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THE IDENTIFICATION OF PARAMETERS OF THEORIES USED FOR PROGNOSES OF POST MINING DEFORMATIONS BY MEANS OF PRESENT SOFTWARE

IDENTYFIKACJA WARTOŚCI PARAMETRÓW TEORII PROGNOZOWANIA WPŁYWÓW PRZY WYKORZYSTANIU WSPÓŁCZESNYCH NARZĘDZI INFORMATYCZNYCH

The characteristic of specialized computer programs has been presented, serving for identification of W. Budryk-S. Knothe theory parameters, used for description of asymptotic state of post-mining deformations, as well as for transient state. The software is the result of several years of authors' work. It is a part of complete software system designed for forecasting of underground mining influences on the rock mass and land surface and graphical processing of calculations results. Apart from software description, a short example of its practical utilization has been attached.

Keywords: mining subsidence, forecasting of underground mining influences, identification of parameters

W artykule przedstawiono charakterystykę systemu programów służących do identyfikacji wartości parametrów teorii W. Budryka-S. Knothego, zarówno dla ustalonego stanu deformacji jak i dla stanów nieustalonych. Oprogramowanie to jest efektem wieloletnich prac autora i stanowi fragment całego systemu komputerowego służącego do prognozowania pogórniczych deformacji górotworu i powierzchni, a także do graficznej interpretacji ich wyników. Schemat całego systemu przedstawiono na rys. 1, a jego część omówioną w ramach niniejszej pracy oznaczono na tym rysunku prostokątną obwiednią ograniczoną linią kreskową.

Omawiane programy to :

- program o nazwie DEFK_PARAM, który służy do wyznaczania kompletu parametrów teorii W. Budryka-S. Knothego na podstawie profili niecek asymptotycznych: $\{a,\text{tg}\beta,d\}$.
- program BK_CTX, który służy do wyznaczania wartości współczynnika prędkości osiadania $\{c\}$.

Centralnym elementem całego systemu, przedstawionego na rys. 1, jest relacyjna baza danych, zawierająca dane dotyczące dokonanej i projektowanej eksploatacji górniczej. Dane w bazie można w komfortowy sposób przeglądać, poddawać edycji oraz filtrować w celu wybrania odpowiedniego zakresu parcel eksploatacyjnych do określonych zadań obliczeniowych.

W obydwu programach do wyznaczania parametrów można wykorzystać dowolny zakres eksploatacji dokonanej o dowolnej geometrii wyrobisk eksploatacyjnych.

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Procedury obliczeniowe wszystkich programów w systemie oparte są na idei dyskretyzacji pola eksploatacyjnego w kierunku postępu frontu eksploatacyjnego – rys. 2. Pola elementarne mają kształt prostokąta. Identyfikacja wartości parametrów została zrealizowana w oparciu o zadanie optymalizacyjne wykorzystujące funkcję celu wynikłą z metody najmniejszych kwadratów, zgodnie z zależnością (1). Do poszukiwania minimum funkcji celu wykorzystano bezgradientową metodę Hooke'a-Jeevesa. Opracowane oprogramowanie pozwala na wyznaczanie kompletu parametrów, lub też dla dowolnego ich podzbioru, przy założeniu, że pozostałe parametry mają określoną, stałą wartość w procesie identyfikacji (rys. 4). W trakcie optymalizacji można nałożyć ograniczenia na przedział wyznaczanych wartości parametrów – rys. 5.

W programie BK_CTX, służącym do identyfikacji wartości parametru *c*, odpowiedzialnego za opis nieustalonej fazy deformacji, zaimplementowano trzy metody wyznaczania jego wartości:

1. Na podstawie pojedynczych profili nieustalonych niecek obniżeniowych, uzyskanych w kolejnych cyklach pomiarowych (czyli w przestrzeni współrzędnych geometrycznych $\{x,y\}$, dla ustalonego czasu pomiaru *t*). W ten sposób dla każdego cyklu pomiarowego otrzymuje się odrębną wartość parametru *c*.
2. Na podstawie osiadania w czasie pojedynczych punktów obserwacyjnych (czyli w kierunku współrzędnej czasowej $\{t\}$, dla ustalonych współrzędnych geometrycznych punktu: (x,y)). W ten sposób dla każdego punktu obserwacyjnego otrzymuje się odrębną wartość parametru *c*.
3. Według zaproponowanej przez autora metodyki, opartej na jednoczesnym wyznaczaniu wartości parametru *c* z wszystkich punktów i cykli obserwacyjnych (czyli w przestrzeni współrzędnych $\{x,y,t\}$). Przy wykorzystaniu tej metodyki, otrzymuje się jedną wartość parametru *c*. To rozwiązanie, z punktu widzenia wykonywanej w dalszym etapie prognozy, daje najbardziej reprezentatywną, „uśrednioną” wartość tego parametru, z uwagi na wykorzystanie całej przestrzeni danych pomiarowych.

W rozdziale 4 przedstawiono przykład wykorzystania programów do identyfikacji parametrów odpowiedzialnych zarówno za opis stanu asymptotycznego deformacji : $\{a, \text{tg}\beta, d\}$, jak też i współczynnika prędkości osiadania $\{c\}$. W ramach tego przykładu posłużono się wynikami pomiarów geodezyjnych z linii obserwacyjnej B-L, z terenu byłej kopalni „Dębieńsko”. Lokalizację linii obserwacyjnej w stosunku do wybranego pola przedstawiono na rys. 6, natomiast na rys. 7 pokazano porównanie profili niecek asymptotycznych: uzyskanej z pomiarów oraz określonej na drodze teoretycznej, przy wykorzystaniu wartości parametrów otrzymanych w procesie identyfikacji. W drugim etapie wyznaczono współczynnik prędkości osiadania, wykorzystując do tego celu własną metodykę, o której wspomniano powyżej w punkcie 3. Fragment wyników z procesu identyfikacji przestawiono w tabeli 1.

Słowa kluczowe: prognozowanie wpływów podziemnej eksploatacji górniczej, identyfikacja wartości parametrów

1. Introduction

To meet the appropriate quality of prognoses of underground mining influences on the rock mass and land surface with using geometric-integral theories, one must know the proper values of the parameters to be taken into the calculations. The distribution of post-mining deformations of rock mass and land surface depends on many factors (Chudek, 2010), thus proper method of parameters determination has an important impact on the prediction quality. The most appropriate way of evaluating them is their identification on the basis of geodetic measurements. Procedure for determining the values of parameters for geometric-integral theories should take place according to the following rules:

1. The values of parameters should be determined on the basis of relevant results of surveys, conducted earlier in the area for which the forecast is being developed.
2. If there is a lack of measurements from the area of interest, one should use the results from neighbouring region or area with similar geological structure.
3. If there are no suitable survey results, the corresponding empirical formulas may be employed.

Originally, for parameters determination, a simple analytical or graphical methods were used, where the basic requirement, which allowed the use of the surveys results for this task was, that extraction should be of so called "infinite half-plane" shape (Knothe, 1984). This means that recorded subsidence along the observing line should present the influence of a single extraction edge, preferably situated perpendicularly to the line. At a time, when the mining extraction was carried out at shallow depths, this condition was relatively easy to meet. Today, when the extraction is led usually at great depths, it is virtually impossible to satisfy this condition. Thus, all simplified methods of parameters identification do not work today.

So, it became necessary to use programmatic tools for this purpose, where it was possible to take into account the shape of extraction field. First programs dedicated to parameters identification were created in the late 60's and early 70's of the last century. The main centres, where the software was developed were : Silesian University of Technology, AGH University of Science and Technology and the Central Mining Institute. At that time, created software was essentially intended to identify the parameters responsible for the description of the asymptotic state of deformation. These were the solutions primarily for the theories of T. Kochmański and W. Budryk-S. Knothe.

The 80's of the last century brought the development of software for the identification of parameters responsible for the description of transient subsidence troughs – mostly coefficient of subsidence rate *c* for W. Budryk-S. Knothe theory (Knothe, 1953a,b).

This software was being developed in the environment of existing at that time operating systems, which inherently limited the possibility of building a computational large-scale and easy-to-use systems. Hence, these programs typically were limited in their capabilities – mainly allowed to determine the parameters in cases, where the extraction field had a shape of single rectangle, or could be approximate by such a shape. The use of these programs also bother the many problems due to their textual interface – without the possibility of using the graphic screen.

The turning point was the appearance of the Windows operating systems, and along with them – the modern informatics tools for building software equipped with a convenient user interface and having a huge computing capabilities.

It should be noted here, that despite of the significant development of software tools for the identification of the parameters, still apply the same basic principles of the selection of appropriate measurements results for the proper performance of this task (Ścigała, 2008). It is worth at this point to mention them, especially in case of determination of parameters responsible for the description of asymptotic subsidence troughs, of what is presented below.

The measurements results to be used for determination the values of parameters, must satisfy many conditions, among which, the most important are the following:

- subsidence trough profile obtained from measurements should present an asymptotic state of deformation. In other words – it should be registered after the end of the surface post-mining movements at the location of observation line,
- it must be possible to clearly determine the set of extraction fields, which influences were recorded during measurement cycle, when asymptotic trough was measured. It is recommended that it should be a single, isolated extraction field (but it is not mandatory),
- a field, whose extraction caused recorded asymptotic subsidence on the surface, should have a sufficiently large area, relative to the depth of extraction,
- measurement results can not be disturbed by any indirect impacts, related for example to dehydration of the rock mass or the presence of faults or secondary impacts – for example, the activation of gobs voids,

- measurements must include all revenues caused by the performed mining extraction – this means that the first measurement (preferably the first two measurements) should be led prior to the disclosure of extractions influences on the surface, and the last – when the movements on the surface ceased,

Presented in this article two programs are part of the whole software system, which consists of author's own and commercial programs. They serve in the Department of Geomechanics, Underground Construction and Surface Protection Management at the Faculty of Mining and Geology, Silesian University of Technology, to perform a variety of calculations related to the prediction of post-mining rock mass and land surface deformations. This system is being built by the author of this article for several years. Its scope is associated with the implementation of various stages of the works related to the forecasts. These stages are presented in Figure 1, along with the program names. In this figure, a rectangle outlined by dashed line indicates the part of system discussed in this work. The general description of predictive part of the system is presented in (Ścigała, 2005).

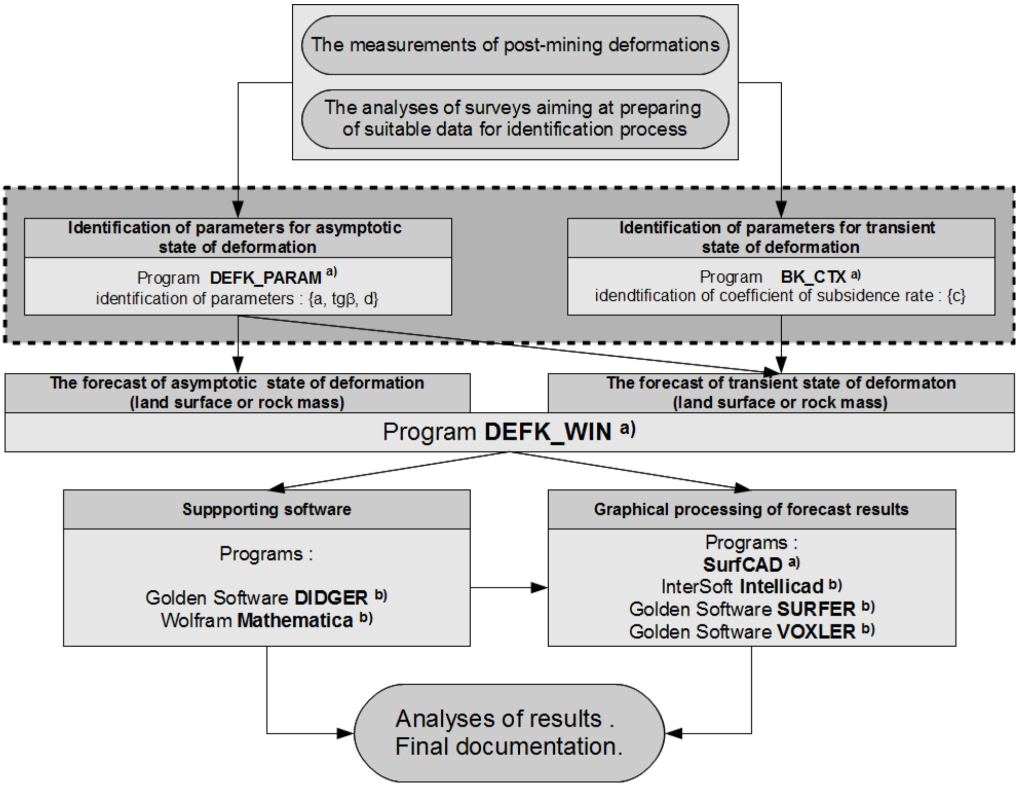

Fig. 1. The general stages of works connected with forecasting of post-mining deformations in relation to discussed software system elements. [a)] own software; [b)] commercially available software

2. The basic elements of used algorithms

The central part of the system is a relational database, that contains data concerning the extraction fields: finished and planned. Within the database, one can create any number of so-called "project accounts", each of which can hold any number of extraction fields of any geometry. All computing programs share this database, which greatly facilitates the use of the information recorded in one place. The database can be conveniently viewed, edited, and filtered, to select an appropriate range of extraction fields necessary to given computational task.

Computational procedures in all of the programs base on the idea of dividing the extraction field into the elementary areas of a rectangular shape. The division is led toward the extraction direction – Fig. 2. This way of approximation of extraction field geometry allows for easy use of so-called "discrete model" for calculation of transient state of deformation (Strzałkowski, 2012; Ścigała, 2008), and carrying out simulations of extraction in space-time coordinates (Ścigała, 2003).

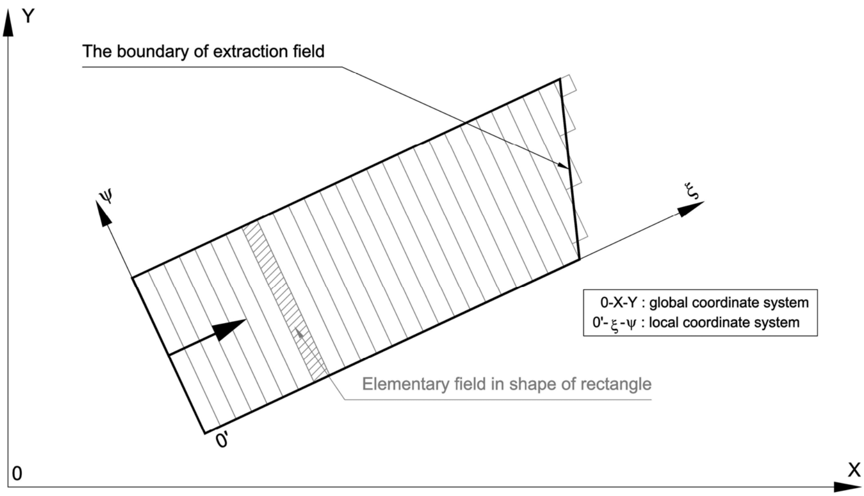

Fig. 2. The sketch of extraction field discretization idea

In the programs discussed in this work, intended for parameters identification, the optimization problem is being solved with using the objective function resulting from the least squares method, according to the equation (1):

$$F\left(\Omega(.)\right) = \sum_{i=1}^{N}\left[w_i^{pom} - w_i^{mod}\left(p, q, \Omega(.)\right)\right]^2 \tag{1}$$

where:

i — measurement point counter,

N — number of points on observing line,

w_i^{pom} — subsidence measured at i-th point,

w_i^{mod} — subsidence calculated for i-th point by using considered theoretical model with current parameters values in the $\Omega(.)$ set,

p, q — spatial coordinates of i-th point,

$\Omega(.)$ — the set of parameters values : $(\Omega = \{a, \text{tg}\beta, d\}) \cup (\Omega = \{c\})$.

The optimal solution condition takes the following form:

$$\Omega(.)_{opt} = \Omega(.) \cdot F\left(\Omega(.)\right) < \varepsilon \tag{2}$$

where: ε — the stop criterion, defining the quality of the fit of the theoretical subsidence trough profile to the obtained one from surveys.

For the search of objective function minimum, the Hooke-Jeeves method is utilized. The developed software allows determination of a complete set of parameters, or for any subset combination, assuming that other parameters have given, constant value in the identification process.

The calculation results are stored on disk as a text file and include the following:

- *in the header:* project account code, determined set the model parameters Ω,
- *in the main part:* the subsidence values taken from the measurement w^{pom} and obtained using a theoretical model w^{mod} (Ω), deviation $[V] = w^{pom} - w^{mod}$, deviation squares $[VV]$ and the corresponding cumulative sums calculated: $[SumV]$ and $[SumVV]$
- *at the bottom part of the file:* the measures of fit quality:
  - average error of a single observation: $m_w = \sqrt{\dfrac{SumVV}{N-1}}$,
  - percentage error: $m_{\%} = \dfrac{m_w}{\max(|w^{pom}|)} \cdot 100.$

3. The user interface

The user interface is identical to all programs, due to their functioning in the environment of the Windows operating system as well as the authors' intention to facilitate the operation of all programs in the package. Obvious differences exist in terms of content, associated with a variety of tasks for which these programs were developed. The main application window is shown in Figure 3.

The main application window serves as a mining extraction fields database controller. The most important interface elements in this window are:

- 1.1 – the projects navigation panel;
- 1.2 – the currently selected project account code;
- 1.3 – the mining-geological data of currently displayed extraction field;
- 1.4 – the extraction fields navigation panel (allows changing and editing the current extraction field within the current project);
- 1.5 – the window displaying the shape of current extraction field;
- 1.6 – the table with the coordinates of current extraction field vertices.

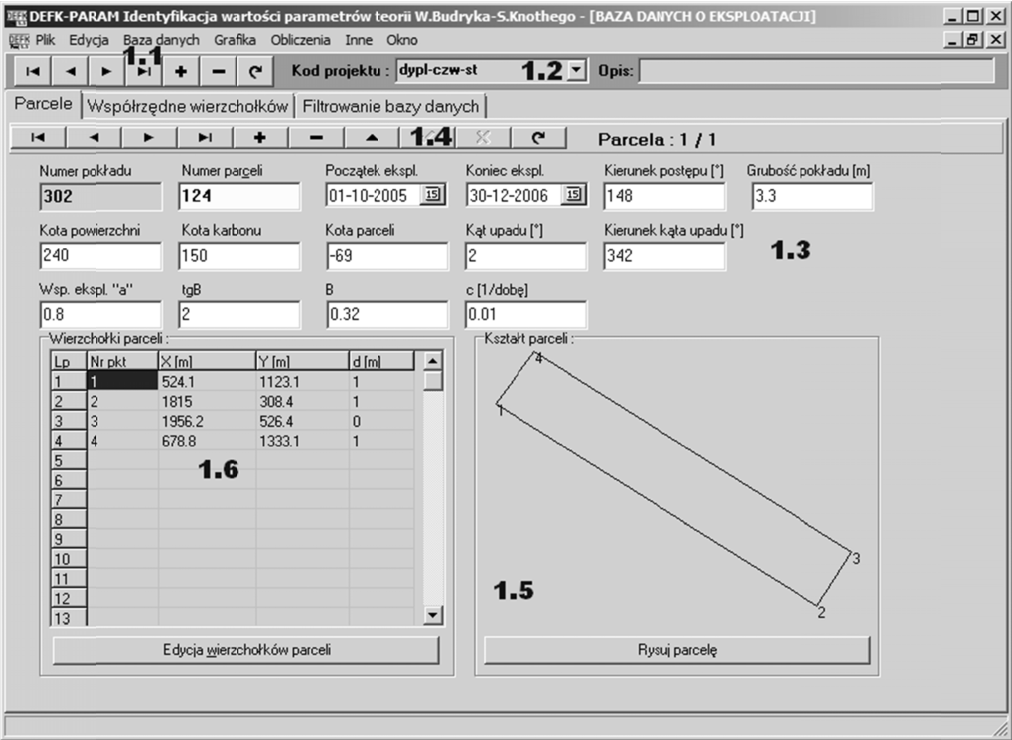

Fig. 3. The applications main window

In the "Calculations" menu, there is a function designed, that starts the calculation process. Before starting the identification process, user has to prepare the relevant data. The corresponding window for entering the data is shown in Fig. 4. Key elements of these data are:

- 2.1 – the input and output file names;
- 2.2 – the parameters of Hooke – Jeeves algorithm;
- 2.3 – the starting values of parameters to be optimized;
- 2.4 – the button to constrain the search space for optimal parameters (see Fig. 5);
- 2.5 – the button for starting the optimization procedure (see Fig. 5);
- 2.6 – the set of parameters determined on the basis of asymptotic subsidence trough, used as constants in identification of the parameter *c* – only BK_CTX program;
- 2.7 – the controls for choice of method for determining the parameter *c* (Ścigała, 2009) – only BK_CTX program.

During optimization calculations, the window shown in Fig. 5 on the right is displayed, where one can observe the values of parameters at the current stage of optimization process, as well as the objective function value.

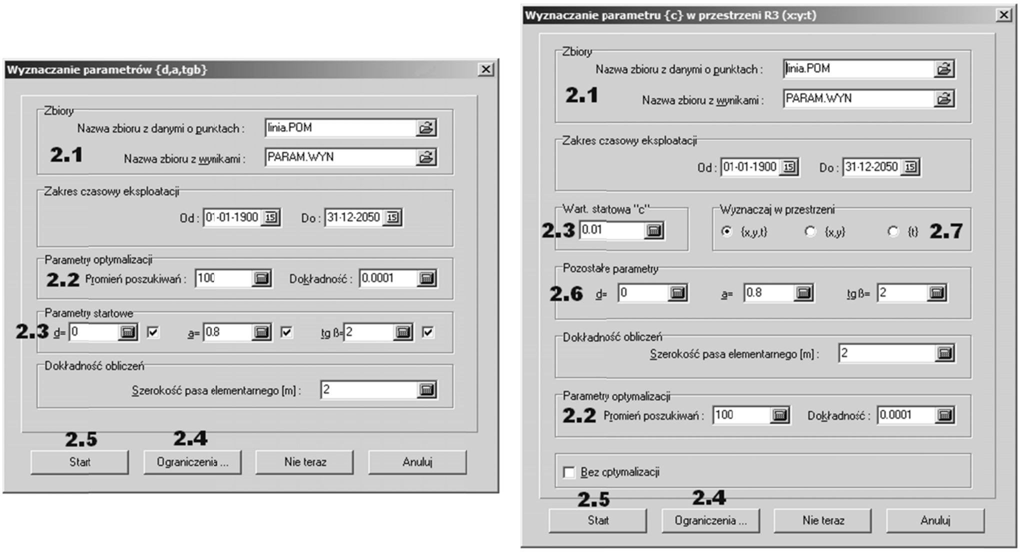

Fig. 4. The windows serving for definition of identification process
(DEFK_PARAM program on the left, BK_CTX program on the right)

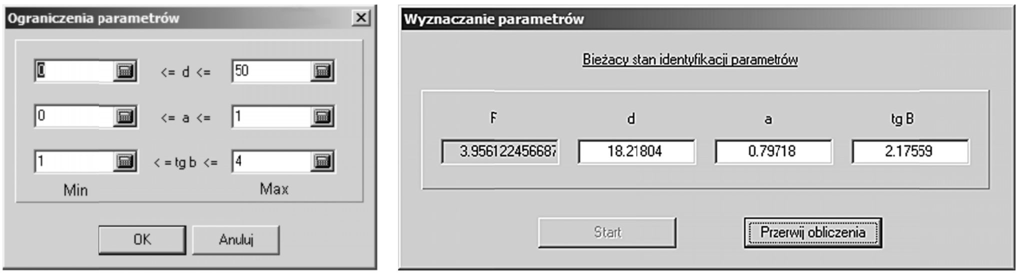

Fig. 5. The window for constrain the search space of parameters (left)
and identification process window (right)

4. The example of programs application

The use of discussed programs for identification of W. Budryk-S. Knothe theory parameters on the basis of surveys results taken from measuring line B-L, located in the area of the former coal mine "Dębieńsko", has been presented below.

The line "B-L" consists of 43 measuring points; the average distance between points was 15 m. Measurements were led at time intervals of 10 days average. In the vicinity of the line, mining extraction of coal seam 326/5 was led with longitudinal longwall caving, at an average depth of 160 m. The average height of extracted seam was about 1.3 m. The rate of face advance was variable, and ranged from 1.5 m/day to 4.5 m/day. The location of the observing line in relation to extracted field is shown in Figure 6. For analysis purposes, the measurement cycles from 8 to 13 were selected, according to the sketch shown in Figure 6. Additionally, in this sketch, the location of extraction edge is presented at the time of selected measurement actions (number of measurement is shown at the bottom edge of extraction field).

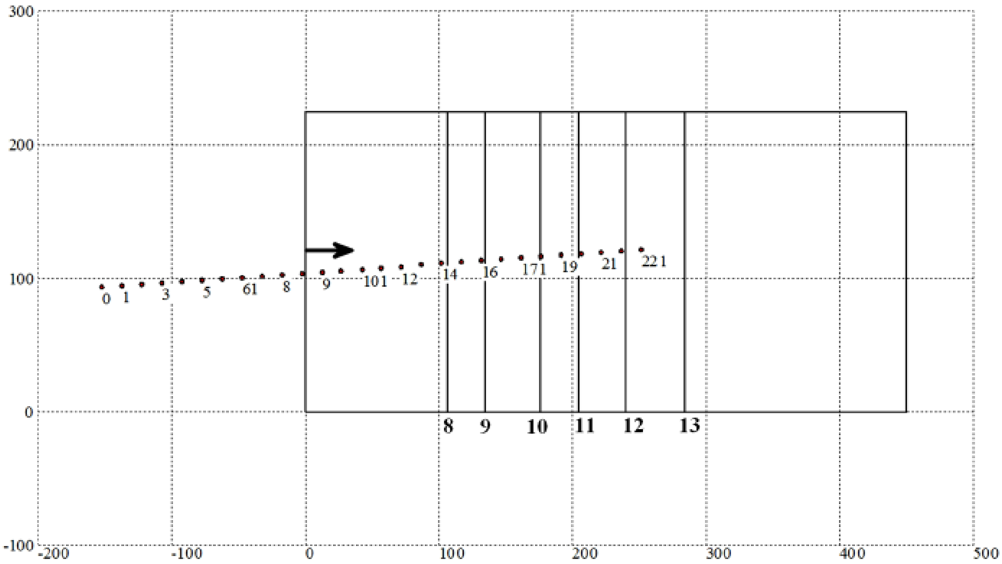

Fig. 6. The location of observing line in relation to extracted field

In the first stage of the identification of W. Budryk-S. Knothe parameters, there were determined values of $\{a, \mathrm{tg}\beta, d\}$, on the basis of asymptotic trough profile. For this purpose the DEFK_PARAM program was used. The following values were obtained:

- $a = 0.795$,
- $\mathrm{tg}\beta = 2.1$,
- $d = 18.0$ m.

Percentage error of fit the subsidence trough taken from measurement and calculated with using optimal values of parameters was equal to 2%. The graphical comparison of considered trough profiles is shown in Figure 7.

The abovementioned parameters $\{a, \mathrm{tg}\beta, d\}$ were taken then as constants in the process of identification of parameter c. The BK_CTX program was used for this purpose. The identification was carried out by using authors' proposed methodology (Ścigała, 2009), which bases on the simultaneous determination in space-time coordinates $\{x, y, t\}$.

A part of the obtained results is shown in Table 1. Percentage error of fit between the all considered transient subsidence troughs taken from measurement and calculated with using optimal value of parameters c was about 6%. Due to limited volume of the paper it has not been presented a graphical comparison of transient troughs profiles.

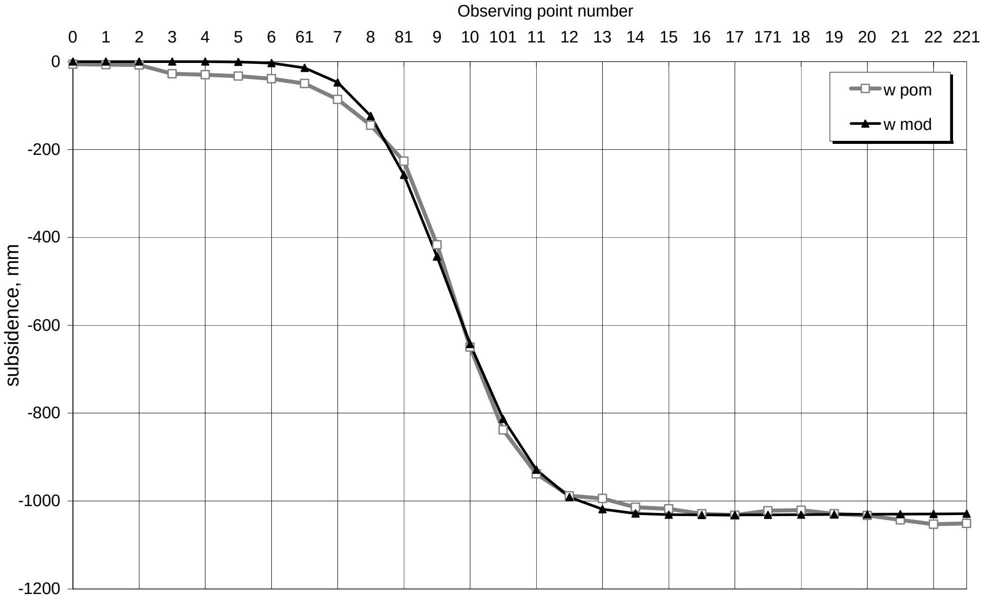

Fig. 7. The comparison of the theoretical asymptotic trough defined by using the parameters obtained in the identification process, with the obtained one from measurements

TABLE 1

The results of parameter c identification in the $\{x,y,t\}$ space

Obtained value of parameter c : c_opt = 0.065 [1/day]							
Asymptotic trough parameters : a = 0.795, tgβ = 2.1, d = 18.03							
The profiles of transient subsidence troughs for selected measurements							
Point No	01-10-1974		10-10-1974		.....	20-11-1974	
	w^{pom} 8	w^{mod} 8	w^{pom} 9	w^{mod} 9	.....	w^{pom} 13	w^{mod} 13
1	2	3	4	5	6	7	8
5	-23	-0.9	-25	-0.9	.....	-28	-0.9
6	-28	-4.2	-26	-4.2	.....	-32	-4.3
61	-33	-15.8	-35	-16.1	.....	-43	-16.3
7	-50	-48.7	-57	-49.5	.....	-79	-50.5
8	-80	-121	-106	-123.6	.....	-136	-126.6
81	-150	-244.7	-178	-251.2	.....	-213	-258.8
9	-300	-410.4	-355	-425.1	.....	-402	-442.5
10	-468	-575	-565	-604.8	.....	-633	-640.7
101	-555	-686.4	-719	-741.6	.....	-819	-811
11	-523	-706.1	-767	-798.5	.....	-919	-923.9
12	-413	-632.1	-734	-769.2	.....	-967	-979.5
13	-275	-492.5	-616	-669.5	.....	-971	-996.5
14	-171	-331.7	-484	-526.5	.....	-987	-992.8
15	-103	-191.7	-325	-371.6	.....	-987	-979.4

1	2	3	4	5	6	7	8
16	-65	-93.1	-195	-230.9	.....	-989	-960.2
17	-41	-37.5	-114	-124.3	.....	-983	-934.3
171	-30	-12.5	-62	-57.4	.....	-959	-899.3
18	-21	-3.4	-42	-22.2	.....	-940	-850.5
19	-18	-0.7	-28	-7.1	.....	-917	-785.7
20	-11	-0.1	-20	-1.9	.....	-869	-702.4
Average error of a single observation: 59.085					Percentage error : 5.97%		

5. Concluding remarks

In the framework of this paper, the characteristic of two computer programs used for identification of W. Budryk-S. Knothe theory parameters has been presented. They are the components of a complete system designed for forecasting of underground extraction influences on the rock mass and land surface, which was built by the author of this work. Advanced calculation options of programs DEFK_PARAM and BK_CTX allow to determine in a comprehensive way the optimal set of parameters, on the basis of surveys results. It contributes to improving the quality of predictions made by using such values of parameters.

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