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DEFORMATION PHENOMENA IN SUBSIDENCES AND THEIR MODELLING AT THE SLOVAK COALFIELDS

Summary. The dynamic nature of the earth surface subsidences is dependent on a mining technology and the time of its activity. The determination of subsidence development over time is the main phase of the related deformation analysis as of the subsidence models. Modelling subsidence development is presented as a convenient subsidence prediction technique. The proposed prediction method of mining induced subsidence development applied at the Slovak Handlová coalfield with the mining longwall operations is based on a prediction method based on the theory of modelling subsidence development follows from a method proposed by Knothe. Theoretical calculations in modelling were verified using data collected from surface monitoring, from which the appropriate site - specific parameters were obtained. Accuracy of the investigated subsidences is determined on the basis of comparing subsidences of monitoring station points, which were experimentally geodeticaly determined, with those subsidences determined modelling. The results with accuracy analysis in subsidence development modelling have confirmed the applicability of this method in deformation surveying practice.

ZJAWISKA OSIADAŃ I DEFORMACJI I ICH MODELOWANIE W SŁOWACKICH ZAGŁĘBIACH WĘGLOWYCH

Streszczenie. Charakter dynamiki osiadań powierzchni terenu zależny jest od technologii wybierania oraz okresu jej stosowania. Rozwój osiadań w czasie jest głównym czynnikiem związanym z badaniem deformacji przy analizowaniu modeli subsydencji. W Zagłębiu Węglowym Slovak Handlová eksploatacja prowadzona jest systemem ścianowym. Zaproponowana tu metoda rozwoju osiadania, spowodowanego stosowanym systemem eksploatacji, oparta jest na teorii modelowania subsydencji Knothego.

Wyliczenia teoretyczne, dokonane przy modelowaniu, zostały zweryfikowane przez zastosowanie danych zebranych w trakcie monitoringu powierzchni z przeznaczonego do tego celu obszaru. Uzyskano tu specyficzne parametry. Dokładność badanych osiadań określo-

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no na podstawie porównania danych osiadań z punktów objętych monitoringiem, w których osiadania wyznaczono za pomocą modelowania.
Wyniki i dokładność analiz przy modelowaniu rozwoju subsydencji potwierdziły praktyczne możliwości stosowania tej metody.

Introduction

The dynamic nature of mining subsidences of the hanging walls on the earth surface is dependent on a mining technology and the time of its activity. The determination of subsidence development over time being the final phase of the related deformation analysis as a convenient subsidence prediction techniques a basis of the subsidence models. Many methods for determining the nature of subsidence can be used to simulate in advance the final and continuous state of the subsidence process (Schenk 1997, Novák 1998).

The theory of modelling subsidence development follows from a method proposed by Knothe. The method is based on the Gauss distribution of effects. The method determining the time dependence of subsidence is verified by several studies of the undermined area in the Slovak brown coal deposit at Handlová (Kunák et al. 1985, Sedlák 1992 a & b).

The main methods of simulating the movement of the earth surface caused by mining activitiy are generally oriented to the final asymptotic strain state. The process of development of subsidence with time does not make it possible to carry out detailed calculation of the deformation parameters in the individual intermediate stages of its development, during subsidence. Even the most efficient mining projects, such as planning of deformation measurements to prevent or minimise the damage caused by mining activity in the earth service, requires a suitable method for determining the development of subsidence and a method enabling prediction of the procedure of formation of the process of subsidence in relation to the time factor.

The currently available solutions of the time dependence of formation of subsidence often disregard many important subsidence data in the stage from monitoring subsidence up to scientific analysis. The development of the methods of the time dependence makes it possible to use data which support the formation of several reliable and convincing technologies which can be used in predicting the nature of the subsidence process.In this paper, the existing method defining the gradual development of subsidence in relation to time is described, mainly for mining coalfields by the longwall mining operations. This method is analyzed and suitably applied to the specific mining and geological conditions of the Handlová brown coalfield in Slovakia.

The computer modelling subsidence development is very important from a mining surveying view. The periodic monitoring subsidence data at each observed measurement point of the monitoring station must be adjusted and saved. A process of computer modelling subsidence development can be simplified and sped up by some integrated measurement systems - the total geodetic stations, hardware and software (for example MicroStation). The MicroStation Development Language (MDL) can be used for modelling mine subsidences (Sedlák & Havlice 1994).

Modelling subsidence development

Theoretical principles

The effect of time during subsidence can be expressed by the function (Knothe 1953)

$$z(t) = 1 - exp(-ct), \tag{1}$$

and, considering that $c(t)$ is constant, the subsidence rate $\dot{s}(t)$ can be expressed by means of the difference (Knothe 1953, 1957)

$$\dot{s}(t) = c[s_f(t) - s(t)], \tag{2}$$

where:

$s_f(t)$ is the final (asymptotic) subsidence at time t ;

$s(t)$ is the actual subsidence at time t ;

$[s_f(t) - s(t)]$ is the subsidence potential at time t ;

c is the time coefficient.

Solving this relation the actual subsidence $s(t)$ at time t is obtained

$$s(t) = s_f(t) - exp[-c(t)]\int_0^t \dot{s}_f(g)exp[c(g)]dg, \tag{3}$$

where:

$\dot{s}_f(g)$ is the rate of the final subsidence development;

g is a coefficient which takes into account the geometrical parameters of the mined coalfield and influence radius.

The final form of the solution depends on the relation describing the final (asymptotic) state of subsidence $s_f(t)$. If the final subsidence is described using the influence function method based on the normal distribution of influences (Knothe 1957,1984), then the specific solution for a rectangular excavation panel with one advancing side approximating longwall mining, can be developed (Fig.1).

If the most simple example of the rectangular block mining operations with a single moving wall representing longwall operation is taken into account (Fig.1), the final subsidence can be expressed by using the method of the function of the effect using the normal distribution of subsidence (Knothe 1957,1984)

$$s_f(x_1, x_0, y_1, z) = \frac{s_{max}}{r_h^2} \int_{x_0}^{x_1} \int_{y_1}^{y_2} exp[-\pi(x^2 y^2 / r_h^2)]dxdy \tag{4}$$

where:

s_{max} is the maximum subsidence, $(s_{max} = -am)$;

a is the subsidence factor;

m is the thickness of the mined layer;

r_h is the influence radius on the horizon h.

Subsidence at the longwall layers

The origin of the coordinate system is placed at the point $A(0,0)$ at which subsidence is examined, with the mining advancing at a constant rate v in the x -axis (Fig.1). The time development of subsidence of the longwall layers over the mined layers which can be indicated by periodic monitoring of the observed point network in the earth surface, has three main subsidence phases. All phases are conditional on mining excavation technology and its time working schedule. The first subsidence phase is the initial phase and begins from the start of mining activity up to the moment when the face wall moves below the observed point in the earth surface. The second phase is defined by the time period t conditioned by the mining rate v, time coefficient c and influence radius r. The time period of this main subsidence part can be expressed by the simple Eqn. 5 (Karamis et al. 1990).

$$t = (r / v + 1 / c). \tag{5}$$

The third phase presenting the final subsidence is limited by the end of the second phase and the time at which the observed point acquires the final subsidence value. Because in this phase the final subsidence at time $s_f(t)$ equals to the result subsidence value of whole subsudince, then it can be used as the constant (s_f) at the following onsiderations.

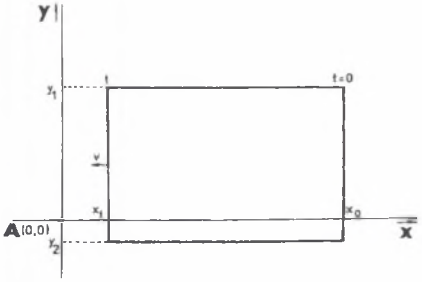

Fig.1. Geometry of the longwall mining operation with a single moving wall.
Rys.1. Geometria obszaru wybierania z pojedynczym wyrobiskiem ścianowym

The second main phase of subsidence development in time participates on the maximum rate of subsidence $\dot{s}_{max}$ which is approximated by Eqn. 6

$$\dot{s}_{max} = \frac{s_f v}{r + (v/c)}, \tag{6}$$

where:

s_f is the final subsidence value.

In the case in which the subsidence process is continuous without interruption $(c = \infty)$, the maximum rate of subsidence will be

$$\dot{s}_{max} = (s_f / r) v. \tag{7}$$

Then modelling subsidence development can be possible for each observed point of a monitoring station in the earth surface or some mine horizon as the maximum rate of subsidence in any time of mining activity.

Application of the method in modelling to the handlová brown coalfield

The Handlová brown coalfield belongs to the largest and the most economically significant coalfield in Slovakia. The longwall mine method is the typical extraction method for this coalfield. Two coal flat technically faulted seams with an extraction thickness *m* of 2 m are found at the mining depth *H* of 300÷400 m.

On the basis of long-term examination of deformation changes in the earth surface of the Handlová brown coalfield we collected and analysed subsidence data of three main subsidence lines from more than 90 measurement points in the monitoring station (Fig.2). In all cases of the subsidence examination we selected, from the final subsidence curves, characteristic parameters for the functional method of the subsidence effect with respect to time, such as (Sedlák 1993):

- the influence radius $r = (170 \div 200\ \text{m})$;
- the final subsidence $s_f = (0.2 \div 2.5\ \text{m})$;
- the distance of the so-called "edge effect" d, i.e., the distance by which the wall must advance to ensure that the rock on the undermined region comes to assume a regular form, $d = (1/4 \div 1/5)$ of the mined depth h, (theoretical calculated distance $d' = (72 \div 78\ \text{m})$ and the actual one $d = (70 \div 87\ \text{m})$ of the "edge effect" were taken to modelling);
- the mined depth $h = (300 \div 400\ \text{m})$;
- the mining rate $v = (0.9 \div 1.2\ \text{m.day}^{-1})$;
- the phase of main subsidence $t = (194 \div 216\ \text{days})$.
- the content of hard rock in hanging wall layers $TH = (35 \div 40\ \%)$, (at the Handlová brown coalfield it is approximately 36 %);
- the time coefficient $c = (0.036\text{day}^{-1}$,i.e., $1.3\ \text{year}^{-1})$.

Tab.1 shows the comparison of the maximum subsidence development rate values $\dot{s}_{maxG}$ from periodic geodetic measurements and calculated (modelling) ones $\dot{s}_{max,M}$ from Eqn. 6. The final subsidence values s_f were considered as the geodetic ones s_{f_G}, because the final subsidence values s_{f_G} were observed by using the very accuracy geodetic total station (TOPCON GTS 6A).

If the subsidence over the advancing face of extraction is less than 10% of the final subsidence s_f, then subsidence at any time $s(t)$ can be approximated by equation

$$s(t) = s_f \{ 1 - exp[-c(t - \Delta t_o)] \} \quad \text{for } t \in (\Delta t_o, \propto), \tag{8}$$

where

t is time calculated from the moment the face of excavation passes under the subsiding point;

Δt_o is time adjustment value due to „edge effect „ present at the excavation face, which creates some additional deal in subsidence development, (at the Handlová brown coalfield it is approximately 75 days), ($d' = \Delta t_o v$).

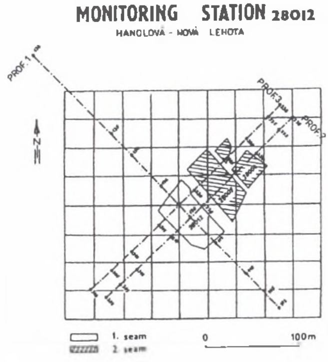

Fig.2. Monitoring station in Handlová-Nová Lehota
Rys.2. Schemat stacji monitoringu

Tabela 1

Subsidence development rate values

Profile	Point	h	v	s_f =		
		[m]	[m.day^{-1}]	[m]	[m.day^{-1}.10^{-3}]	
1/28012	120	346	0.9	1.775	7.8	7.6
1/28012	123	337	0.8	2.281	8.5	8.8
2/28012	220	370	1.2	1.530	8.6	8.4
3/28012	312	392	1.1	0.996	5.3	5.1
3/28012	320	313	1.1	1.324	6.7	6.8

Fig.3 demonstrates cases of the single function (Eqn.8) approximating the time dependence of subsidence development for two chosen observed points of the monitoring station. Modelling subsidence development of each observed point of the monitoring

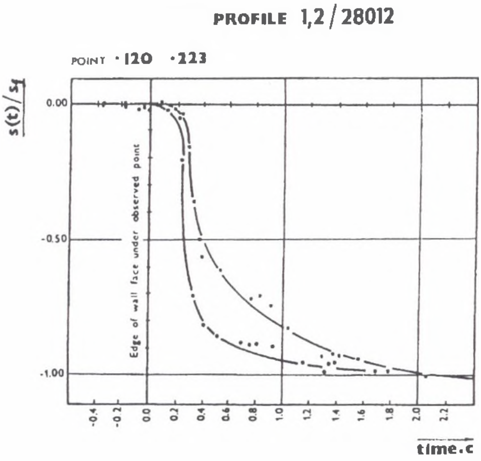

Fig.3. Time dependence of subsidence for chosen points
Rys.3. Czasowe zależności osiadania wybranych punktów

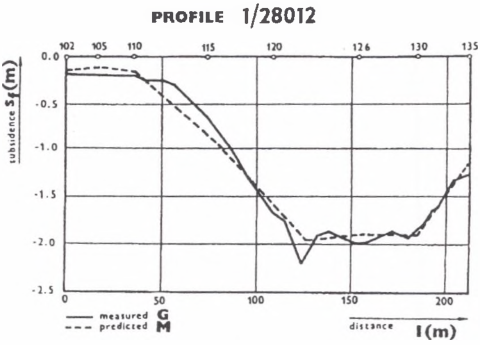

Fig.4. Graphical comparison of measured and predicted subsidence development - PROFILE1/28012
Rys.4. Graficzne porównanie osiadań przewidywanych i mierzonych - PROFILE1/28012

station at the Handlová brown coalfield can be made out from the presented theory about the time dependence of the subsidence development for a various moment of mining activity. In this way the predicted subsidence development of the earth surface over a mined space can be obtained. Comparison of the measured final subsidence development (s_{f_G}) and calculated one (s_{f_M} - Eqn. 4) at the profile No 1/28012 of the Handlová monitoring station is shown in fig.4.

Analysis of subsidence accuracy

Accuracy of the investigated subsidences is determined on a basis of comparing subsidences of monitoring station points, which were experimentally determined in a geodetic way, with these subsidences determined in a modelling way (Sedlák 1997, 1998).

Notice : For a purpose of simplification of the symbols, we have introduced the following ones:

- geodetic subsidences:

$$s_{GEOD} = s_{(120-120')G} = s_{G_1}; s_{(123-123')G} = s_{G_2}; \ldots s_{(320-320')G} = s_{G_n} = s_{(ij)G} = s_G$$

- modelling subsidences:

$$s_{MODEL} = s_{(120-120')M} = s_{M_1}; s_{(123-123')M} = s_{M_2}; \ldots s_{(320-320')M} = s_{M_n} = s_{(ij)M} = s_M$$

Every space distance $s_{ij}; i, j\rangle 1, n\langle$ (subsiding point makes a space distance from its start, for example point *120*, to final subsidence value, point *120'*) is defined by two points

B_i, B_j whose coordinates x, y, z are determined in a cartesian three-dimensional (3D) rectangular system by convenient geodetic method.

For these subsidences hold

$$s_{120-120'} = \sqrt{(x_{120'} - x_{120})^2 + (y_{120'} - y_{120})^2 + (z_{120'} - z_{120})^2}$$

$$s_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$$

$$\boldsymbol{s} = f\,(\boldsymbol{c}_1, \ldots\ \boldsymbol{c}_i,\ \boldsymbol{c}_j, \ldots) \tag{9}$$

where:

$$\boldsymbol{c}_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \tag{10}$$

is the 3x1 vector of coordinates of a point B_i and

$$\boldsymbol{\Sigma}_{c_i} = \begin{bmatrix} m_{x_i}^2 & & \\ & m_{y_i}^2 & \\ & & m_{z_i}^2 \end{bmatrix} \tag{11}$$

is its covariance matrix (with zero covariance components).

In order to express the variances of s, the known law of propagation of variances can be applied to Eqn.9 in the form

$$\boldsymbol{\Sigma}_s = \boldsymbol{F}\boldsymbol{\Sigma}_c\boldsymbol{F}^T, \tag{12}$$

where $\boldsymbol{\Sigma}_c$ is the covariance matrix of all coordinates of six chosen points and $\boldsymbol{F}$ is the matrix of related coefficients (Jacobian matrix). The standard errors m_x, m_y, m_z in Eqn.12 were determined by calculation of the average measured geodetic values: horizontal angles ϖ, zenit distances z and lengths l: $m_x^2 = 12.3\ \mathrm{mm}^2$, $m_y^2 = 12.4\ \mathrm{mm}^2$ a $m_z^2 = 2.2\ \mathrm{mm}^2$ have been then introduced into the matrix $\boldsymbol{\Sigma}_c$.

The covariance matrix $\boldsymbol{\Sigma}_s$ indicates the variances of determined subsidences s_{ij}. The variances $m_{s_{ij}}^2$ of these subsidences are situated on the diagonal of this matrix and the covariances $m_{s_{ij}}$ off the diagonal.The analogous numerical procedure (Gauss-Markov model) was applied for determining variances $m_{s_{ij}}^2$ of the modelling subsidences s_M. Tab.2 shows a total review of the mean square (standard) errors obtained. If the reality is taken into consideration where the subsidences s_G are determined with the standard error $m_G = \pm 4.0$mm, it means that these subsidences are not absolutely exact. Then the final standard error m_{MODEL} of the modelling determined subsidences will be given by equation

$$m_{MODEL} = \pm\sqrt{m_M^2 - m_G^2} \tag{13}$$
$$m_{MODEL} = \pm\, 29.8\text{mm}$$

For the purpose of a detailed accuracy analysis of the subsidences determined by the modelling way it is necessary to take into account the standard errors of the parameter values mentioned in chapter 3 (the influence radius r, final subsidence s_f, edge effect d, mined depth h, mining rate v, phase of main subsidence t, content of hard rock in hanging wall layers TH, time coefficient c, etc.), too. However, in mining damages the $\pm 3\%$ accuracy in subsidence developments predicted by the modelling is very exactly.

Tablica 2

Mean square errors of the subsidences

(s_{f_G}, s_{f_M}).

Point	Subsidence		Mean square error			
	s_{f_M}	s_{f_G}	$m^2_{s_{ij}}$		$m_{s_{ij}}$	
	[m]		[mm^2]		[mm]	
			M	G	M	G
120	1.716	1.775	972.1	15.6	31.2	3.9
123	2.260	2.281	912.9	14.8	30.2	3.8
220	1.511	1.530	860.4	10.2	29.3	3.2
223	0.872	0.967	845.7	18.3	29.1	4.3
312	0.870	0.996	984.0	16.6	31.4	4.1
320	1.269	1.324	867.2	19.5	29.5	4.4
$m_{AVERAGE}$:	$m_{s_M} = 30.1$mm			$m_{s_G} = \pm 4.0$mm		

Conclusions

The results of modelling subsidence developments obtained in this paper confirm the close correlation between the measured and predicted subsidence data. This approximation can be efficiently used for the mining and geological conditions of the Handlová brown coal-field. An analysis of the results indicates that for mined depths of approximately 300÷400 m with the wall heading advance of the face front from 0.9÷1.2 m.day^{-1} and the content of hard rock in the hanging wall layers in the range from 35÷40 %, the time coefficient c is 0.036 day^{-1}, i.e., 1.3 year^{-1}.

Theoretical examination of the problem of subsidence with time,described in this paper, and comparison of the calculated and measured results for the given examples of the Handlová brown coalfield confirm and validate the efficiency of the modelling method of characterisation of the time dependence of subsidence.

To determine more accurately the time coefficient , it is necessary to analyse some further deformations parameters, for example tiltings, tensile and compressive strains, horizontal movements, etc. It will be a part of the future research in this problem.

REFERENCES

1. Karamis, M., Agioutantis, Z. & Jarosz, A., 1990: Subsidence techniques in the United States: a state-of-the-art review. Mining Research Engineering **3**, (3), 1990, pp.197-210.
2. Knothe, S., 1953: Wplyw czasu na kasztalovanie sie niecki osiadenia. Archiwum Gornictwa i Hutnictwa, Katowice, Tom.1, Zv.1, 1953, 247pp.
3. Knothe, S., 1957: Observations of Surface Movements under Influence of Mining and the Theoretical Interpretation. In: Proceedings of the Ground Movement. University of Leeds, 1957, pp.210 -215.
4. Knothe, S. 1984: Prognozowanie Wplywow Exploatacji Gorniczej. Slask, Katowice, 391pp.
5. Kunák,L., Okál,M., Dianiška,P., Krepelková,K. & Kuráň,Š., 1985: Vplyv dobývania na deformácie v okolí banských diel. Research report, TU Košice, 1985, 151pp.
6. Novák, J., 1998: K systematice účinků poddolování na hornickou krajinu. In: Sborník přednášek 6. Důlní měřické konference, Malenovice, 14.-16. září 1998, s.68-76.
7. Schenk,J., 1997: Časový faktor, důležitý prvek při zkoumaní dynamiky vývoje poklesové kotliny. Monograph, VŠB-TU Ostrava, 1997,94pp.
8. Sedlák, V., 1992 a): Solving the Time Dependence of Subsidence in Mined Areas. Transections of the Technical University of Košice, **2**, (2), 1992, pp.302-307.
9. Sedlák, V., 1992 b): Časový faktor pri vytváraní poklesov v handlovskom hnedouhoľnom ložisku. Uhli/Rudy, **11**, (1), 1992, pp.398-401.
10. Sedlák, V., 1993: Modelling Subsidence Development - Experiences from the Slovak Coalfields. In: Proceedings of the Seventh International FIG Symposium on Deformation

Measurements and Sixth Canadian Symposium on Mining Surveying. The University of Calgary, May, 3-5, 1993, pp.354-363.

11. Sedlák, V. & Havlice, K., 1994: Time Coefficient in Modelling Subsidence Development at the Slovak Coalfields. Proceedings of the IXth International Congres and Exhibition ISM. Leica, Prague, April, 18-22, 1994, pp.104-107.
12. Sedlák, V., 1997: Modelling subsidence deformations at the Slovak coalfields. Kuwait Journal of Science & Engineering, **24**, (2), 1997, pp.339-349.
13. Sedlák,V., 1998: Measurement and Prediction of Land Subsidence Above Longwall Coal Mines, Slovakia. In: Land Subsidence, Case Studies and Current Research,Belmont, California, 1998, pp.257-263.

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Podsumowanie

Wyniki badań modelowych osiadania przedstawione w tym artykule pozwalają na osiągnięcie dużej zgodności pomiędzy wartościami prognozowanymi i mierzonymi. To przybliżenie skutecznie może być wykorzystywane dla warunków górniczo-geologicznych Zagłębia Węgla Brunatnego Handlová. Analiza wyników wskazuje, że dla głębokości eksploatacji 300÷400 m oraz eksploatacji z postępem wyrobiska ścianowego 0.9÷1.2 m/dobę oraz udziale w masywie skalnym zwięzłych warstw rzędu 35÷40%, współczynnik czasowy c wynosi 0.036 [dzień$^{-1}$], tj. 1.3 [rok^{-1}].

Teoretyczne rozwiązania problemu osiadania w czasie opisane w tym artykule i porównanie wyników obliczeń z wartościami mierzonymi dla przykładu Zagłębia Węgla Brunatnego Handlová pozwalają na skuteczne stosowanie tej metody do modelowania czasowych zależności osiadania.

Bardziej dokładne określenie parametru c wymaga dokładniejszej analizy wskaźników deformacji, takich jak: nachylenia, naprężeń rozciągających oraz ściskających, ruchów poziomych itp. Stanowić to będzie przedmiot przyszłych badań.