MODELING OF SUBSIDENCE TROUGH DISTURBANCES CAUSED BY FAULT ACTIVATION

MODELOWANIE ZABURZEŃ NIECKI OBNIŻENIOWEJ WYWOŁANYCH AKTYWACJĄ USKOKU TEKTONICZNEGO

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Abstract

Problem of fault activation due to underground mining seems to be important issue, especially when its outcrop passes urbanized area. Mining activated fault usually manifests its presence on the surface in the shape linear discontinuous deformations. One of the most common anomalies in such cases is ground steps, flexures or fissures in the vicinity of fault outcrop. This work presents the author's model that serves for prediction of ground steps or fissures creation due to fault activation. The proposed model was derived from the idea of using modified influence function of any geometric-integral theory, taking into account the translational impact of the fault as a function of the horizontal distance from its outcrop. The translational effect has been achieved by using convolution of the original influence function with so-called “modifying function”. In considered solution, the W.Budryk-S.Knothe function has been implemented.

Abstrakt

Problém oživení tektonických poruch v důsledku hlubinného dobývání je důležitou otázkou pro ochranu povrchu, zejména v případech, kdy se výchoz poruchy nachází v zastavěných plochách. Aktivace poruchy se projevuje nejčastěji ve formě nespojité lineární deformace. Nejběžnější deformace tohoto typu jsou: stupně, praskliny, trhliny a ohyby, které se vyskytují nejčastěji v bezprostřední blízkosti výchozu poruchy. Tento článek se zabývá charakteristikami modelu navrženého autorem, který se používá k předpovědi vzniku poruch ve formě stupňů nebo ohybu. Řešení je založeno na myšlence použití modifikovaných funkcí geometricko – integrální teorie. Modifikace zahrnuje efekt přenosu vlivu přes poruchu, přičemž účinek je závislý na horizontální vzdálenosti od výchozu. To bylo dosaženo použitím konvoluce původní funkce vlivu, tzv. "modifikovaná funkce". V daném řešení je využito funkcí vlivů dle teorie W.Budryka-S.Knothego.

Keywords

underground mining influences, geometric-integral theories, mining-induced fault activation

Klíčová slova

Vliv hlubinného dobývání, geometricko-integrální teorie, oživení tektonických poruch v důsledku dobývání

1 Introduction

The problem of tectonic faults influence on the distribution of post mining deformations was relatively rarely the subject of research for both, in Poland and abroad. The reasons for such situation should be seen in a number of facts, namely:

- the influences transfer across the fault zone is extremely difficult to study in situ,
- diversity of mining - geological conditions inside the fault zone and in its close proximity makes it difficult to clearly determine the properties of individual faults,
- there are significant difficulties in determining the precise course of tectonic disturbances through the rock mass and position of their outcrops (if they're covered by overburden layers),
- comprehensive surveys in areas of fault zones are rarely carried out. However, when performing such measurements, there are numerous situations, where the measuring points are damaged due to discontinuous deformations. This usually results in poor quality of the recorded deformations.
- faults are also often a natural extraction border. This leads to a situation, when there is an overlap of extraction edges in number of seams in the area demarcated by the fault zone, which in itself may be the cause of discontinuous deformations of linear type. In such cases, it is impossible to determine whether the resulting deformations are the effect of fault activation, either extraction edges overlapping, or both factors simultaneously.
- activation of the fault zone as a result of the underground extraction is a phenomenon with large share of random factor, which complicates both: the empirical recognition of phenomena, as well as attempts to theoretical description.

2 Some views concerning mining-activated faults behaviour derived from practical findings

T. Klenczar (Klenczar, 1952) noted that the slope of fault plane is a very important factor which determines usually the influence range. According to his view, the dislocation line, as the line of least resistance, limits influences propagation (see fig. 1).

The most important conclusions from A.Tyrała works (Tyrała, 1979) are :

- fault activity depends mainly on the : angle of dip, cohesion of fault zone, position of extraction against fault, thickness of overburden layers. Author states, that faults with angle of dip up to 26º do not activate, moreover - faults of "+" type (see fig. 2) have twice the activity.
- discontinuous deformations occur mainly in case of absence of overburden layers. The presence of younger cover layers causes a smoothing effect - instead of

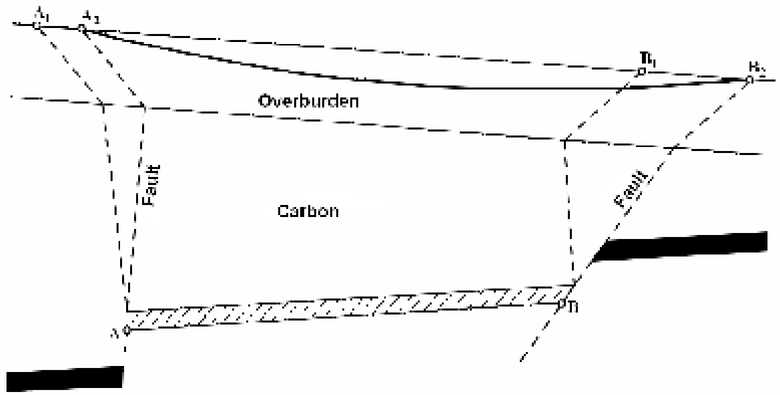


Fig.1 The deformations in the vicinity of tectonic zones according to T. Klenczar

ground steps, transitional forms in the shape of flexures arise. Author concludes that, if the thickness of overburden layers exceeds 5% of the depth of extraction, ground steps are usually not present.

- for extraction and fault location as shown in figure 2b, the disturbance appears as influence range shortening ("cut-off") along the outcrop line. At the same time, reduction of subsidence past the outcrop line is balanced by an increase in subsidence in front of the fault plane. The magnitude of deformations depends on the angle of the fault dip.
- for the extraction carried out on both sides of the fault, trough profile anomalies depend on the size and symmetry of the extraction fields in the relation to fault location.

H. Kratsch states (Kratsch, 1983), that the nature of fault impact depends on whether the extraction is carried out in upthrown or downthrown block, and whether the fault outcrop is covered with overburden layers. If the fault outcrop does not reach the surface, the following situations may be distinguished:

- when extracting in the downthrown block, steps or various forms of flexures may develop on the surface,
- when extracting in the upthrown block, usually different forms of steps or fissures may be created.
- the size of ground step depends on the fault plane dip angle [a] against limit angle [g] (lower magnitude of steps if $a < g$, higher - if $a > g$).

Some of the main conclusions reached by J.Donelly and co-authors (Donelly, 2000; Donelly, et al. 2008) read as follows :

- fault reactivation usually occurs in phases of activity, separated by periods of stability. It may continue for many weeks to years after mining subsidence is complete, but will eventually cease,
- ground steps are restricted in distribution to the area of influence of the subsidence trough,
- reactivation is most likely when workings are located in the footwall block,
- when fault outcrop is located in strong, well-jointed rock, fissuring is likely to develop in addition to steps,
- geological factors that control fault reactivation are : the prevailing and pre-existing stress field; the geological history of the fault; geotechnical properties of the fault (friction, cohesion and pore-fluid pressure); the proximity of the fault to the ground surface, the density and orientation of other rock mass discontinuities,
- mining factors that control fault reactivation are : depth of extraction, mining works geometry, horizontal distance of the workings, rate of mining, extraction thickness, history and intensity of mining.

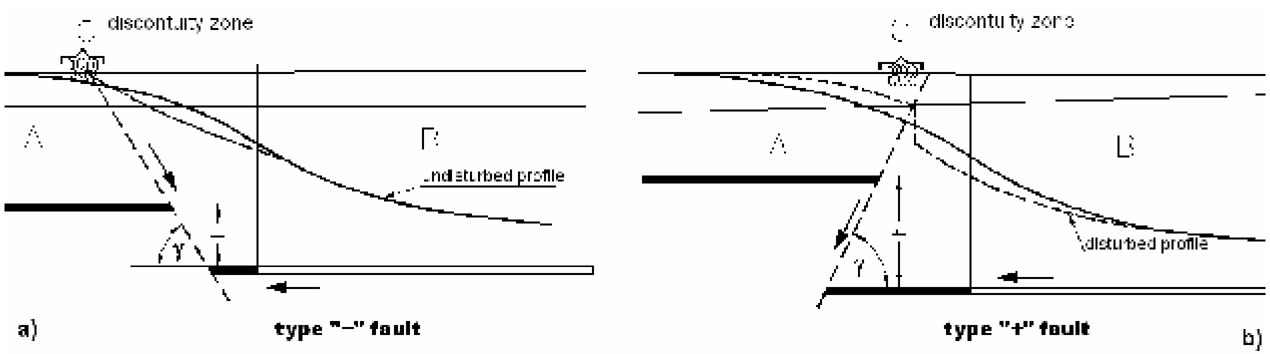


Fig.2 The distribution of disturbances near fault outcrop according to A. Tyrała

3 Chosen theoretical models known from literature

In the work (Tyrała, 1979), Author proposed simplified empirical model for determination of disturbed subsidence trough profile in the zone of activated fault outcrop $\overline{w}(x_i)$ - fig.3:

$$\overline{w}(x_i) = w(x_i, b) \pm \Delta w(x_i, b_k)$$

where:

- $w(x_i, b)$ – subsidence of a given point in case when fault is inactive,
- $\Delta w(x_i, b_k)$ – subsidence correction coefficient describing the anomaly due to fault activation,
- b, b_k, r_o – parameters of T. Kochmański's theory,
- $x_i = \frac{x_i}{r_o}$ – dimensionless distance between given point location and extraction edge.

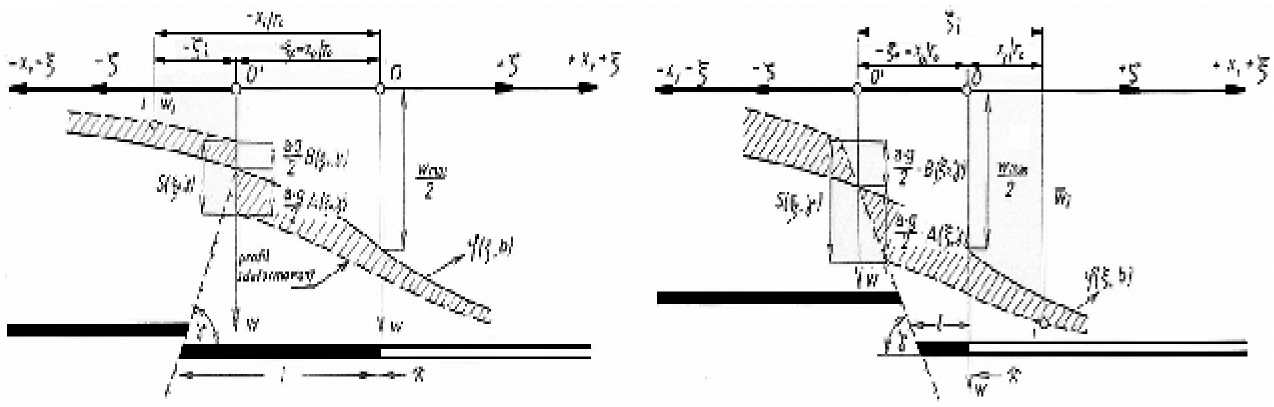


Fig.3 The sketch illustrating the rules of trough profile determination disturbed by fault activation according to A. Tyrała

Another model has been proposed by Z.Kowalczyk (Kowalczyk, 1982). It bases on some empirical findings and states that the possible height of the ground step equals to :

$$\Delta Z_e = a \cdot g \cdot e^{a\, r^2} + \frac{a \cdot g \cdot H \cdot \sin(j)}{2000(0.1\, d + 1)}$$

where :

- a = coefficient of roof control,
- H = extraction depth,
- α = coefficient, $a = \frac{0.69}{H^2 \cdot \cot^2(g)}$,
- r = distance between extraction edge and fault line,
- g = thickness of extracted seam,
- d = thickness of overburden layers.
- φ = angle of dip of fault surface,
- g = limit angle,

A. Jeleński and E. Jędrzejec proposed model (1994), that bases on the differential equation describing continuity of medium:

$$\frac{\partial^2 w(x,z)}{\partial x^2} = \frac{\partial w(x,z)}{\partial z}, \qquad z = \frac{1}{4p} r_z^2$$

where:

r_z = the radius of main influence range at the vertical level [z]

It was assumed that fault divides the rock mass into separate blocks, so it suggests seeking of two separate solutions, with special boundary conditions along the fault line - see figure 4. Having such assumption, solution to above equation leads to the following formulae :

- for the left side of model (zone A in figure 4); $x \le x_u$:

$$w_-(x,z) = \int_{-\infty}^{x_u} f_-(l)\left[G(x-l,z) + qG(x+l-2x_u,z)\right]dl + (1-q)\int_{x_u}^{+\infty} f_+(l)G(x-l,z)\,dl$$

- for the right side of model (zone B in figure 4); $x > x_u$:

$$w_+(x,z) = (1-q)\int_{-\infty}^{x_u} f_-(l)\,G(x-l,z)\,dl + \int_{x_u}^{+\infty} f_+(l)\left[G(x-l,z) + q\,G(x+l-2x_u,z)\right]dl$$

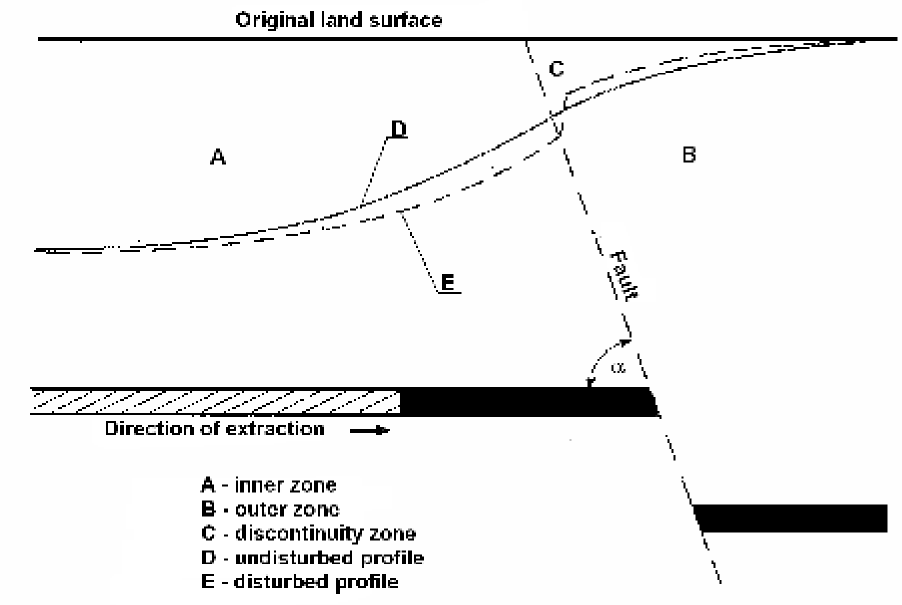


Fig.4 The disturbance of subsidence trough according to A. Jeleński and E. Jędrzejec

where:

G = Green's function for the equation and boundary condition : $w(x,0)=f(x)$,

θ = parameter, $0 \le \theta \le 1$; $\theta = 0$ means lack of fault activity, whereas $\theta = 1$ stands for full activity, which means that no influence is transmitted through the fault line,

x_u = the special horizontal coordinate of fault at given vertical level "z".

4 General description of the author's model

The following assumptions of mining-activated fault behavior have been taken for proposed model (Ścigała, 2013):

- the disturbance of subsidence trough profile takes place in the vicinity of fault outcrop up to the certain distance (x_w, x_z); the width of outer and inner zones may be different (fig.5),
- the process of rock mass displacement in the vicinity of active fault zone is mostly driven along natural slip surface, which is the fault surface. In case of steps creation, they are directed ("thrown down") toward location of extraction field.
- the slope of the fault surface is an important factor influencing the transmission of deformations across the discontinuity. The steeper the slope, the more likely the slip, that may lead to ground steps formation.

- overburden layers, covering the fault outcrop give a "damping effect" - with thicker overburden, instead of steps, flexures may be formed on the surface.

The proposed model was derived from the idea of using a modified influence function [f_u] of any geometric-integral theory, taking into account the translational impact of the fault as a function of the horizontal distance from its outcrop. The translational effect is achieved by using convolution transform of the original influence function f_1 with so-called "modifying function" f_2 :

$$f_u(h,s) = \left[f_1(x,s) * f_2(x,s) \right](h,s),$$

where:

$*$ = convolution operator, h = new independent variable.

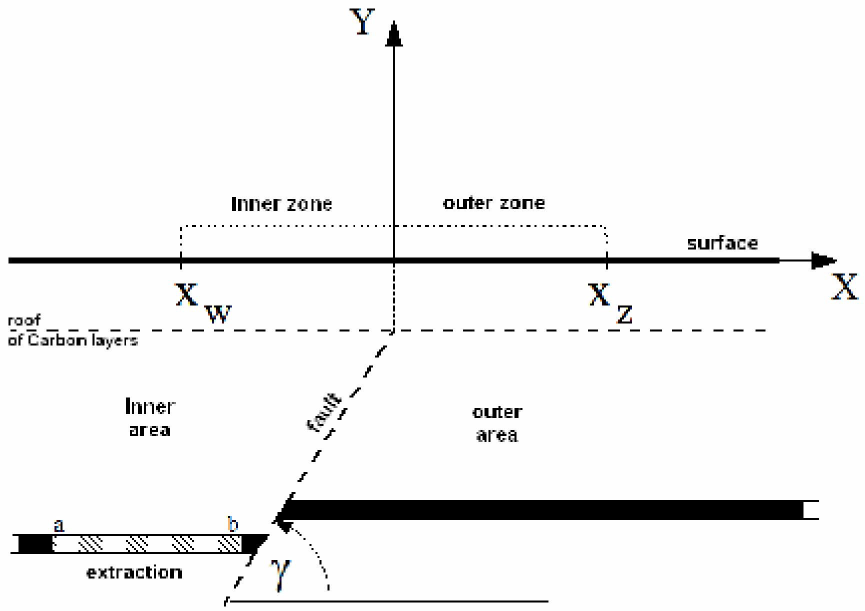


Fig.5 The fault influence range at the surface level:
x_w -limit of disturbed zone from extraction side);
x_z -limit of disturbed zone from behind the fault side

Using W.Budryk-S.Knothe influence function (Knothe, 1953) as f_1 and Dirac d distribution as f_2, one obtains the following definition of modified influence function f_u, which allows to describe disturbances of trough profile in the vicinity of fault outcrop :

$$f_u(h,s) = \frac{a \cdot g}{r} \cdot e^{\frac{-p\left(h-s+\Gamma(s)\right)^2}{r^2}}$$

where :

$G(s)$ = parameter describing variable translation of original influence function,
a = coefficient of roof control,
s = coordinate of given point on the surface.
r = radius of main influence range,
g = thickness of extracted deposit,

Figure 6 presents the course of [f_u] function along with original Budryk-Knothe influence function [f_1]. The equation of subsidence trough profile disturbed by fault activation (for the extraction in the shape of infinite stripe defined by edges "*a*" and "*b*") takes the form:

$$w(x,s) = \int_a^b f_u(x,s)dx = \frac{w_{\max}}{r}\int_a^b \exp\left(\frac{-p\left\{x-s+\Gamma(s)\right\}^2}{r^2}\right)dx$$

and after integration :

$$w(s) = -\frac{w_{\max}}{2} \cdot \left(erf\left(\frac{\sqrt{p}\,(a - s + \Gamma(s))}{r} \right) - erf\left(\frac{\sqrt{p}\,(b - s + \Gamma(s))}{r} \right) \right)$$

where: $erf(x) = \frac{2}{\sqrt{p}} \int_0^x e^{-l^2}\, dl$, $w_{\max} = a \cdot g$

The presence or absence of overburden layers has a significant impact on the nature of changes to trough profile. Thus, adoption of the function *G(s)* as the sum of two suitably parameterized functions has been proposed:

$$\Gamma(s) = g_1(s) \cdot (1-n) + g_2(s) \cdot n$$

- $g_1(s)$, in the absence of overburden, when discontinuity may appear on the surface in the form of steps,
- $g_2(s)$, in case, where effect of overburden layers "suppress" the step formed at the roof of Carboniferous layers and its movement towards the surface,

  n = parameter characterizes suppressing influence of overburden layers. Its value ranges between *<0,1>*, having limits with the following meaning:

  § *n=0.0* - lack of overburden layers. Ground step forms on the surface.

  § *n=1.0* - overburden layers have such thickness, which suppresses discontinuity, but allows to create disturbance in the form of flexure.

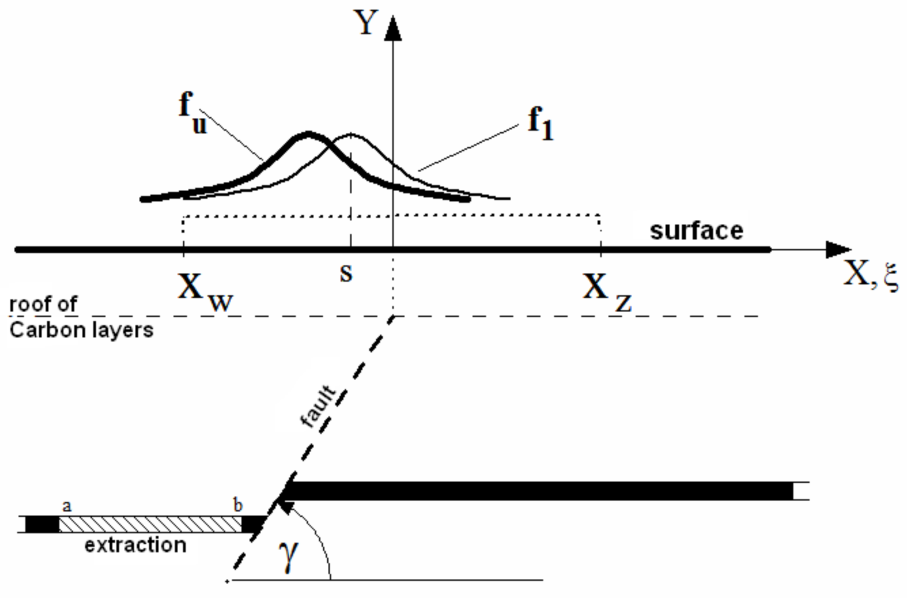
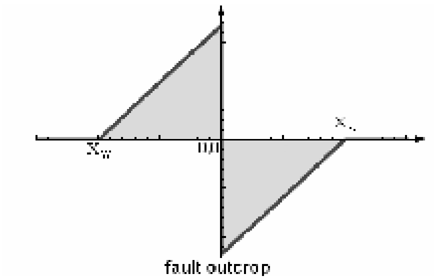


Fig.6 The exemplary course of modified influence function f_u in the zone of fault outcrop for points located at s coordinate by using proposed solution.

Functions [g_1] and [g_2] are defined as :

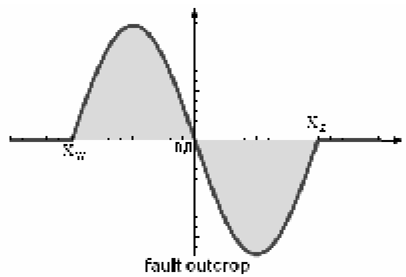
- in case of lack of overburden layers :

$$g_1(s) = \begin{cases} 0 & for\ s < x_W \\ f_Z \dfrac{s - x_W}{|x_W|} & for\ x_W \le s \le 0 \\ f_Z \dfrac{s - x_Z}{|x_Z|} & for\ 0 < s \le x_Z \\ 0 & for\ s > x_Z \end{cases}$$



- in case of thick overburden :

$$g_2(s) = \begin{cases} 0 & for\ s < x_W \\ -f_Z \cdot \sin\left(\dfrac{p\,s}{|x_W|} \right) & for\ x_W \le s \le 0 \\ -f_Z \cdot \sin\left(\dfrac{p\,s}{|x_Z|} \right) & for\ 0 < s \le x_Z \\ 0 & for\ s > x_Z \end{cases}$$



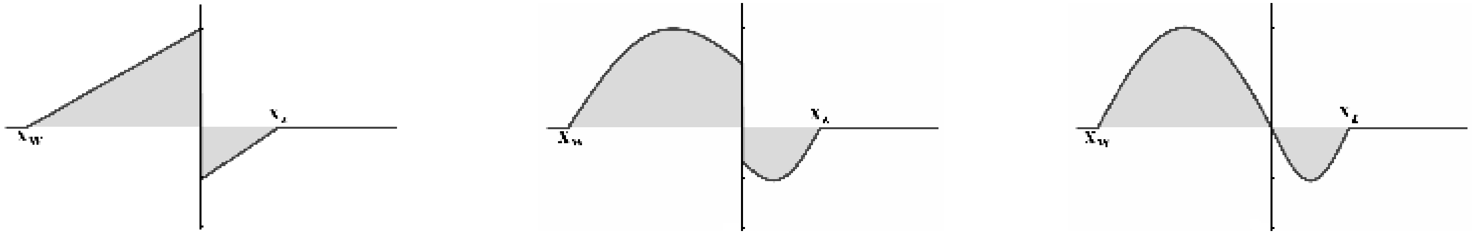
where:

$f_Z = f_Z(g) = k \cdot \sin(g)$,

g = the angle of dip for fault surface in the relation to X axis,

k = parameter endearing characteristics of the fault due to the possibility of a slip along the fault surface.

With such functions, different combinations of parameters set : $\{n, x_w, x_z, k_w, k_z\}$ lead to different courses of *G(s)* - as it is shown in fig.7.



n=0.0 n=0.5 n=1.0

Fig.7 ***The course of G(s) function for chosen values of parameter n, taking into account asymmetrical influence of fault zone ($x_w{}^{1}x_z$, $k_w{}^{1}k_z$)***

Putting above equations together, one obtains the following equation enabling calculation of disturbed subsidence trough profile, for extraction in the shape of infinite stripe with boundaries *<a;b>*:

$$w(s)_{P=<a,b>} = \frac{-w_{max}}{2}\left\{ erf\left(\frac{\sqrt{p}}{r}\left[a - s - (n-1)\cdot\left(\begin{cases} 0 & -\infty<s<x_W \\ \frac{k_W \sin(g)(s-x_W)}{|x_W|} & x_W \le s \le 0 \\ \frac{k_Z \sin(g)(s-x_Z)}{|x_Z|} & 0<s\le x_Z \\ 0 & x_Z<s<\infty \end{cases}\right) + n\cdot\left(\begin{cases} 0 & -\infty<s<x_W \\ -k_W \sin(g)\sin\left(\frac{p\,s}{|x_W|}\right) & x_W \le s \le 0 \\ -k_Z \sin(g)\sin\left(\frac{p\,s}{|x_Z|}\right) & 0<s\le x_Z \\ 0 & x_Z<s<\infty \end{cases}\right)\right]\right) - erf\left(\frac{\sqrt{p}}{r}\left[b - s - (n-1)\cdot\left(\begin{cases} 0 & -\infty<s<x_W \\ \frac{k_W \sin(g)(s-x_W)}{|x_W|} & x_W \le s \le 0 \\ \frac{k_Z \sin(g)(s-x_Z)}{|x_Z|} & 0<s\le x_Z \\ 0 & x_Z<s<\infty \end{cases}\right) + n\cdot\left(\begin{cases} 0 & -\infty<s<x_W \\ -k_W \sin(g)\sin\left(\frac{p\,s}{|x_W|}\right) & x_W \le s \le 0 \\ -k_Z \sin(g)\sin\left(\frac{p\,s}{|x_Z|}\right) & 0<s\le x_Z \\ 0 & x_Z<s<\infty \end{cases}\right)\right]\right)\right\}$$

Having the above equation, it is quite easy to obtain the formula for calculation of subsidence for extraction field in the shape of rectangle. In figures 8, 9 the exemplary theoretical profiles have been shown, which present the influence of fault activation in two different situations : in case of thick overburden layers (fig.8) and lack of overburden (fig.9). It is assumed, that in real cases, parameters of the model should be determined on the basis of surveys taken from the area of interest.

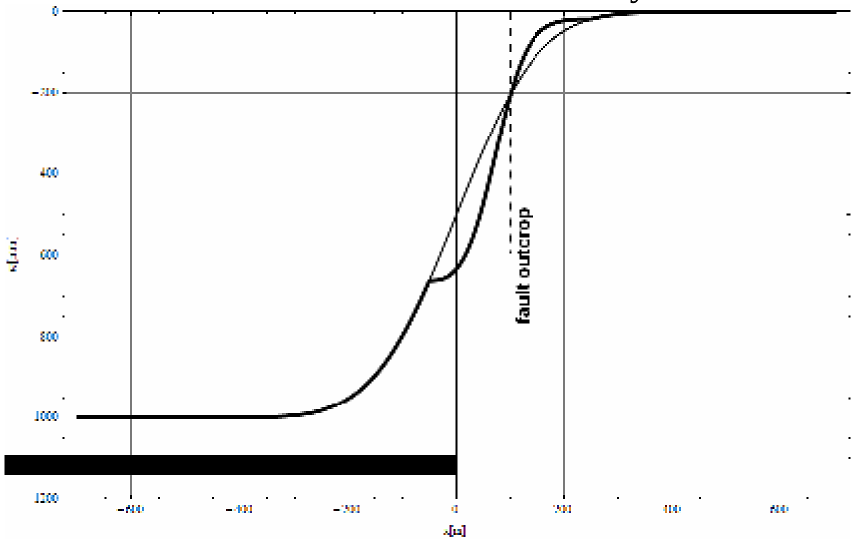


***Fig.8* The exemplary profile of subsidence trough obtained with assumptions: n=1.0, $k_w=k_z=50$, $x_w=x_z=150$, g=70°, H=450 m, tgb=2.0**

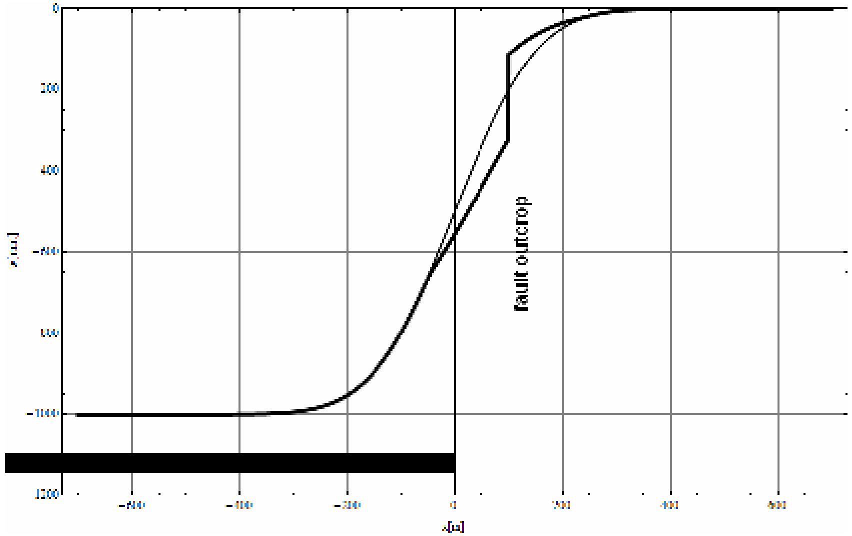


***Fig.9* The exemplary profile of subsidence trough obtained with assumptions: n=0.0, $k_w=k_z=50$, $x_w=x_z=150$, g=70°, H=450 m, tgb=2.0**

5 Conclusions

The recognition of present knowledge in the field of mining-induced fault activation points, that there is lack of complete theoretical solutions, that enable prediction of subsidence trough disturbances in the vicinity of fault outcrop. There is also not enough detailed survey results, that fully document creation of such disturbances in practice.

The main goal of the research, which results are presented in this paper, there has been working out of theoretical model (Ścigała, 2013), that can serve as a tool for description of post-mining subsidence trough profiles, disturbed by fault activation. Some preliminary verifications of the model not presented here point on its practical usability. At the same time it is necessary to mention, that for predictions purposes, it is obligatory to determine the values of model’s parameters on the basis of proper survey results taken earlier from the area of interest, which is not a straightforward task. Another important issue, not pointed in this paper, is the randomness of mining-induced fault activation process. There are several cases known from practice, when fault was not activated by mining works, in spite of favorable mining and geological conditions, or the effects on the surface were untypical.

Further development works are planned aiming at simplifying the model, as well as its parameters recognition on the basis of survey results.

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