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COMPARISON ANALYSIS OF THE THEORETICAL AND FORECASTED VALUES OF MINING TERRAIN CURVATURES WITH REFERENCE TO THEIR VALUES CAUSED BY MULTI-DEPOSIT EXPLOITATION CONDUCTED AT THE GREAT DEPTH

In this article were presented the results of comparison analysis of mining terrain curvatures values, which were caused by a multiple exploitation of hard coal in several coal beds numbered 338/2, 341 and 358/1. The curvatures values (observed on the measuring line) were compared with their theoretical values calculated on the base of subsidence forecasted by the use of the Białek's formula (with the values of its parameters determined from the survey results) and with the curvatures values modeled with this formula directly. On the base of this comparison, there was made an evaluation of effectiveness of made forecasts and conducted theoretical calculations. Taking into account the values of correlation coefficients and standard deviations between the 'measured' and theoretical, and forecasted graphs of curvatures, it was defined which graphs fit better to the real results of geodesic measurements. It should be marked that an exploitation of three coal beds was conducted by the longwall system with the roof rocks falling into the post-exploitation emptiness, at a great depth amounts from 600 m (the 338/2 coal bed) to 1,000 m (the 358/1 coal bed). The influences coming from the exploitation of these coal beds were observed within 10 years on 53 points of measuring line, which was located above the middle of the B – 2 longwall in the 338/2 coal bed and parallel to the runs of excavations in this coal bed. The surveys of the points heights and distances between the measuring points were done in the three– and four–monthly cycles. Based on these measurements, the values of mining terrain curvatures were designated.

Keywords: multi-seams extraction; exploitation at the large depth; observed, theoretical and forecasted curvatures of mining terrain; J. Białek's formula

1. Introduction

The observed values of mining terrain curvatures caused by underground mining exploitation of hard coal deposits are compared with the curvatures values obtained from numerical modeling.

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Curvatures are designated from subsidence of three neighboring points of measuring line [1] stabilized in the ground above an exploitation field. Thus the curvature value occurs along of two neighboring segments of measuring line. It's difficult to say in which place of these segments occurs a curvature value determined from the survey results [2]. Therefore it's assumed that this value occurs in the middle point of these segments. Only when the segments have the same lengths, the curvature value occurs exactly in measuring point.

Forecasts of deformation indicators values of mining terrain (inter alia of curvatures) are getting done for the measuring points.

To make an evaluation of effectiveness of made forecasts, it's necessary to compare the forecasted values of curvatures with the empirical values or their average values [3, 4]. But the question is how to compare the curvatures values 'measured' along the segments and forecasted in the points? Can be compared the forecasted values, mainly calculated by use of the formulas of the geometric-integral theories of exploitation impacts with the 'measured' values, calculated only as the difference of subsidence measured in the points and divides by an average length of the neighboring segments?

Therefore in the article have been presented the comparison results of 'measured' values of curvatures conventionally assigned the mid–points of two neighboring segments with the curvatures values forecasted in the points by use of Białek's formula [5–8] (with the values of its parameters determined from the results of geodesic measurements) and with the theoretical values of curvatures (see more in the point 2.4) calculated using the same formula as when calculating of 'measured' values of curvatures (using only the subsidence forecasted in the points and the measured lengths of segments). On the base of values of standard deviations and correlation coefficients between the 'measured', forecasted and theoretical values of curvatures, it was possible to indicate which graph (forecasted or theoretical) describes better the observed values of curvatures.

2. Research methods

In this point have been presented a real case of hard coal exploitation carried out in several coal seams occur at great depths and the obtaining methods of the observed, forecasted and theoretical values of mining terrain curvatures.

2.1. Exploitation case

Some hard coal mine located in the southern part of Poland has been carried out in the years 2001–2011 an exploitation of hard coal in seams named 338/2, 341 and 358/1 (figure 1). Coal excavation was conducted by the use of longwall system with the roof rocks falling into the post-exploitation emptiness.

The 338/2 coal bed was exploited in the years 2001–2006 at the depth of 600 m. The height of longwalls numbered from B-1 to B-4 and C-1 was amounted from 2.5 m to 3.0 m.

Hard coal was excavated from the 341 seam in the years 2007–2011 by the use of longwalls numbered from B-1 to B-4. This coal seam was occurred at the depth of 635 m and its thickness was amounted from 2.3 m to 3.0 m.

The 358/1 coal seam was exploited at the depth of 1000 m and the height of longwalls numbered from B-1 to B-7 was amounted from 2.0 m to 2.9 m. Exploitation of this coal bed took place in the years 2002–2006.

Inclination of these coal beds was amounted from 4° to 6° in the south-eastern direction.

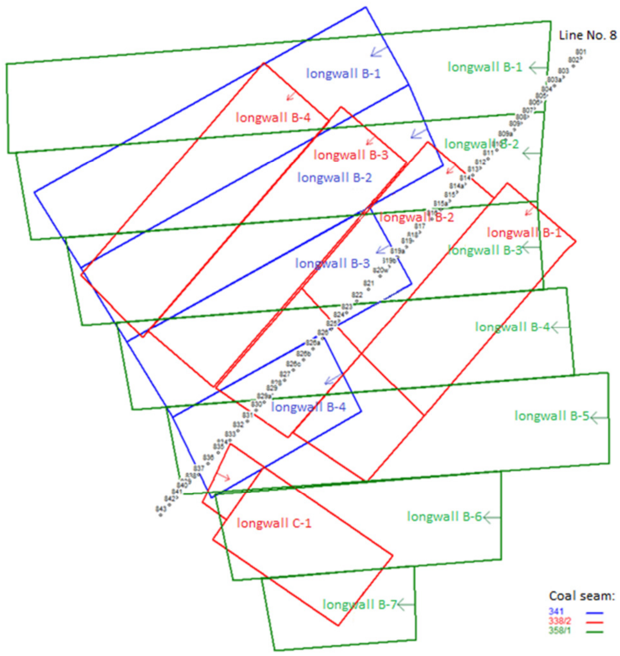

Fig. 1. Longwalls in the 338/2, 341, 358/1 coal seams and the measuring line No 8 (source: own elaboration)

2.2. Observed curvatures

Mining exploitation impacts on terrain surface have been observed at the measuring line No 8 which was established above the middle of longwall B-2 in the 338/2 coal seam, parallel to the runs of mining excavations located in this coal bed. Line was consisted of 53 measuring points and an average distance between subsequent points was amounted 35 m.

There have been carried out the geodesic survey before the beginning and after the ending of exploitation of the 338/2, 341 and 358/1 coal seams. There were measured the absolute heights of points in reference to the ‘Kronsztadt’ level and the lengths of measuring line segments.

On the base of difference of the points heights measured before and after the exploitation, there were designated the subsidence of measuring points (S_i) caused by exploitation of three coal beds. On the base of subsidence of three neighboring points S_{i-1}, S_i, S_{i+1} and the average length of two neighboring segments $L_{i-1,i}$; $L_{i,i+1}$, there were calculated the 'measured' values of curvatures in points connecting the subsequent segments C_i from the following formula [9–10]:

$$C_i^{meas} = 2\frac{S_{i-1}^{meas} - 2S_i^{meas} + S_{i+1}^{meas}}{L_{i-1,i}^{meas} + L_{i,i+1}^{meas}} \tag{1}$$

where: C_i^{meas} – curvature 'measured' in the i point connecting two neighboring segments [$10^{-6} \cdot 1/m$];
$L_{i-1,i}^{meas}$ – measured length of the $i-1,i$ segment [m];
S_{i-1}^{meas} – measured subsidence of the $i-1$ point [mm];
i – measuring point.

2.3. Forecasted curvatures

The forecasted values of curvatures have been calculated in the measuring points by the use of the *EDBJ1a* computer program and using the second derivative of the Białek's formula for calculation of subsidence [6–7]:

$$S_f = (1 - a_s)s(r_1) + a_s s(r_2) - A_1\left(2 + \frac{A_3}{2}\right)\frac{s(r_1)[r_1\gamma(r_1)]^2}{A_3\left[\frac{s(r_1)}{2} + \frac{s(r_2)}{2}\right]^2 + [r_1\gamma(r_1)]^2} \tag{2}$$

where: β – range angle of main influences [°];
γ – simplified octahedral strain [mm/m];
A_1 – dimensionless multiplier which takes into account an asymmetry of subsidence trough profile;
A_3 = 6.667;
S_f – final subsidence [mm];
a_s – coefficient constant for each subsidence trough, it defines what part of final subsidence was calculated by the use of the r_i radius ($a_s = 0.4 \div 1.25A_1$);
h – exploitation depth [m];
r_i – radius of influences dispersion for each subsidence trough [m];
$r_1 = \frac{h}{tg\beta}F_r(A_1)$;
$r_2 = 2r_1$;
$s(r_1)$, $s(r_2)$ – subsidence calculated using the Knothe's formula with the use of two different radiuses of influences dispersion r_1, r_2 [mm].

For calculation of curvatures values forecasted after the termination of exploitation in three coal seams, there were used the parameters values of the Białek's formula determined from the results of geodesic measurements conducted after an extraction end in all longwalls and all hard coal beds. These values have been calculated by the use of the *TGB* computer program, namely: $a = 0.889$; $\mathrm{tg}\beta = 2.520$; $A_1 = 0.138$.

There were taken into account the immediate impacts in done predictions of the subsidence and curvatures values.

2.4. Theoretical curvatures

The theoretical values of curvatures have been calculated from the same formula as when calculating of 'measured' curvatures. The subsidence values measured in the points have been replaced by the subsidence values forecasted by the use of the Białek's formula with the values of its parameters determined from the survey results:

$$C_i^{theor} = 2\frac{S_{i-1}^{fore} - 2S_i^{fore} + S_{i+1}^{fore}}{L_{i-1,i}^{meas} + L_{i,i+1}^{meas}} \tag{3}$$

where: C_i^{theor} – theoretical value of curvature in the i point connecting two neighboring segments [$10^{-6} \cdot 1/m$];
$L_{i-1,i}^{meas}$ – measured length of the *i-1,i* segment [*m*];
S_{i-1}^{fore} – subsidence forecasted by the use of the Białek's formula in the *i-1* point [*mm*];
i – measuring point.

There have been adopted the measured lengths of line sections in the formula number 3, because these lengths are real and most appropriate after the exploitation completion in three coal seams.

To differentiate the curvatures values obtained on the way of direct forecasting by the use of the Białek's formula from the curvatures values calculated by the use of the formula (3), the second one have been named as the theoretical curvatures because they have been obtained from the subsidence values predicted by the use of a chosen theory of mining exploitation influences.

3. Research results

At the figure 2 have been presented the 'measured', forecasted by the use of the Białek's formula and theoretical graphs of curvatures along the measuring line No 8, calculated on the base of formulas (1)–(3) and after the ending of exploitation in the 338/2, 341 and 358/1 coal seams. A red continuous line means the 'measured' graph of curvatures, a green continuous line presents the forecasted graph of curvatures and a blue continuous line represents the theoretical graph of curvatures.

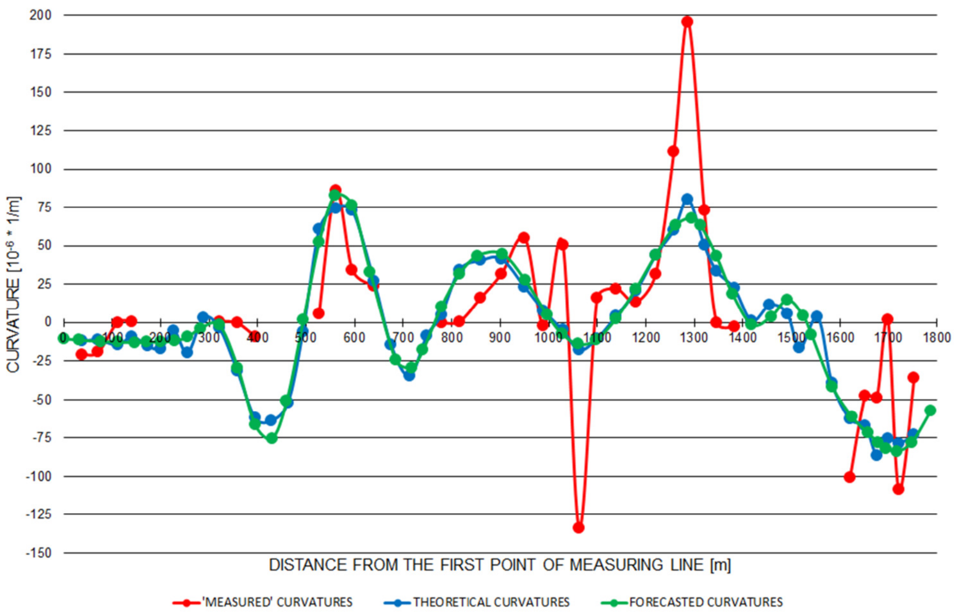

Fig. 2. 'Measured', forecasted and theoretical graphs of curvatures along the measuring line No 8 (source: own elaboration)

In order of comparison of curvatures 'measured' graph with their forecasted and theoretical graphs, there have been calculated the values of: the *R* correlation coefficient between these graphs, the *P* percentages of extreme 'measured' curvatures which correspond the extreme forecasted and the extreme theoretical curvatures, and the standard deviation marked as σ obtained from the formula (4):

$$\sigma_{Cmeas}^{Cfore/theor} = \sqrt{\frac{\sum_{i=1}^{n}(C_{imeas} - C_{ifore/theor})^2}{n-1}} \tag{4}$$

where: $\sigma_{Cmeas}^{Cfore/theor}$ – standard deviation between the 'measured' curvatures and the forecasted / theoretical curvatures [$10^{-6} \cdot 1/m$];

C_{imeas} – 'measured' value of curvature in the *i* point [$10^{-6} \cdot 1/m$];

$C_{ifore/theor}$ – forecasted / theoretical value of curvature in the *i* point [$10^{-6} \cdot 1/m$];

i – measuring point;

n – number of points.

The results of done calculations have been shown in the table 1.

Table 1. Comparison of curvatures 'measured' values with their forecasted and theoretical values (source: own elaboration)

'Measured' curvatures	
C_{meas}^{max} [$10^{-6}\cdot$1/m]	195.83
C_{meas}^{min} [$10^{-6}\cdot$1/m]	-133.54
Forecasted curvatures	
C_{fore}^{max} [$10^{-6}\cdot$1/m]	82.60
$Pmax_{Cmeas}^{Cfore}$ [%]	42.18
C_{fore}^{min} [$10^{-6}\cdot$1/m]	-83.60
$Pmin_{Cmeas}^{Cfore}$ [%]	62.60
R_{Cmeas}^{Cfore}	0.6488
σ_{Cmeas}^{Cfore} [$10^{-6}\cdot$1/m]	∓46.36
Theoretical curvatures	
C_{theor}^{max} [$10^{-6}\cdot$1/m]	80.25
$Pmax_{Cmeas}^{Ctheor}$ [%]	40.98
C_{theor}^{min} [$10^{-6}\cdot$1/m]	-86.36
$Pmin_{Cmeas}^{Ctheor}$ [%]	64.67
R_{Cmeas}^{Ctheor}	0.7178
σ_{Cmeas}^{Ctheor} [$10^{-6}\cdot$1/m]	∓42.35

4. Results discussion

From the curvatures graphs shown at the figure 2 and the data presented in the table 1 results that the minimal 'measured' curvature reached the value of $-133.54\cdot 10^{-6}$ 1/m and it occurred about 1,050 m from the beginning of measuring line. The maximal 'measured' curvature reached the value of $195.83\cdot 10^{-6}$ 1/m and it occurred about 1,300 m from the first point of measuring line.

The minimal forecasted curvature reached the value of $-83.60\cdot 10^{-6}$ 1/m and it occurred about 1,720 m from the first point of measuring line. The maximal forecasted curvature reached the value of $82.60\cdot 10^{-6}$ 1/m and it occurred in 560-th meter of measuring line.

The minimal theoretical curvature reached the value of $-86.36\cdot 10^{-6}$ 1/m and it occurred about 1,680 m from the beginning of measuring line. The maximal theoretical curvature reached the value of $80.25\cdot 10^{-6}$ 1/m and it occurred about 1,300 m from the 801 point.

The percentages values of extreme ‘measured’ curvatures which correspond the extreme forecasted and the extreme theoretical curvatures indicate that the extreme values of forecasted and theoretical curvatures reached the values more than half smaller than the extreme values of ‘measured’ curvatures. It can be seen that the percentages values of minimal ‘measured’ curvatures ($Pmin_{Cmeas}^{Cfore}$ = = 62.60% and $Pmin_{Cmeas}^{Ctheor}$ = 64.67%) are bigger than the values of percentages of maximal ‘measured’ curvatures ($Pmax_{Cmeas}^{Cfore}$ = 42.18% and $Pmax_{Cmeas}^{Ctheor}$ = = 40.98%).

The extreme forecasted and theoretical curvatures occurred generally in the other places than the extreme ‘measured’ curvatures but the minimal forecasted and the minimal theoretical curvatures occurred in principle in the same places.

As can be seen at the figure 2, the forecasted curvatures (green line) and the theoretical curvatures (blue line) have similar graphs. However, to the ‘measured’ graph of curvatures fits better the theoretical graph of curvatures than the curvatures forecasted graph. It’s evidenced by the values of: the R correlation coefficient (R_{Cmeas}^{Ctheor} = 0.7178) which is higher than for the forecasted curvatures (R_{Cmeas}^{Cfore} = 0.6488) and the σ standard deviation ($\sigma_{Cmeas}^{Ctheor} = \mp 42.35 \cdot 10^{-6}$ 1/m) which is smaller than for the forecasted values of curvatures ($\sigma_{Cmeas}^{Cfore} = \mp 46.36 \cdot 10^{-6}$ 1/m).

5. Summary and conclusions

In this article was shown an example of hard coal exploitation conducted at the large depth amounted 745 m in three coal seams numbered 338/2, 341 and 358/1. For observation of mining exploitation influences on terrain surface, it was established a measuring line No 8 which was consisted of 53 measuring points. This line was located above the middle of exploitation field and parallel to the run of longwall B-2 in the 338/2 coal bed. At measuring line were carried out the geodesic surveys of points altitudes and distances between neighboring points. On the base of surveys results, there were calculated the measured values of points subsidence and, based on them, the ‘measured’ values of segments curvatures. The value of ‘measured’ curvature was adopted in the joint point connecting two neighboring sections. It was also done the prognosis of curvatures values in measuring points. Forecast was done using the *EDBJ1a* computer program and by the use of the Białek’s formula with the values of its parameters determined from the results of geodesic measurements. Additionally there were calculated the theoretical values of curvatures from the analogical formula as when calculating of ‘measured’ values of curvatures but instead the measured subsidence there were used the forecasted subsidence.

This method allows to solve the problem of comparison ambiguity of the curvatures ‘measured’ along the line segments and forecasted in the measuring points. As indicate made calculations, a theoretical graph of curvatures fits to the empirical data better than a forecasted graph of curvatures. But also this method isn't free from defects. However, it occurs a problem: what lengths of measuring line segments should be used, since the prognosis is made before an exploitation start. Then aren't known the segments lengths after the termination of exploitation. It can be assumed the designed lengths of sections known before stabilization of measuring line points in the ground or the segments lengths measured in the first measuring cycle which takes place before an exploitation beginning.

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