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EXAMPLES OF THE KNOTHE-BUDRYK THEORY PARAMETER DETERMINATION UNDER COMPLEX GEOLOGICAL AND MINING CONDITIONS

Bartosz APANOWICZ[1*], Andrzej KOWALSKI[1], Piotr GRUCHLIK[1], Piotr POLANIN[1]

[1] Department of Surface and Structure Protection, Central Mining Institute, 1 Gwarkow Square, 40-166 Katowice, Poland

Abstract: As is characteristic of every theoretical model, its application necessitates the adoption of appropriate parameters. Adopting incorrect parameters leads to erroneous results. This also concerns the application of the Knothe-Budryk theory of rock mass movement. The complexity of the geological and mining conditions means that the a priori adoption of the appropriate parameters requires analyzing the measured deformation factors. Geodesic measurements are performed for this purpose, which apart from enabling deformation prediction control, also serve to provide a posteriori parameter determination, which is subsequently used to predict the deformation induced by mining exploitation conducted under analogous conditions. The article presents the determination process and results of the following Knothe-Budryk theory parameters: the extraction coefficient (a), the rock mass parameter (tgβ), the offset of the inflection point (p) and the coefficient of influence deviation depending on the inclination of Carboniferous strata (k), based on two examples of exploitation. The examples are characterized by diverse geological and mining conditions. In the first example, the panels exhibit varied shape and dimensions, and are located on two sides of a trough, which has resulted in a deviation of the deformation in two opposite directions. The second example presents an analysis of deformations induced by the exploitation of one longwall located at a great depth of over 1000 m, on a tilted side of a trough and within an area exhibiting a diverse degree of prior mining.

Key words: *Knothe-Budryk theory, parameters, complex mining conditions*

*, Corresponding authors: bapanowicz@gig.eu (B. Apanowicz)

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1. INTRODUCTION

It is well known that even the best theoretical model is useless without the correct and appropriately determined parameters. Adopting incorrect parameters for the calculations will lead to erroneous results.

Applying the parameters of the Knothe-Budryk theory to prediction deformations remains a valid and important issue, despite the fact that the theory has been in use for over 70 years. This can be attributed to the changing geological and mining conditions. The mining depth continues to change, and in 2021 it exhibits an average of 800 m. The mining conditions evolve as well, the scale of exploitation increases, and the deformations induced by the simultaneous mining of multiple longwalls add up.

Due to the mining depth as well the scale and shape of the longwall, partial troughs are generated on the surface, which are used for determining the parameters of the theory, which in turn results in errors. Furthermore, the quality of the parameters is also influenced by deformation measurement results depending on the number of measurement points and their location relative to the longwalls.

The surface deformation measurements are conducted in order to control deformation predictions. The purpose of the mining activity is not to obtain the measurement data for parameter determination – it merely serves as the opportunity for doing so (Kowalski 2007).

The goal of this article is to present the determination process and interpretation of the following parameters: the extraction coefficient (a), the rock mass parameter (tgβ), the offset of the inflection point (p) and the coefficient of influence deviation (k) depending on the inclination of Carboniferous strata (in the trough), based on two examples of exploitation. The examples are characterized by complex geological and mining conditions.

In the first example, the longwalls are located on the opposite sides of a trough and are characterized by diverse mining conditions: three longwalls with varied scopes and periods of exploitation, as well as different scales of prior mining activity. In the second example, the longwall is located on the tilted side of a trough and at a great depth of over 1000 m, with Carboniferous strata reaching up to the surface.

2. STATE OF KNOWLEDGE

In Polish hard coal and copper ore mining, surface deformation is most commonly (almost exclusively) predict by means of the Knothe-Budryk theory of rock mass movement (Knothe 1953, Knothe 1984). As with all theories, knowledge regarding its parameters is a significant issue, and this can be reflected in the numerous monographs and articles on the subject: (Białek 2003, Popiołek 2009, Mierzejowska 2010, Kwinta

2012, Ostrowski 2015, Kowalski 2020) and many others. The Erdhardt-Sauer theory published in 1961 is concurrent with the Knothe-Budryk theory, and it finds application in German hard coal mines (Sroka 1999, Kratzsch 2008).

The key parameters for estimating the subsidence curve in the Knothe-Budryk theory are the rock mass parameter $tg\beta$ and the extraction coefficient a. The $tg\beta$ parameter characterizes the structure of the rock mass located above the mining exploitation. It is generally accepted that for compact layers the range is greater and the slope of the subsidence is gentler. This parameter changes with the number of times the operation is carried out.

The extraction coefficient determines the method of steering the roof during exploitation. It is defined as the quotient of the greatest decrease in W_{max} to the thickness of the exploited seam g:

$$a = \frac{W_{max}}{g} \tag{1}$$

The definition applies to large longwalls. Currently, at the USCB, mining is carried out with the cave-in. On the basis of 30 cases from USCB, the average parameters of the Knothe - Budryk theory were determined (Kowalski 2020):

- The extraction coefficient: a = 0.8,
- the rock mass parameter: tgβ = 1.93 ≈ 2.0.

The values of the theory's parameters are a subject of study at the Central Mining Institute, where the Knothe-Budryk theory is also applied in deformation prediction. Comparisons of the deformation factors adopted a priori with the forecasts including factors measured a posteriori are performed as well, which results in the determination of factor difference deviations (Kowalski 2020). At GIG, the theory parameters are determined by means of the method of least squares, by comparing the theoretical and measured subsidence in troughs using specialist software (Jędrzejec 2002).

In 2012, A. Kwinta presented a method for determining the parameters of the Knothe-Budryk theory for asymptotic and transient states using multiple measurement points (Kwinta 2012). It should be noted that the methodology proposed by A. Kwinta may be correct in theory, but practical experience indicates the limited possibilities of applying this procedure for actual parameter determination.

Substantial knowledge regarding the determination and accuracy of the parameters is provided by the research conducted at the Silesian University of Technology in Gliwice, where prediction is accomplished by expanding the Knothe-Budryk theory through the inclusion of the offset of the inflection point (Białek 2003). A. Mierzejowska developed an algorithm for estimating the accuracy of the determined parameters: the extraction coefficient (a), the rock mass parameter (tgβ) and the offset of the inflection point (p) by applying J. Białek's formula for subsidence calculation (Białek & Mierzejowska 2012, Mierzejowska 2014). Including the offset of the inflection point as a parameter is the simplest way of improving the theoretical description according to the classic formulas of the theory. A broader analysis of this parameter is presented in the article (Kowalski & Jędrzejec 2015).

3. METHODOLOGY FOR DETERMINING PARAMETERS

The parameters of the Knothe-Budryk theory should be determined on the basis of geodetic measurements of mining deformations measured in a given area or in similar mining and geological conditions. Determining parameters from their definition is a good approach, but nevertheless, nowadays mainly incomplete subsidence are observed. Therefore, the parameters are determined by the method of successive approximations by performing calculations for various combinations of parameters, using the least squares method. The basic parameter that determines the accuracy of the determined parameters is the standard deviation between the specified theoretical distribution of decreases and the actually measured one.

In the absence of *in situ* geodetic measurement, the average parameters described in chapter 2, are taken first. It should be noted that determining the correctness of the application of average parameters and their adoption in order to obtain good results requires a lot of experience and knowledge about the rock mass.

In the research, the described recommendations were followed and the parameters were determined by the method of successive approximations. First, two basic parameters of the theory were used, i.e. the extraction coefficient a, and the rock mass parameter $tg\beta$. By the method of successive approximations, successive parameter values were checked and another parameter of the offset of the inflection point p was added. Based on the standard deviation of the theoretical reduction from the measured one, the best fit was determined.

4. EXAMPLE 1 – MINE B

4.1. GEOLOGICAL AND MINING DATA

The geological and mining conditions in the analyzed example are diverse. Exploitation was conducted in two coal seams – 503 and 504 – in three longwalls (4, 7 and the end of longwall 5). The longwalls exhibited varied shapes and dimensions, and their characteristics are presented in table 1, whereas the shape and dimensions are depicted in fig. 1.

Deformation measurements on a measurement line situated along trunk road DK 88 were conducted from 13.01.2018 to 30.11.2020. The line was located above the south part of longwalls 4 and 5 and above longwall 7. The distance between the measurement points was 30-40 m. The geodetic height measurements were carried out through precise optical levelling with a mean error of ±2.4 mm/km.

Tab. 1. Geological and mining data of the mined longwalls

Coal seam	Long-wall	Thick-ness [m]	Depth [m]	Longwall lenght [m]	Longwall width [m]	Start date	Stop date	Com-ments
504	4	2,88	714	1650	280	01.08.2018	01.08.2020	-
504	7	2,70	684	420	135	01.06.2018	01.04.2019	-
504	5	2,30	683	270 (1325)	285	01.01.2018 (01.03.2016)	01.06.2018	(Data for entire longwall) – analysis from 01.2018

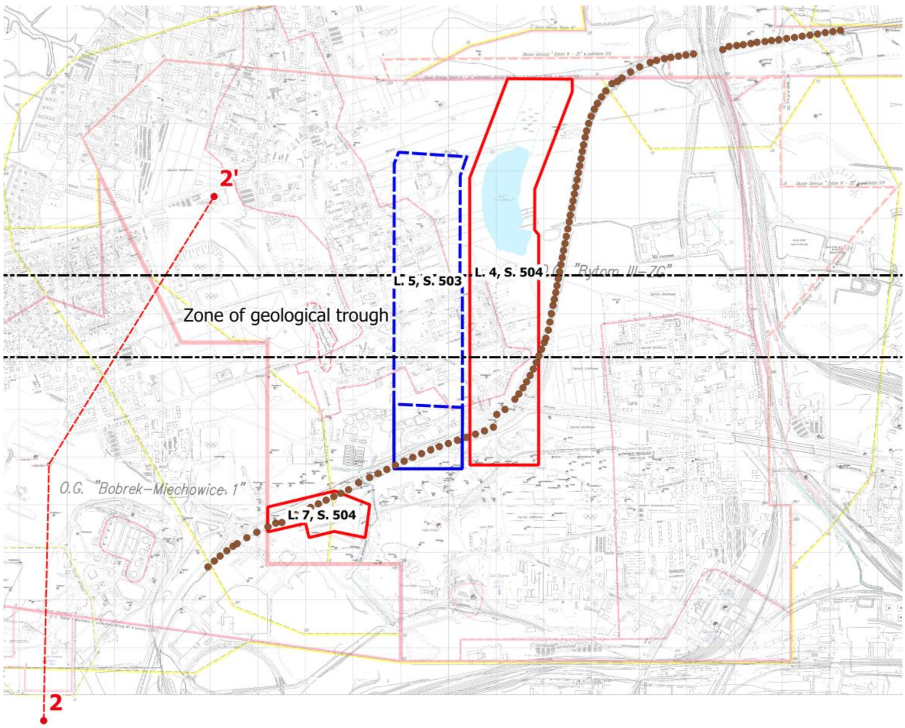

Fig. 1. Location of the longwalls, the observation line and the 2-2' geological section line

The longwalls were located on the opposite sides of a trough. Longwall 7 was on the south side with an average inclination of 12° NNE, the end of longwall 5 on the south side with an inclination of 5° NEE, and longwall 4 on the north and south sides and the bottom of the trough with an average inclination of 6° SSE. Such a varied panel inclination resulted in the displacement of the deformations in opposite directions. The Triassic overburden had an average thickness of 150 m (fig. 2).

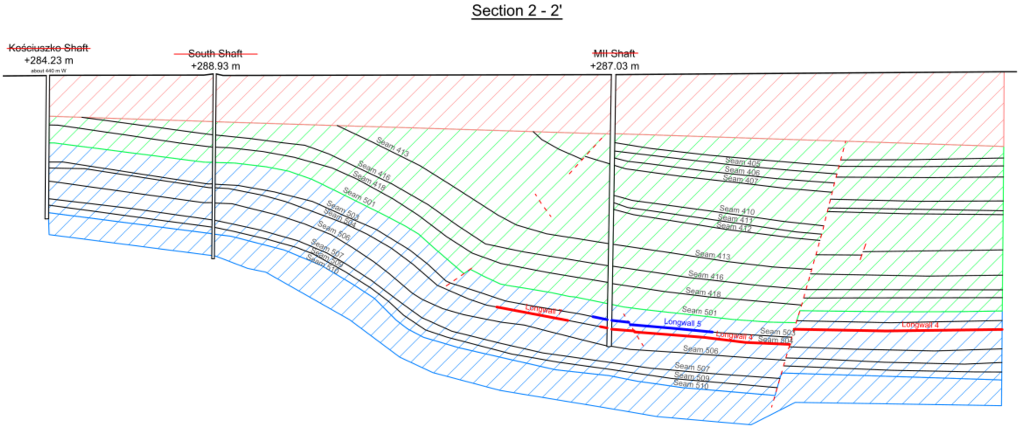

Fig. 2. 2-2' geological section

4.2. DETERMINED THEORY PARAMETERS AND THEIR DISCUSSION

The theory parameters were determined based on subsidence measurements on the measurement line by means of the method of least squares. The SZKODY 5.0 software was used for this purpose (Jędrzejec 2002). The parameter selection was performed based on the standard deviation of the differences in theoretically calculated and measured subsidence. The process began with preliminary calculations that did not include the offset of the inflection point and the influence of the inclination of Carboniferous strata on the deformation deviation towards the dip of the trough. The fitting error was $\sigma = 237mm$. The subsidence calculation and measurement results are presented in fig. 3.

In the next stages, the parameter determination was carried out through consecutive tests using different values of the offset of the inflection point and the coefficient of influence deviation. The best fitting of theoretical and measured subsidence is presented in fig. 4, where the standard deviation was $\sigma = 54mm$, which was deemed satisfactory.

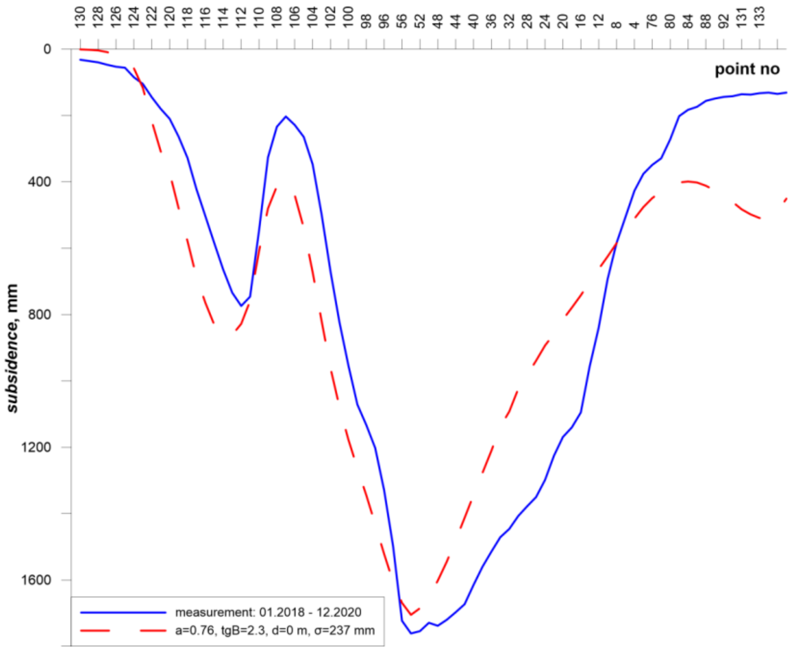

Fig. 3. Preliminary fitting results of theoretical and measured subsidence for the basic theory parameters

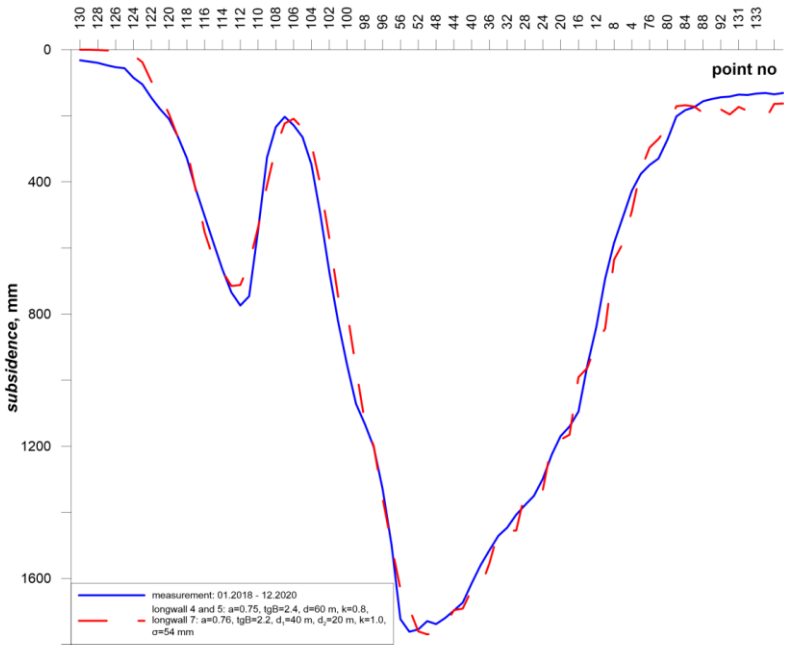

Fig. 4. Fitting results of theoretical and measured subsidence (for theory parameters including the offset of the inflection point and the influence of the inclination of Carboniferous strata)

The parameters corresponding to the best subsidence fitting are varied for longwall 7 as well as for longwalls 4 and 5. They are presented in table 2.

Tab. 2. Determined parameters of the Knothe-Budryk theory

Coal bed	Longwall	a	tg β	p [m]	k
504	7	0.76	2.2	40 – for the west part of the longwall, -40 – (negative offset) from the north side, 20 – for the east part of the longwall	1.0
504	4	0.75	2.4	60	0.8
503	5	0.75	2.4	60	0.8

The subsidence charts presented in fig. 3 and 4 demonstrate that the key element in the process was to apply the appropriate values of the offset of the inflection point (p) and the coefficient of influence deviation (k).

A classic offset of the inflection point as well as a negative offset of 60 m were applied in the case of longwalls 4 and 5. The coefficient of influence deviation is 0.8, which is a classic value for coal beds with inclinations lower than 10°. The extraction coefficient (a) is 0.75, whereas the rock mass parameter tgβ = 2.4. These values are lower than the parameters determined previously for the large panel encompassing both longwalls 5 and 6 in coal seam 503 over the entire longwall length, or when the fitting included scattered measurement points within the protected area of an adjacent district. The parameters determined at the time were a = 1.1 and tgβ = 3.15 (Kowalski 2020). The explanation for these differences can be found in the location of the measurement line relative to the extraction outline of longwalls 4 and 5, with a partial trough on the surface. The other factor that may have had an influence on the determined parameter values was the omission to include the influence of a part of longwall 5, which was being mined before 01.01.2018, and whose deformations appeared after that time.

The parameters a = 0.76 and tgβ = 2.2 determined for the influence of longwall 7 are close to the classic values, though they were determined on the basis of a partial subsidence trough generated by the mining of a small and irregular panel. The greater extraction coefficient a > 0.7 may be the result of the prior exploitation of longwall 7, two years earlier in coal seam 503, which was deposited 30 m closer to the surface. Diverse values of the offsets of inflection points were assumed by way of consecutive tests, with determined values of 40 m on the west side, and 20 m on the east side (fig. 5).

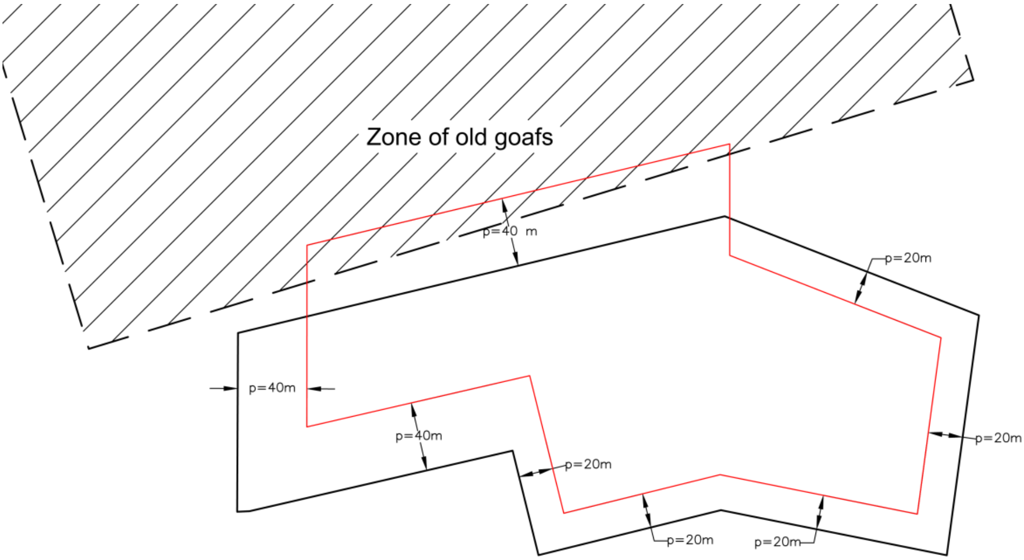

Fig. 5. Assumed diverse offsets of inflection points for longwall 7

The reason for this is that north of the longwall 7, in the west part of the coal seam, there was a narrow strip of the body of coal with a width of 15 to 30 m, beyond which were the goafs generated by prior mining conducted in this coal seam. The value of the coefficient k for longwall 7 was k = 1.0, which is related to the inclination of the south side of the trough (12°.

5. EXAMPLE 2 – MINE R

5.1. GEOLOGICAL AND MINING DATA

Longwall VIII-E-E1 was mined in coal seam 703/1 to an average height of 2.15 m from February to December 2019 (fig. 6). The longwall width was 200 m, and the longwall length was 800 m. The exploitation was conducted north to south, at a depth of 1080 m to 1007 m. This was the final longwall in panel E-E1, and it was located adjacent to longwall VII E-E1, which was mined out over the years 2016-2017. The coal seams of group 600 had been mined directly above the E-E1 longwalls in coal seam 703/1, and they were deposited much closer to the surface, with respective depths of coal seam 624 – 420 m, 620 – 570 m and 615 – 700 m. The exploitation of these deposits had been conducted long ago, before the year 2000.

In the east, beyond the border pillar, with a width of 100 m in coal seam 703/1, the exploitation was conducted by the adjacent mine M, using longwalls M6-M8 with caving over the years 2000-2001 (fig. 6). Later on, mine M mined coal bed 707 with caving over the years 2009-2010 and coal seam 712 with packing and caving over the years 2012-2018.

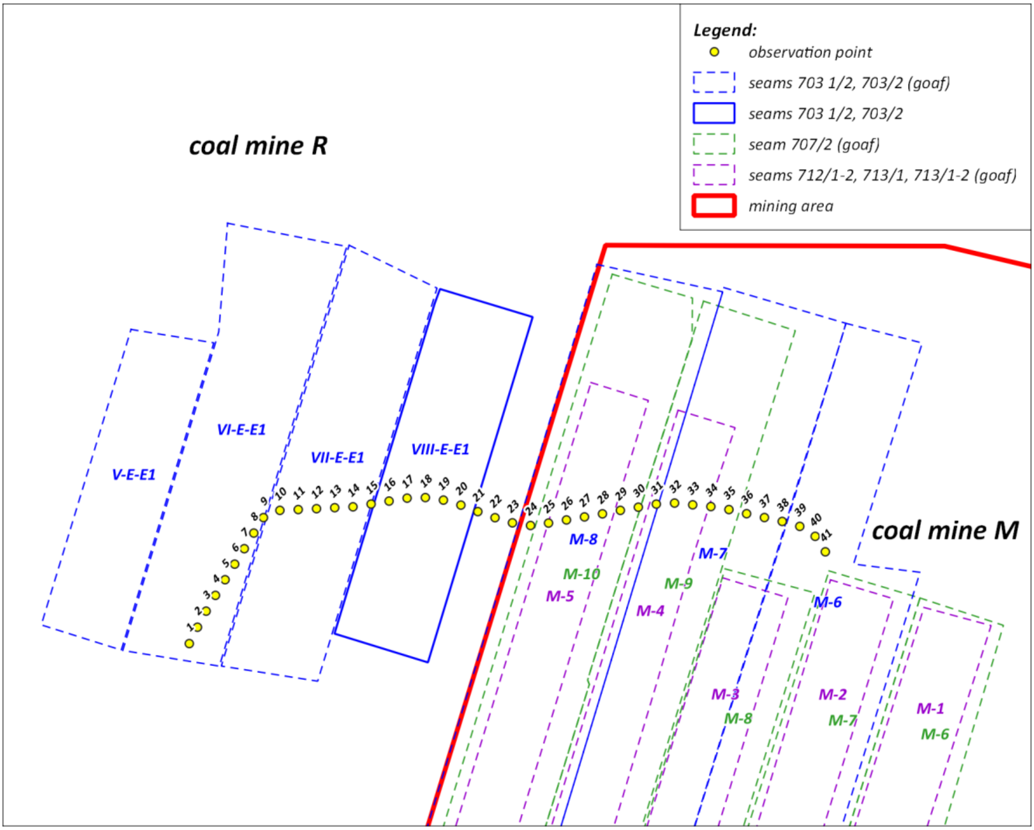

Fig. 6. Panels in coal seam 703/1 in district E-E1 and the location of the measurement line (on the surface)

The coal seam inclination ranged from 3 to 10 degrees, 8° NW on average. The roof of coal seam 703/1 contains clay shale (claystone) with varied sand content, whereas the floor contains arenaceous shale (mudstone) with local presence of sandstone. The overlying rock mass reaching towards the surface contains alternating strata of shales, sandstones and conglomerates, and a 150 m sandstone stratum is deposited 150 m above coal seam 703/1.

5.2. DETERMINED THEORY PARAMETERS AND THEIR DISCUSSION

Fig. 7 presents charts of subsidence along the measurement line, which demonstrate that a shallow and extensive trough had formed on the surface, with the greatest depression of 0.34 m (the area of measurement points 13 and 14) located about 70 m west of the mining face and 170 m from the longitudinal axis of longwall VIII E-E1. The westward shift of the bottom of the trough induced by the exploitation of longwall VIII E-E1 is influenced both by the tilt of the Carboniferous strata (NW) and the offset of the inflection point from the goafs of longwall VII E-E1.

The subsidence charts in fig. 7 indicate that about 70% of the subsidence manifested itself directly after the conclusion of exploitation in December 2019, and the subsidence for the end of December 2019 was adopted as the average value of the measurements taken in 12.11.2019 and 22.02.2020.

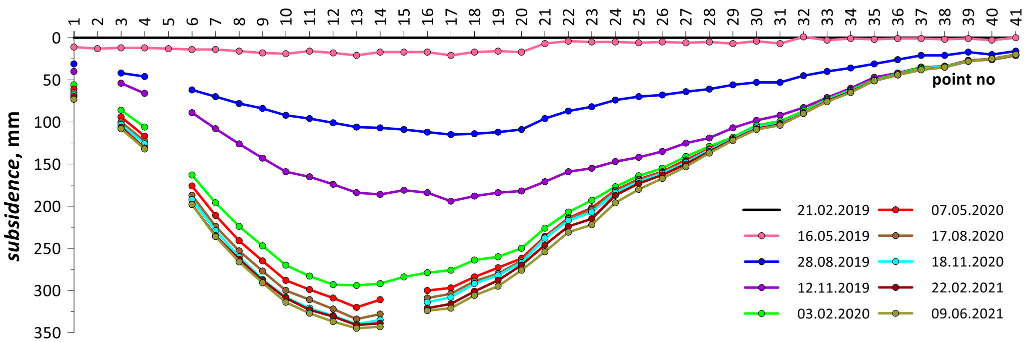

Fig. 7. Subsidence along the measurement line induced by the mining of longwall VIII E-E1

Fig. 8 presents the final fitting results of theoretical and measured subsidence (for the adopted theory parameters including the influence of the offset of the inflection point and the inclination of Carboniferous strata). The fitting process was complex given the diverse tilt of the trough on the west and east sides, as the average trough inclinations were 1.0 mm/m and 0.5 mm/m respectively.

Fig. 8 demonstrates that the coefficient of deviation k = 1.0 and the offset of the inflection point p=0.1*H=100 m adopted a priori can be deemed correct. However, two of the basic theory parameters, the extraction coefficient and the rock mass parameter, could not be determined for the entire trough.

The best fitting for the trough on the west side is achieved for parameters a = 0.75 and tgβ = 1.7, whereas for the east side of the trough, the values are a = 0.9 and tgβ = 1.2, where the value of the extraction coefficient would need to be increased by 40%! The subsidence on the east trough side is affected by the renewed influence of goafs in coal seams 707 and 712 as well as 703/1.

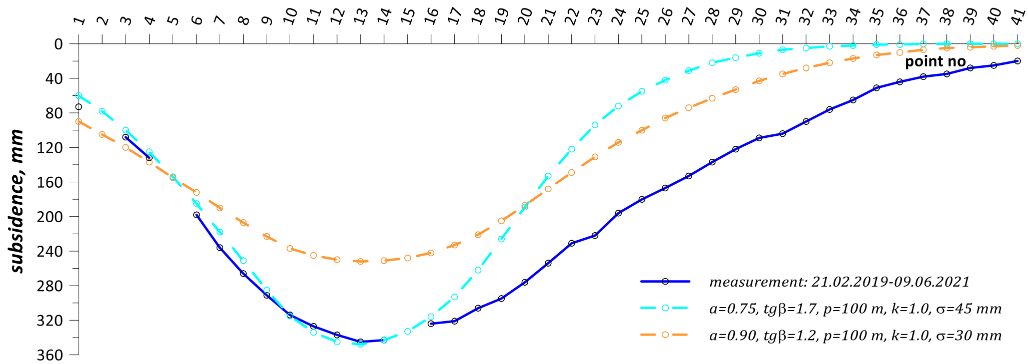

Fig. 8. Fitting results of theoretical and measured subsidence for theory parameters including the offset of the inflection point and the influence of the inclination of Carboniferous strata

To conclude, it is recommended to adopt the parameters obtained on the west side for the deformation prediction for mine R, which is confirmed by analysing the measurements taken in other regions of the mine, where the determined values of the extraction coefficient are a = 0.7-0.8 and the rock mass parameter is tgβ = 2.0, and to factor in the influence of the inclination of Carboniferous strata.

6. CONCLUSIONS

The following conclusions can be drawn based on the two presented examples of surface deformation prediction theory parameter determination:

1. The deformation prediction parameters adopted a priori are burdened with errors resulting from the ever-limited knowledge regarding the behavior of a rock mass subjected to deformations and also from the theoretical model (theory) used for the prediction.
2. The two presented examples of determined parameters demonstrate the difficulty of their determination for small exploitation fields, which can be overcome through the analysis and interpretation of the geological and mining conditions.
3. In the first and second examples, it was demonstrated that the influence of the inclination of Carboniferous strata and so-called the offset of the inflection point should be taken into account. The offset of the inflection point is not the original parameters of the Knothe-Budryk theory's but it is included in accurate prediction in an geometrical and operator manner.
4. In the second example, it was demonstrated that it is necessary to determine the parameters of the theory from one measurement line for the neighboring hard coal mines.

5. The condition for improving prediction is to conduct deformation measurements and to analyze them. A field where no measurements are taken is a dead zone for science.

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