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Anton Sroka

Technische Universität Bergakademie Freiberg, Germany

Krzysztof Tajdus

Strata Mechanic Research Institutes, Polish Academy of Science

Axel Preusse

RWTH Aachen, Germany

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CALCULATION OF SUBSIDENCE FOR ROOM AND PILLAR AND LONGWALL PANELS

Anton Sroka^{1,2}, Krzysztof Tajdus² and Axel Preusse³

ABSTRACT: A European method of surface subsidence calculation for partial room and pillar and longwall panel mining of coal deposit is presented. The article focuses on the Knothe' method, that describes the subsidence trough by the Gauss influence function method. This method provides calculation of tilt, curvature radius, horizontal and vertical movements, and horizontal strain of the surface subsidence trough. The method to forecast surface subsidence serves to design exploitation with respect to minimalisation of its influence so that the forecast subsidence should not exceed a limit value.

INTRODUCTION

The development of surface subsidence methods refers to a mining exploitation process started by Keinhorst (1925). The breakthrough dissertation was published in 1931/1932 and it is called Bals Method (Kratzsch, 1983). The function influencing the aforementioned method was descended from Newton Law of Gravitation and interaction between two substances.

By considering the accepted the influence function method, the segments mesh of equal impact relates to subsidence on the middle point of the potential mesh that have been created. The subsidence of any point on the ground caused by free shape panel excavation can be determined using the graphic integration. This graphical integration as described in the exploitation field where the middle point of the mesh of segments will be superimposed with the calculated point.

Reference to similar solution is reported in Beyer (1944), Sann (1949) (see Kratzsch, 1983), Knothe (1953), Kochmanski (Collective Work, 1980), Ehrhardt and Sauer (1961), and Geertsma (Kratzsch, 1983).

The essence of surface subsidence is schematically presented in Figure 1.

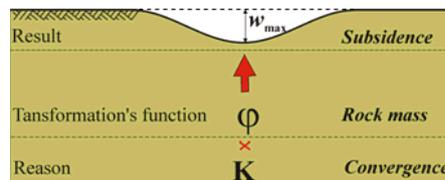


Figure 1 - The general scheme of surface subsidence methods

In general, the occurrence of surface subsidence (present on Figure 1) might be:

- Filling of the void caused by mining and subsequent roof caving);
- Gradual convergence of some competent rock layers such as rock salt cavern; or
- Compaction of porous deposits during exploitation of oil and gas.

CALCULATION OF SURFACE SUBSIDENCE

The general formula to calculate the subsidence of a surface point by geometrical-integration methods can be presented in the form:

$$w(x_p, y_p) = a \cdot g \cdot \iint_p \varphi(x - x_p, y - y_p) dx dy \quad (1)$$

On condition that:

¹ Technische Universität Bergakademie Freiberg, Germany

² Strata Mechanic Research Institutes, Polish Academy of Science, Poland, tajdus@img-pan.krakow.pl

³ RWTH Aachen, Germany

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \varphi(x, y) dx dy = 1$$

Where: a - subsidence factor, its value depends on an established system of exploitation and from a method of filling the void;

g - thickness of excavated seam;

φ - influences function, whose value is dependent on the method of calculation.

The combination of the most important past and currently applied influences function is presented in Table 1.

Table 1 - An influences function φ according to various authors

Author	An influences function φ	Parameters	Description
Bals	$\frac{1}{\pi \cdot \ln\left(1 + \tan^2 \xi_{gr}\right)} \cdot \frac{1}{l^2 + H^2}$	$\xi_{gr}, l \leq H \tan \xi_{gr}$	l - the horizontal distance of reference point from taken out element,
Beyer	$\frac{3}{\pi} \cdot \frac{1}{r_B^2} \cdot \left(1 - \frac{l^2}{r_B^2}\right)$	$\gamma_B, r_B = H \cot \gamma_B$ $l \leq r_B$	H - depth of exploitation r - range of main influence, its value depends on applied method,
Knothe	$\frac{1}{r_K^2} \cdot \exp\left(-\pi \cdot \frac{l^2}{r_K^2}\right)$	$\beta, r_K = H \cot \beta$ r_0, b	γ, ξ_{gr}, β - angles of influence, its value depends on applied method,
Kochmans ki	$\frac{1}{2\pi \cdot r_0^2 \cdot c(b)} \cdot \exp\left(-\left(\frac{l}{r_0}\right)^b\right)$	$c(b) = \int_0^{\infty} \lambda \cdot \exp(-\lambda^b) \cdot d\lambda$ $b(H) = \frac{5 - 1.120 \log H}{1 + 0.672 \log H}$	r_0 - scale coefficient horizontal influence b - influences function shape coefficient
Ruhrkohle	$\frac{k}{\pi} \cdot \frac{1}{r_R^2} \cdot \exp\left(-k \cdot \frac{l^2}{r_R^2}\right)$	$\gamma, k = -\ln 0.01$ $r_K = H \cot \gamma$	
Geertsma	$\frac{1 - \nu}{2\pi} \cdot \frac{H}{(l^2 + H^2)^{3/2}}$	ν	

From Table 1, the most important function applicable to the European mining industry includes both 'the Knothe and the Ruthrkohle methods (Knothe 1953; Ehrhardt and Sauer 1961). Knothe assumed that the influence function method was adequately presented by Gauss' function with proper parameters. This assumption has a strong theoretical background e.g. dissertations written by Kolmogorow (1931), Litwinski (1956) and Smolarski (1967) (collective work, 1980) which are related to stochastic medium theory and the application of probability calculus.

According to the Knothe' method, the elementary subsidence trough has the Gauss' function shape, on condition that an elementary mining exploitation has the Dirac's function shape (Figure 1). The assumption was achieved in 1960 - 1970 at The Strata Mechanic Research Institute of the Polish Academy of Science in Cracow, where the explorations in the loose medium (loose sand model) as a medium with a high degree of freedom have been carried out (Krzyszton, 1965). The single example of obtained results for the test are presented in Figure 2 and Figure 3.

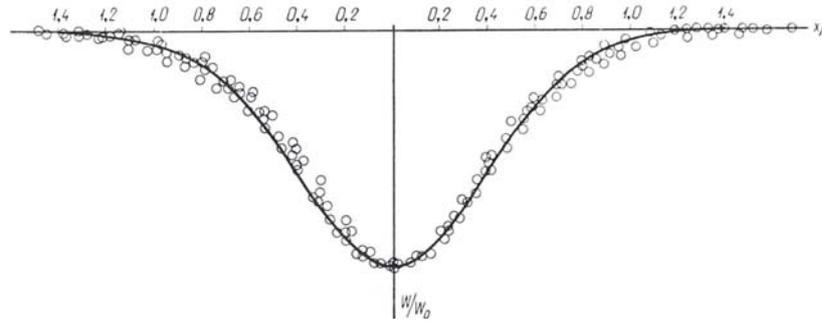


Figure 2 - Comparison of subsidence results for the loose sand model with the Gauss' function model

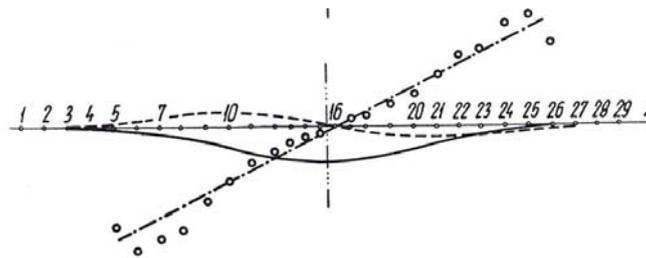


Figure 3 - The profile of trough subsidence $w(x)$, the curvature of horizontal displacement $u(x)$ and ratio of $u(x)$ and $w(x)$ for loose sand model

The conformity between results of the explorations and the Gauss' curve is shown in Figure 2. The graph of Figure 3 shows the dependence of subsidence distribution w , horizontal displacement distribution u , and their relation on u/w .

Based on the initial results the following relationship hold:

$$\frac{u(x)}{w(x)} = -\alpha \cdot x \tag{2}$$

Where: x - distance of the consider point from the taken out element realised as "dump slotted";
 α - certain coefficient dependent on density of medium.

Sroka (1984) proposed a computable model based on discretization (division) of the completed exploited field on small ended surface elements. The elements are square shaped with a side of Δx . The formula of such a subsidence value is:

$$w(l,t) = \frac{M(t)}{r^2} \cdot \exp\left(-\pi \frac{l^2}{r^2}\right) \tag{3}$$

$$M(t) = a \cdot V \cdot z(t)$$

Where: $M(t)$ - volume of elementary trough subsidence in moment t .
 l - distance of calculation point from excavated element of deposit,
 r - radius of main influence according to Knothe' theory,
 V - volume of excavated element ($V = \Delta x^2 \cdot g$),
 β - angle of main influence.
 $z(t)$ - function of time.

Radius of main influence r is calculated as:

$$r = H \cdot \cot \beta \tag{4}$$

The advantage of this solution is the fact, that each element can be described separately through a chosen thickness of excavated seam g_i , depth of exploitation element H_i , and time of excavated element t_{o1} . The calculation of element subsidence for the whole exploitation can be estimated by linear superposition, i.e. trough sum up partial subsidence from single elementary field.

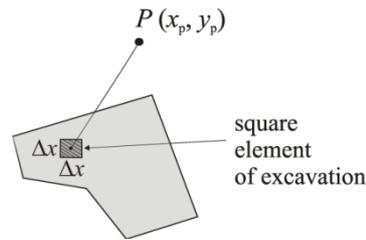


Figure 4 - The scheme of determination of point subsidence P caused by taken out single deposit element

Because of accuracy of the calculation, the length of square side should not be higher than $\Delta x_{\max} \leq 0.1r$, and because of the possibility of analysis of the influence on mining exploitation velocity and stoppage of face advance on strata deformation in time – the length of element side should not be higher than average face advance.

The Ruhrkohle' method, which is widespread in Germany, and the Knothe' method are the same because of identical background of the Gauss' function.

The selection of time function is a key element during the space-time continuum analysis. The collection of functions, which are used in European mining industry, was presented in Table 2. From all functions, which were described, the Knothe' function (1953), the Sroka and Schober' function (1985), the Kwiatek' function (2002) are worthy of mentioning.

In time function $c(t)$, time t is calculated from the moment of excavation of the deposit element. The time equations given by Knothe', Schober' and Sroka are approximately equal for dependences:

$$c = \frac{\xi \cdot f}{\xi + f} \quad (5)$$

For time function according to Kwiatek, the following dependences can be presented:

$$\begin{aligned} c_1 &\gg c_2 \\ 0.60 &\leq A_1 \leq 0.85 \end{aligned}$$

In Europe, the primary hazard index is an index of horizontal strain. Other indices like curvature (or curvature radius) do not have significant meaning because of increased depth of mining over 1000 m.

Fundamental dynamic hazard indices, among the static one are (especially in German mining industry), the speed of element subsidence, the growth speed of horizontal displacement and disturbance index of subsidence arising from the stoppage of longwall panel exploitation (Table 3).

Both the Knothe' method and the Ruthrhohle' method assumes, that the horizontal displacements need to be calculated according to the Awierszyn' hypothesis (1947). This hypothesis makes an assumption on a proportionality between tilt vector T and a horizontal displacements vector u (Formula 6). This assumption also determines the relationship between a tensor strains and a tensor curvature K (Formula 7).

$$u = -B \cdot T \quad (6)$$

$$\varepsilon = -B \cdot K \quad (7)$$

Where B is the factor of proportionality, its value is located in limits of particular inequality $0.28r < B < 0.40r$. Factor B is a computational additional parameter and it should be estimated considering *in-situ* measurements.

The fact, that the Awierszyn' hypothesis is qualitatively compatible with results of laboratory research results shown in Figure 3. The same hypothesis is also compatible with a modified method "centre of gravity point" which was published by Keinhorst.

Table 2 -Time function $z(t)$ based on various authors (Sroka 2003)

Author	Time function	Parameters
Knothe (1953)	$z(t) = 1 - \exp(-ct)$	$w_k(t)$ - final subsidence in time t ,
	$\dot{w}(t) = c[w_k(t) - w(t)]$	$w(t)$ - subsidence in real time t ,
Martos (1956)	$z(t) = 1 - \exp(-\alpha \cdot t^2)$	c - the relative velocity of mining influences propagation,
	$\dot{w}(t) = c(t)[w_k(t) - w(t)]$	
Trojanowski (1972/1973)	$z(t) = 1 - \exp\left(-\int_0^t c(\lambda) d\lambda\right)$	ξ - the relative velocity of convergence (e.g. value 0.02 year ⁻¹ correspond to clip passing velocity characterized by value of 2 % annually),
Schober, Sroka (1983)	$z(t) = 1 - \frac{f}{f-\xi} \exp(-\xi \cdot t) + \frac{\xi}{f-\xi} \exp(-f \cdot t)$	0.02 year ⁻¹ correspond to clip passing velocity characterized by value of 2 % annually),
	$z(t) = C \ln(Bt + 1)$	
Sroka (1985)	for	f - the relative velocity of transmission of mining influences by rock mass,
	$t \leq (\exp\left(\frac{1}{C}\right) - 1) / B$	
Kittlaus (1986)	$z(t) = 1 - \exp(-\mu t^{0.5})$	
Schreiner, Kamlot (1991)	$z(t) = \left[1 - \exp\left(-\frac{t}{t_0}\right)\right]^2$	
Sroka (1994)	$z(t) = [1 - \exp(-\xi \cdot t)] \cdot [1 - \exp(-f \cdot t)]$	
	$z(t) = 0$ for $0 \leq t \leq t_0$	
Kowalski (1999)	$z(t) = 1 - A \cdot \exp(-c(t - t_0))$ for $t > t_0$	
Kwiattek (2002)	$z(t) = 1 - (1 - A) \cdot \exp(-c_1 t) - A \cdot \exp(-c_2 t)$	
Sroka (2003)	$z(t) = 1 - \exp\left[-\left(\frac{t}{t_0}\right)^m\right]$	

In European mining industry (excluding UK) the longwall panel exploitation is carried out without leaving pillars between longwall panels. In consequences, the fact of leaving pillars between longwall panels (especially in the American and Australian mining industry) leads to irregularities of subsiding troughs characterised by huge hazards, not even on the surface but also in the overburden. Additionally, leaving the pillars can lead to crumps, earth tremors and other hazards in water-bearing levels.

In longwall panel exploitation without leaving the pillars between them, formulas to calculate the maximum value of deformation indices are relatively simple, e.g. for full field (field bigger than $2r \times 2r$) the formulas are following:

$$\text{Maximum subsidence: } w_{\max} = a \cdot g \quad (8)$$

$$\text{Maximum tilt: } T_{\max} = \frac{w_{\max}}{r} = \frac{w_{\max}}{H} \tan \beta \quad (9)$$

$$\text{Minimal radius of curvature: } R_{\min} = \sqrt{\frac{e}{2\pi}} \cdot \frac{r^2}{w_{\max}} = 0.66 \frac{H^2}{w_{\max}} \cot^2 \beta \quad (10)$$

$$\text{Maximum value of horizontal strain: } \varepsilon_{\max} = \pm \sqrt{\frac{1}{e}} \cdot \frac{w_{\max}}{r} = 0.60 \frac{w_{\max}}{r} \tan \beta \quad (11)$$

Table 3 - Boundary values of strain factors describing a dynamic and static impact of mining exploitation on the objects

Category of strength of buildings	R [km]	ε [mm/m]	\dot{w}_{gr} [mm/d]	$\dot{\varepsilon}_{gr}$ [mm/d]	Δw_{gr} [mm]
0	$40 \leq R $	$ \varepsilon \leq 0.3$	1	0.005	1.0
1	$20 \leq R $	$ \varepsilon \leq 1.5$	3	0.015	2.5
2	$12 \leq R $	$ \varepsilon \leq 3.0$	6	0.030	5.0
3	$6 \leq R $	$ \varepsilon \leq 6.0$	12	0.060	10.0
4	$4 \leq R $	$ \varepsilon \leq 9.0$	18	0.100	15.0

This same method can be used for other systems of exploitation in mines and water bearing or aqueous deposits (Sroka and Tajduś, 2009). In general, what is important to determine the convergence (compaction) of the deposit element caused by mining. Later on using the influence function method an adequate description of surface subsidence is achieved (Formula 3).

Figure 5 shows the scheme of surface subsidence calculation when shortwall panel is applied together with leaving pillars between excavations. Roof layers are influenced (deflection occurs) by taken out same part of deposit and the left pillar are loaded by pressure p_z . The pillar is partly crushed by value Δq (Figure 5).

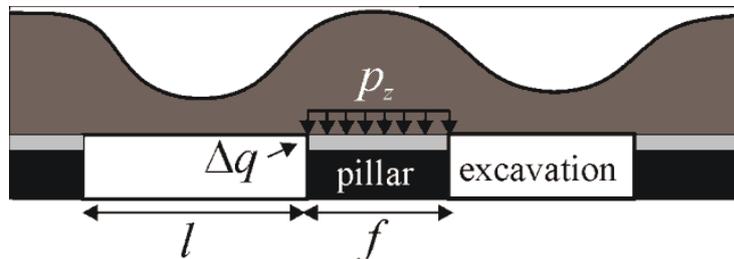


Figure 5 - Surface subsidence and convergence of pillar among shortwall exploitation

Empirical value Δq can be presented in form of:

$$\Delta q = \frac{p_z}{E} \cdot g \quad (12)$$

$$p_z = \gamma \cdot H \cdot \frac{f+l}{f} \quad (13)$$

Where: E - elastic modulus,
 f – pillar width with an infinite length,
 l – excavation width with an infinite length.

The scheme of stress distribution under the pillar is presented in Figure 6.

In this method, the calculation of potential drift (excavation) convergence and value of pillar Δq depression is essential. To achieve this numerical methods of Finite Element Method (FEM) and Finite difference method, (DEM) and alike, etc. (Figure 7) can be applied in which lots of factors should be taken into consideration (i.e. faults, discontinuity, fracturing, porosity, etc.) (Tajduś, 2009; Tajduś, *et al.*, 2009).

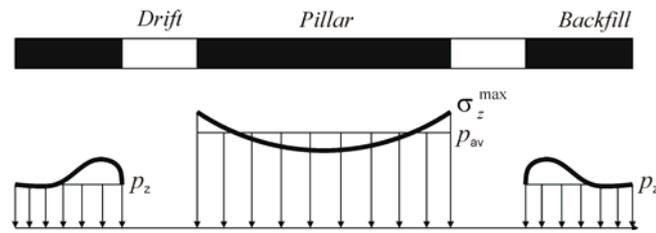


Figure 6 - Stress distribution under the pillar

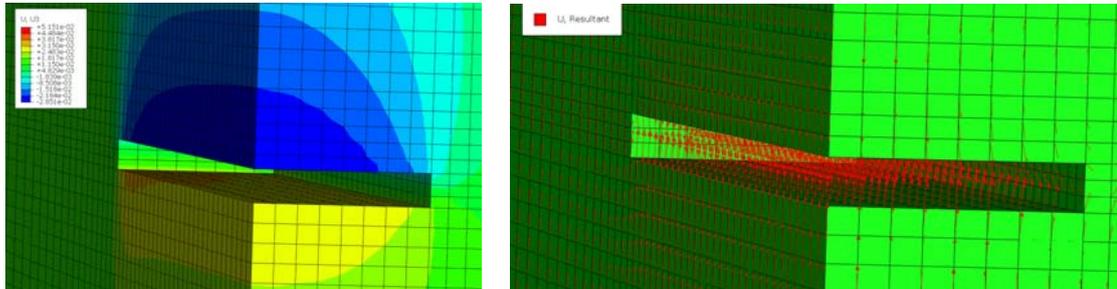


Figure 7 - An example of numerical calculations of drift (excavation) convergence for shortwall panel with left pillars

The presented solution can also be used for continuous miner system (Sroka *et al.*, 2009). Then calculation is carried out for full exploited mining field, in addition the value of subsidence factor received form of:

$$a(\eta) = a_0 \eta^s \quad (14)$$

Where: η - coefficient of coal deposit exhausted;
 a_0 - coefficient of subsidence for full exploitation;
 s - coefficient dependent on type of rocks (for weak rocks and average strength $s=1.5$; for strong rock $s=2.0$).

CONCLUSIONS

European computational methods are used mostly in designing a mining exploitation over build-up areas such as: Ruhrkohle (Germany) and the Upper Silesian Coal Basin (Poland). These methods have a positive impact on the protection of buildings and other infrastructure e.g. heat distribution network, road nets, power network. Moreover, the methods positively influence on industrial infrastructures such as: storage reservoirs and water-bearing layers in a rock mass.

The designing is concerned with the establishment of exploitation geometry, a run of the exploitation considering the time; maximal speed of exploitation and the face advance stopping during the exploitation. Other elements, which have to be taken into consideration during the exploitation designing, are settlement of safety pillars or estimation of final borders of mining exploitation. The presented computational method allows for calculating of surface deformation, taking into account an optional shape and optional time of exploitation.

This method is currently been used not only in the mining industry of hard coal, but also in metalliferous mines, such as salt and copper mines and in oil and gas fields. The computational method, which is based on the Knothe' method can be fully applied to help in predicting subsidence and minimise its impact; this can also be in the Australian mining industry.

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