefore it is necessary to analyze the predictable environmental risks (Juhász, Á. 1976; Erdősi, F. and Lehmann, A. 1984; Fábián, Sz. Á. *et al.* 2006; Szabó, J. 2010). The longwall mining method, which will be applied, is a common technique for coal extraction in many countries, but the mining of large blocks induces severe ground movements - although their rate might be pre-calculated (Raman Rao, M. V. 2010).

Study area description

The study area of 10.5 km^2 is located eclosed by the villages Máza–Váralja–Óbánya (*Figure 1*) in the NE Mecsek Mountain (SE Transdanubia, Hungary). This area belongs to the region „Mecsek- and Tolna–Baranya Hills" (Pécsi, M. and Somogyi, S. 1967) and it is bounded by the Völgység Stream, and the Völgység Hills on the North. The NE and E part of the East Mecsek (Dobogó–Zengő-Group) consist of radially-orientated horst groups. The three main interfluve ridges diverge from the horst of Dobogó Peak (594 m) to N, NE and E direction. The ridges are lowering from the S (490 m) to north (290 m). Both of the two relevant valleys (the Váraljai Creek and the Mázai Creek) and catchment area has SW–NE direction and they are structurally guided erosional valleys. The minimum elevation of study area is 184.15 m in the Váraljai Creek. Erosional valleys, ravines, gullies, alluvial cones, interfluves and ridges are the typical

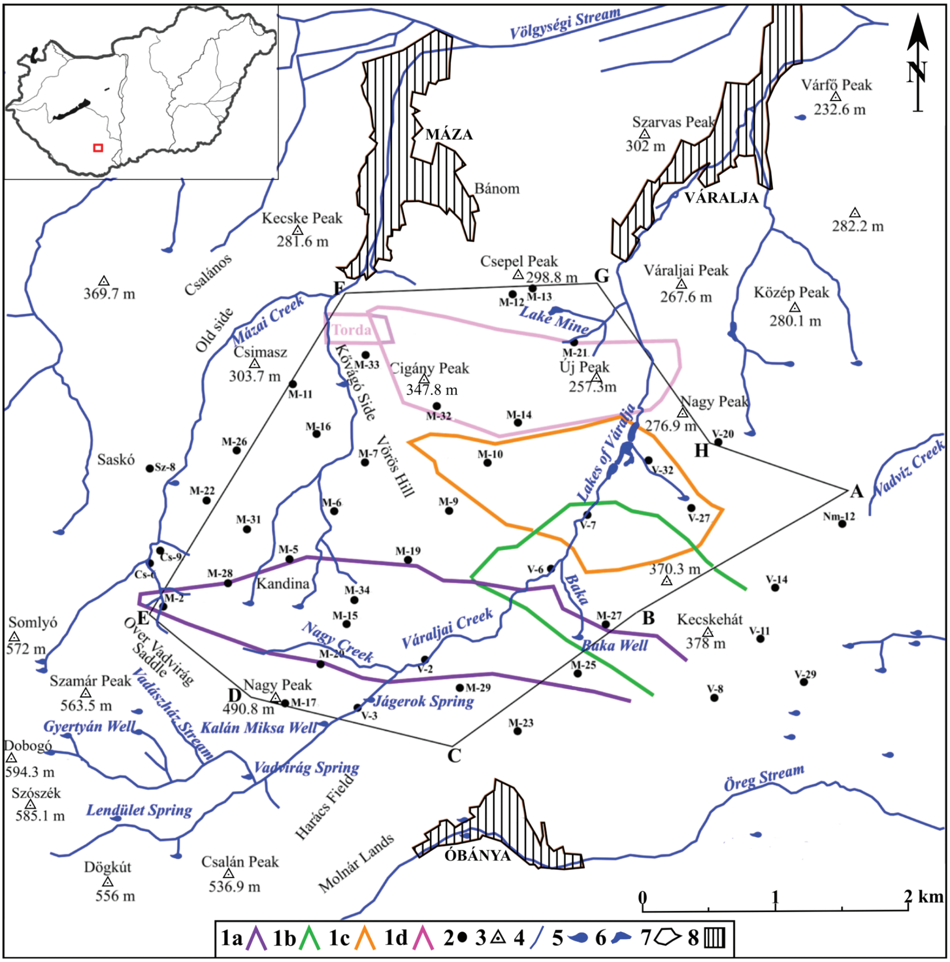

Fig. 1. Map of the study area. – 1a–1d = structural blocks; 2 = boreholes with numbers; 3 = major hill or peak; 4 = stream; 5 = spring; 6 = lake; 7 = study area bordered with cut-off points (A–H); 8 = settlements

landforms of the study area (Lovász, Gy. 1974). Former mine exploitation ended in 1965, therefore many anthropogenic forms, for instance spoil heaps and scarps could be found near settlements. Erdősi, F. (1987) reported four subsidence troughs of 3.75 km^2 area in North Mecsek mining districts.The old pits are located on the northern part of the study area. The large part of the study area is „untouched", and it belongs to the Duna-Drava National Park and the Natura 2000 network.

In ca. 24 km^2 area 62 boreholes were deepened between 1953 and 1985 (Szilágyi, T. and Villám, E. 1985). By a more recent analysis of borehole data seven structural blocks was assessed (Püspöki, Z. *et al.* 2009). These blocks include 24 black coal seams with an average thickness of 2.6 m and dip of 5–40° SSW.

The Lower Jurassic (Hettangian-Sinemurian) black coal seams are covered by Late Mesozoic sediments: marl, clay marl, aleurolite, calcareous marl, sandstone, stone flour and conglomerate. A significant tectonic and volcanic (basalt dykes, explosion breccia) events took place in this area in the early Cretaceous (but much younger movements are also known from the borehole). To the influence of movement the sedimentary deposits were folded and overlapped. According to Püspöki, Z. *et al*. 2010 the blocks have an imbricate structure: the violet block (+1) on the top, the green block (0) in the middle and the orange block (–1) on the bottom (*Figure 1*). The younger cover rocks from the Cenozoic era are lacustrine aleurolite, conglomerate, sandstone, andesite, rhyolite tuff, fluvial coarse-grained conglomerate, marl, lignite and Pleistocene loess, clay with stone flour and colluviums (Hámor, G. 1970; Szilágyi, T.–Villám, E. 1985).

Objectives and methods

The goal of this study was to determine the vertical and horizontal extent of subsidence landforms (sag and trough). Therefore the main goal was to apply a calculating method completed with GIS for mining engineering on the land subsidence. On the one hand, the surface subsidence was calculating as point grid in resolution of 50 m in one structural block (+1 East). On the other hand, surface model was interpolated and compared with real surface in detailed resolution of 5 m.

The method relies on the national and international literature (Somosvári, Zs. 1989). The input data were derived from the geological final report and excavation plans (Püspöki, Z. *et al.* 2009). According to the plans of 2009, the extraction of the total coal amount (to −300 m a.s.l.) would last about 30 years and the model display the predictable final ondition after movements.

The calculation of the data and the analysis was performed in *MacOsX (5.2.)* operation system and cost-effective free softwares were used. The values of subsidence were calculated on *NeoOffice Calc (2.2.4.)* in 50×50 m grid. The expected movements in the subsidence trough were determined from the Somosvári's model, because these differential equations considered the rock mechanical data, beside the mining data (Somosvári, Zs. 1989). Moreover, the geomorphologic data were encased to the equation, the mean relative elevation above the mining block. Natural surface processes were not considered because the anthropogenic subsidence is significantly greater as the natural denudation during 30 years. The surface data derived from 1:10,000 scaled topographic map (24–431, 24–433, 24–342, 24–344 in EOV Hungary's coordinate system). The staff of the University of Debrecen made the digitalization with *GeoMedia (6.0.)* software and I made a refinement with *QGIS (0.5.3.)* software. The mining plans and structural blocks were digitalized with *QGIS* also. The *Grass (6.4.0) GIS* software was applied to the modelling. The interpolation method is "*Regularized spline tension* (*v. surf. rst*)" with resolution of 5×5 m. The *Inkscape (0.48.1)* and *Gimp (2.6)* was applied to the figure editing.

Somosvári's model and the required data

The extraction of the coal seams reaches −300 m a.s.l. and it carries on three levels. Five structural blocks will be affected but in this paper only the +1 block was modelled. The main cross tunnel divides the +1 block into two parts and the width of the protect pillar increases with depth *(Figure 2).*

Both of the mining and rock mechanical data was considered in these differential equations.

In the first step, the basic of the equations the maximum subsidence ($w_0$max) was calculated:

$$w_{0\max} = M \cdot s \cdot (1-\eta_t)$$, where

M is the extracted seam thickness *(Table 1),*

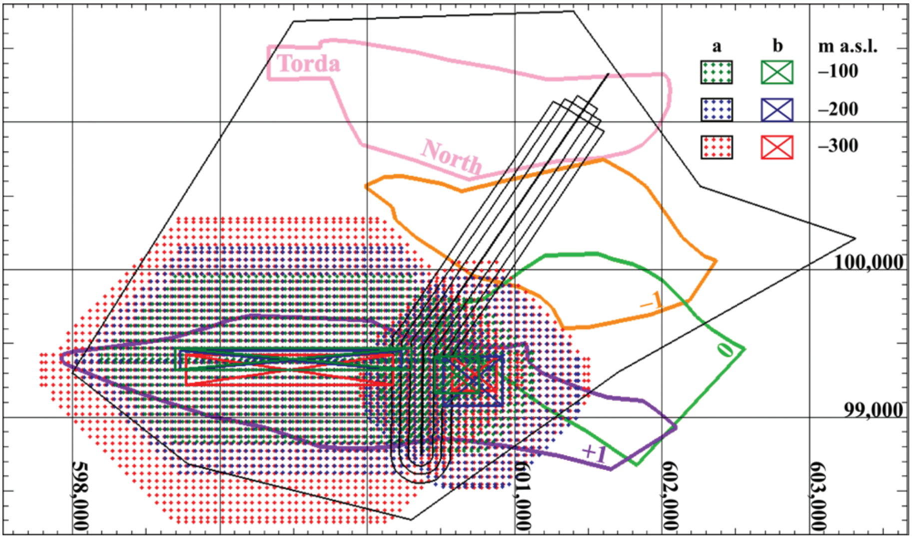

Fig. 2. Map of the mining block and grid points of the subsidence sags in +1 structural block

s is the subsidence factor, which has 0.82 value in the Mecsek Mountain after Hegedűs, Gy. (1971) and

ηt is the backfill coefficient that is an important factor of abandon method. This value is "0" by roof-fall method, "0.8" by machine backfilling, "0.55" by chamber-and-pillar working (Sütő, L. 2000). In the present case with "0" backfill coefficient was calculated, because the rock movements will be ignored naturally.

The system of the differential equation gives the following expression to the surface subsidence, in which the adequate connection and border conditions were considered (Somosvári, Zs. 1989).

If $x \geq 0$

$$\begin{aligned} w(x,y) = w_{0\max} \cdot \cos\frac{a \cdot \alpha \cdot \pi}{180} \cdot \{ & 0.585 \cdot [\exp(-Ax) - \exp[-A(x+2l_x)]] - \\ & -0.085 \cdot [\exp(-Cx) - \exp[-C(x+2l_x)]] - \\ & -0.224 \cdot [1-\exp(-\frac{k}{\sqrt{m-1}} \cdot \frac{y}{H})] \cdot [\exp(-Ax) - \exp(-Cx) - \\ & -\exp[-A(x+2l_x)] + \exp[-C(x+2l_x)]]\} \end{aligned}$$

If $-2l_x \geq x \geq 0$

$$\begin{aligned} w(x,y) = w_{0\max} \cdot \cos\frac{a \cdot \alpha \cdot \pi}{180} \cdot \{ & 1 + 0.585 \cdot [\exp(Cx) - \exp[-C(x+2l_x)]] - \\ & -0.585 \cdot [\exp(-Ax) - \exp[-A(x+2l_x)]] + \\ & +0.224 \cdot [1-\exp(-\frac{k}{\sqrt{m-1}} \cdot \frac{y}{H})] \cdot [\exp(Ax) - \exp(-Cx) + \\ & +\exp[-A(x+2l_x)] - \exp[-C(x+2l_x)]]\} \end{aligned}$$

where

$$A = 0.618 \cdot \frac{k}{H} \quad \text{and} \quad C = 1.618 \cdot \frac{k}{H}$$

where the coefficients depend on the direction in the grid (Staudinger, J. 1972).

The mining blocks have an horizontal extent in dip ($2l_x$) and in strike ($2l_y$) furthermore a vertical extent (*M*). The distance from the center of relative coordinate system is the "l". The rate of dip (*α*) of the coal seams of the mining block is 25°. The mean elevation above the mining blocks from the DEM was queried, thus the cover thickness from bottom edge (*Hb* = *ME*–100/–200/–300) and upper edge (*Hu* = *Hb*–*M*) of the extracted area was calculated in line of dip *(Table 1).*[2]

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[2] +1 = structural block; W = west side of the structural block; E = east side of the structural block; 1 = first level (–100); 2 = second level (–200); 3 = third level (–300); $2l_y$ = extent of

Table 1. Data of the +1 structural block and mining levels[1]

Block and levels	$2l_y$ [m]	$2l_x$ [m]	M [m]	ME [m]	Hu [m]	Hb [m]	k
+1W 1.	1,600	150	13.0	379.71	466.71	479.71	10
+1W 2.	1,500	130	20.9	380.75	559.85	580.75	9
+1W 3.	1,400	200	21.2	383.70	662.50	683.70	8
+1 E 1.	300	250	13.0	266.27	353.27	366.27	10
+1 E 2.	400	330	20.9	285.30	464.40	485.30	9
+1 E 3.	300	230	21.2	277.68	556.48	577.68	8

The Poisson Number (*m*) is a value of the deformation in cross and in length direction by one way tension state. The Poisson number is between 3.2 and 5.0, the rock parameter (*k*) is between 7.5 and 10.0 by medium hard marl and sandstone cover rock seams. The upper limits were applied for both geology determined parameters. Theoretically the rock parameter decreases with depth of mining level according to cracked rocks (*Table 1*). But it would be depend on the order of roof-fall in levels. Thus the limiting angle decreases and the sag becomes wider. The last rock mechanical data are the anisotropy (*a*) approx. 0.5. The delay time (T_0) of a rock movement is $H_u/3.5$ (Turza, I. 2006) that depends on cover thickness (H_u) above a point. Therefore the average time is 189.29 days (0.519 year) above the last mining level of +1 West block.

Results and discussion

The horizontal extent of the sag and trough

The limiting angle (*β*), the impact range (*r*) and the impact parameter (*IP*) is needed for calculating the horizontal extent of subsidence sag and trough. According to Somosvári, Zs. and Buócz, Z. (1993) calculating angle of draw is the first step:

$$\beta = arcctg\left[\frac{1}{0.618k}\ln\frac{0.585\cdot M\cdot s}{\Delta w}\pm\frac{1}{k}\right]$$

where the last point of the subsidence sag (*Δw*) is a new parameter, which has an insignificant value (0.01 m). Limiting angle (*β*) means the inclination of a section between last moving point and the edge of extracted block away from horizontal line. The impact range (*r*) is obtained from multiplying the seam

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the extraction area in strike [m]; $2l_x$ = extent of the extraction area in dip; *M* =thickness of the coal seams or thickness of mining block; *ME* = relative mean of elevation above the mining block; H_u = the cover thickness from upper edge of the extracted area in line of dip; H_b = bottom edge of the extracted area in line of dip.

thickness by cotangent angle of draw. This range is the distance between the edge of the mining block in surface projection and last moving point.

$$r = H_u \cdot tg(90° \pm \beta)$$

The impact parameter is the distance from the centre in a relative grid (50×50 m). The value is totalled on the half horizontal size of extracted block and impact range (Turza, I. 2006). It should be noted, that the subsidence values were calculated from the edge to the centre of the extracted block in line of strike, but in line of dip the extent value could be calculated in both direction by Somosvári's formula in *NeoOffice Calc*. Because the contact conditions require that the calculated subsidence should be equal to each other by both side in the location $y = 0$ (Somosvári , Zs. 1989). The zero point is the connection point that ensures the connection between relative and EOV coordinate system. The zero point equals to centre of the extracted mining block, but the maximum subsidence would not occur here.

Resulting from the exponential function the subsidence of grid points decreasing to zero. The maximum extent of sag was developed belonging to the third level and it belongs to the subsidence trough too. Horizontal extent reaches 3,255.52 m in W–E direction (*y*) from 597,792.24 to 601,047.76 (EOV) and 2,055.52 m in S–N direction (*x*) from 98,292.24 to 100,347.76 (EOV) in western side of the structural block. But in eastern side of the block its extent reaches 1,546.96 m in W–E direction from 599,951.52 to 601,498.49 (EOV) and 1,476.96 m in S–N direction from 98,521.52 to 100,048.48 (EOV). The extent of other levels may be calculated in cognition of the connected point in EOV and impact parameter.

GIS modelling

The relative coordinates were calculated to EOV according to connection point. The 50×50 m grid points were imported to *Grass GIS* for generating the vector file (*Figure 2*). On the west side 4658 and on the east side 1721 grid points were totally calculated in three level of the +1 structural block (*Table 2*)[3]. The intermediate points were interpolated with *"v.surf.rst"* command in each level and the surface of the sags was determined.

The theoretical surfaces of sags on the west and the east side partly overlap therefore the sags were totalled to determine the subsidence trough (*Figure 3*). The map of trough was reclassified in eight categories. In the zero

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[3] β = angle of draw in degree; *r* = impact range; *CP* = connection point in relative and in EOV coordinate system; *IP* = impacts parameter in West, East, North and South direction; *Points* = amount of grid points in 50×50 m.

category, there is no vertical displacement or the value is negligible in terms of surface modification. But the negligible (0–-1) values play a role in the horizontal extent that it was represented by impacts parameter. The first category is the utmost and extends on area of 136.75 hectares (*Table 3*).

Table 3. The reclassified subsidence categories and their extension

Category	Area (ha)
1	136.75
2	37.86
3	23.48
4	17.04
5	15.02
6	11.63
7	1.69

The maximum value of the subsidence is known in sag from the calculated point of the relative grid. But the totalled maximum was queried only from interpolated trough. The minimum point of W–E profile curvature is −27.05 m on West and −32.15 m on East side of the trough (*Figure 3, Table 4*).

The maximum subsidence values are shifted to North. It is clearly visible on the N–S cross-section profile, because the general SSW dip effects closeness of the coal seams to the surface (*Figure 3*). Thereafter, trough DEM was extracted from the recent surface DEM to analyse a theoretical surface changing (*Figure 4*).

Table 2. The horizontal extent of subsidence in mining levels of +1 structural block and the number of the calculated points

Block and levels	β [°]	r [m]	CP [y;x]	CP EOV [y;x]	IP Center [y;x]	IP W	IP E	IP S	IP N	Points
+1 W 1.	43.84	486.01	−800 −75	599,495 99,395	600,295 99,470	2,086.00	486.00	636.00	486.00	1,087
+1 W 2.	38.83	695.57	−750 −65	599,480 99,385	600,230 99,450	2,195.57	695.57	825.57	695.57	1493
+1 W 3.	35.53	927.76	−700 −100	599,470 99,320	600,120 99,420	2,327.76	927.76	1127.76	927.76	2078
Sum										4658
+1 E 1.	43.84	364.87	−150 −125	600,605 99,285	600,755 99,410	647.87	364.87	614.87	364.87	369
+1 E 2.	41.81	519.22	−200 −165	600,715 99,245	600,915 99,395	919.22	519.22	849.22	519.22	664
+1 E 3.	41.75	623.48	−150 −115	600,725 99,295	600,875 99,410	923.48	623.48	853.48	623.48	688

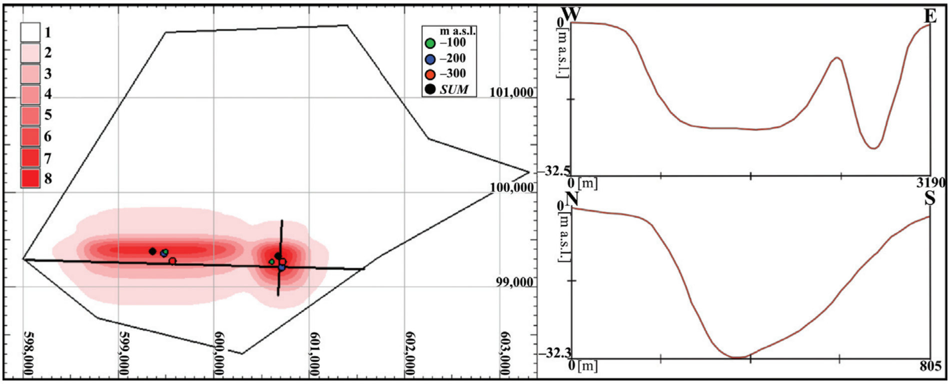

Fig. 3. Interpolated and totalled subsidence value of the trough and its WE and NS profile. 1 = 0 – (− 1); 2 = (− 1) – (−5); 3 = (− 5) – (−10); 4 = (−10) – (−15); 5 = (−15) – (−20); 6 = (−20) – (−25); 7 = (−25) – (−30); 8 = (−30) – (−35)

Table 4. Maximum subsidence of mining levels and trough

Level	S_{max} [m]	S_{max} EOV [y;x]
-100_W	−7.46	599,495; 99,370
-200_W	−10.80	599,480; 99,350
-300_W	−10.78	599,570; 99,270
Sum	*−27.05*	*599,360; 99,380*
-100_E	−8.71	600,605; 99,260
-200_E	−14.07	600,715; 99,210
-300_E	−10.46	600,725; 99,260
Sum	*−32.15*	*600,673; 99,326*

Discussion

Ground subsidence is simply defined as a lowering of the land surface elevation (Larson, K. J. *et al.* 1999). The vertical movements would be manifest not only in lowering of the elevation, but in changes of slope that seems on cross-sections of the *Fig. 4*. The utmost subsidence would occur in the East side of the trough in the upper section of theVáralja Creek. Accordingly, the erosion base would sink and the process explains its effect to every stream in the vicinity of the trough too.

In the calculation process, the 50×50 m grid was not worth to engross, because only 1–2 m difference are seemed between two neighbouring point in this resolution. It was essential to use the adequate interpolation method. The regularized spline tension method was suitable, because this algorithm

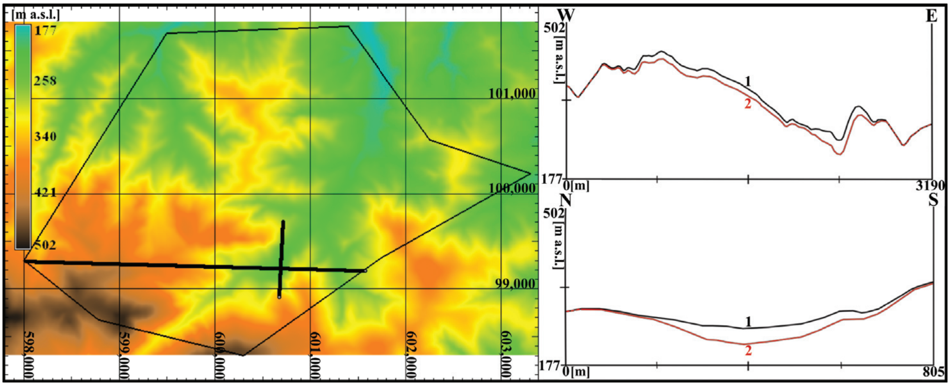

Fig. 4. Digital Elevation Model after subsidence and WE and NS profile of the elevation changes. – 1 = recent; 2 = subsidence surface (red)

produces smooth slope curves that fulfil the condition of orthogonality to contour lines better than standard grid (Mitášová, H. and Mitáš, L. 1993; Mitášová, H. and Hofierka, J. 1993).

The mean of the elevation was involved to the calculations because the separate query of the cover thickness would be difficult for each point. And it is also not justified because the bore log is unknown at each point for calculation of the rock parameters.

Conclusion

The horizontal extent of subsidence trough is 3,706.25 m from 597,792.24 to 601,498.49 in line of y, and 2,055.52 m from 98,292.24 to 100,347.76 in line of x. The extension of the trough is 2.44 km^2 without the zero category. The maximum subsidence is -27.05 on West and - 32.15 m on East side of the trough.

The applied model is suitable to calculation of the conceptual subsidence trough, which give a guideline to the geodesic surveying after starting mining. Thus the location of the maximum vertical movements and their horizontal extent would be recognized.

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