Causes analysis of occurrence of the terrain surface discontinuous deformations of a linear type

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Abstract. In the article some area located in the mining terrain of hard coal mine in Poland has been analysed. In this area the discontinuous deformations of a linear type, for example faults and ground steps have been occurred. They had the substantial dimensions and appeared near or under the residential buildings. That's why they are so dangerous. In this paper the causes of their occurrence have been analysed. Probably a main reason of their creation is an intensive, underground mining exploitation which in two hard coal seams has been carried out. These seams were located at a relatively small depth, inclined at a significant angle, exploited by the use of a longwall system with a roof rocks cave-in and had a considerable thickness. All of these things contributed to accumulation of the adverse stresses concentrated in one area. Release of stresses caused by an extraction of hard coal contributed to the formation of numerous faults.

1. Introduction

Underground mining operation of the hard coal deposits can cause the continuous deformations of land surface, for instance subsidence, inclinations, curvatures, horizontal displacements [1] and horizontal strains and/or the discontinuous deformations of terrain surface [2], for example faults, ground steps [3], sinkholes.

There exist the mathematical models which allow to forecast the continuous [4], [5] and discontinuous [6], [7] land deformations. It should be emphasized that the predictions of discontinuous deformations are less precise than the forecasts of continuous deformations of terrain surface with reference to their sizes, range, place and time of occurrence.

The basic causes of discontinuous deformations occurrence are:

- migration of rain- and groundwater under a land surface and leaching of weakly-concise rocks (ground layers);
- mining exploitation of the zinc, lead and copper ores, conducted on small depths;
- the chamber or pillared-chamber exploitation system;
- weakly-concise rocks which built a direct roof.

As can be seen, an above group of occurrence causes of discontinuous deformations mainly concerns extraction of metal ores. According to the author, it is missing in it the causes induced by exploitation of the hard coal deposits. That's why in the article was presented an example of underground mining exploitation of the hard coal seams, which shows that some geometry of longwalls and geological-mining conditions of mining operation have significant influence on possibility of discontinuous deformations occurrence.

2. Example of exploitation and its consequences

2.1. Extraction characteristic

Operation of hard coal deposits took place in the years of 2013 ÷ 2018. It, in the 404 hard coal seam which has been divided into several layers, has been carried out. Extraction, in two layers called as 3rd and 5th by use of the longwall system with roof rocks cave-in, has been conducted.

Exploitation of the 404/3 seam, by use of two longwalls named the 1/II and the 2/II, has been carried out. Height of the longwalls was substantial and amounted 4.0 m and 3.4 m. The longwalls had a depth from 410 m (on the east) to 575 m (on the west). Seam inclination angle was large and amounted 17°. The 1/II longwall was exploited as a first one (from May to December 2013). Hard coal extraction from the 2/II longwall from August 2016 to February 2017 has been conducted.

The 404/5 hard coal seam was also exploited by use of the 1/II and the 2/II longwalls. Height of excavations was amounted 3.3 m and 3.5 m. Longwalls depth was respectively amounted 470 m and 550 m. Inclination of 5th layer of the 404 seam was amounted 18.5°. The 1/II longwall was conducted from November 2015 to June 2016 and the 2/II longwall – from October 2017 to April 2018.

The most important information about an exploitation realized in the 404 hard coal seam have been presented in the Table 1.

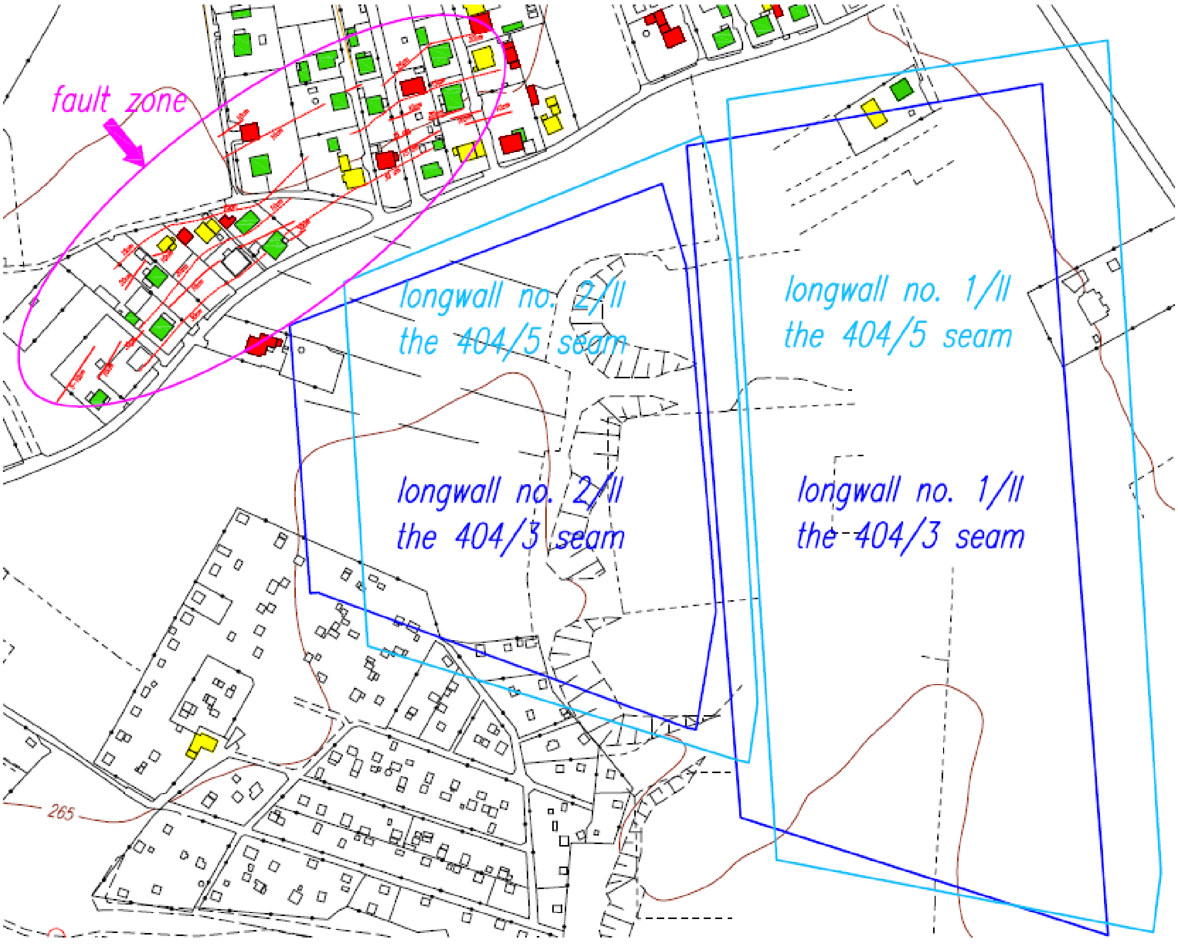


Figure 1. Location of the longwalls in the 404 seam and a fault zone on background of a situational – altitude map

Table 1. Characteristic of exploitation conducted in the years 2013 – 2018, in the 404 hard coal seam

Parameter	the 404 seam			
	3[rd] layer		5[th] layer	
Longwall	1/II	2/II	1/II	2/II
Time	05.2013÷12.2013	08.2016÷02.2017	11.2015÷06.2016	10.2017÷04.2018
Depth [m]	410÷500	500÷575	430÷510	500÷600
Inclination [°]	18.8	15.8	16.9	21.1
Thickness [m]	4.0	3.4	3.3	3.5
Run [m]	460	245	500	300
Length [m]	220	243	230	233

2.2. Terrain and buildings characteristics

Analyzed area is located in the Upper Silesian Coal Basin, in a southern part of Poland. Landform is rather uniform. Only in a middle part of area are localized escarpments. Values of contours (265 m), which at the Figure 1 have been shown, indicate that terrain is located on a lowland.

Land development constitute:

- meadows and pastures in an eastern part of region;
- allotments in a southwestern part of area;
- residential- and outbuildings in a northern part of terrain.

Detached, single-family buildings have two storeys and a load-bearing construction based on the walls. Each of building has a resistance category to mining exploitation influences. The 2[nd] resistance category by yellow colour has been shown (Figure 1). The 3[rd] resistance category represents red colour. The 4[th] resistance category is represented by green colour. Number of buildings, which belong to the particular categories of resistance to operating impacts, in the Table 2 has been shown. Table takes into account all buildings located in the fault zone.

Table 2. Classification of buildings on the resistance categories

Resistance category	Buildings number
2[nd]	5
3[rd]	6
4[th]	19
total	32

2.3. Discontinuous deformations characteristic

Underground mining exploitation of the 404 hard coal seam, which has a large thickness (over 10 m), a substantial inclination (almost 19°) and is located on a relatively small depth (around 500 m), caused land surface discontinuous deformations of a linear type [8] (ground steps and faults).

Zone of discontinuous deformations in north-western part of an area has been occurred. It's located near operating edges of the 2/II longwalls in the 404/3 and the 404/5 seams. These edges initiated an exploitation in the 2/II longwalls. The linear deformations along main road and parallel to the exploitation edges have been arisen. They cross over the residential buildings or are located next to them (Figure 1).

Ground steps and faults have the same direction, different lengths (from 10.5 m to 224.8 m) and heights from an interval of 5 ÷ 30 cm (Figure 2). Detailed characteristic of the discontinuous deformations formed on terrain surface in the Table 3 has been presented. It should be emphasized that the most dangerous fault (the longest and the highest) right next to the main street has been arisen.

Discontinuous deformations caused changes in a landscape, inclinations of the buildings in a horizontal plane and their deviations from vertical [9]. Objects usage of a technical and road infrastructure, and out-/residential buildings is inconvenient (sometimes even dangerous). That's why they exert negative influence on market value of a ground and the properties.

Table 3. Characteristic of the discontinuous deformations caused by an exploitation of the 404 hard coal seam

Faults height [*cm*]	Faults number	Faults total length [*m*]
5	1	41.3
10	9	273.9
15	5	193.2
20	5	299.8
25	1	39.0
30	5	270.9
total	26	1118.1

3. Reprognosis of exploitation impacts

To better understand mechanisms and causes of formation of the discontinuous deformations near an underground exploitation field of hard coal deposits, there reforecasts of mining exploitation influences on a terrain surface have been done. There expected values of subsidence, inclinations and horizontal strains after an exploitation end of all four longwalls have been determined.

Predictions of the above-mentioned deformations indicators of mining area by use of the *EDN-OPN* computer program (the *EDBJ1* and *EDBJ2* modules) have been done.

The Bialek's formula (for subsidence) and its first derivative [10] (for inclinations [11]) have been used. This formula takes into account:

- the far influences;
- an existing of exploitation periphery;
- a reactivation of old goafs;
- a desymmetrization of subsidence trough profile with reference to an exploitation edge;
- a possibility of calculation of impacts coming from several seams.

The parameters values of the formula are equal to:

- an exploitation coefficient (a roof rocks deflection coefficient): $a = 0.9$;
- a tangent of range the β angle of main influences: tg$\beta = 2.0$;
- an exploitation periphery parameter: $A_1 = 0.15$;
- the Awierszyn's proportionality coefficient (important to horizontal strains): $B/r = 0.32$ [*m*];
- an impacts deviation coefficient (deviation due to a seams inclination): $k = 0.7$;
- the subsidence velocity coefficients: $C_1 \cdot r = 1400$ [*m/year*] and $C_2 = 6$ [*1/year*].

Figure 2. Location of the characteristic points of fault zone

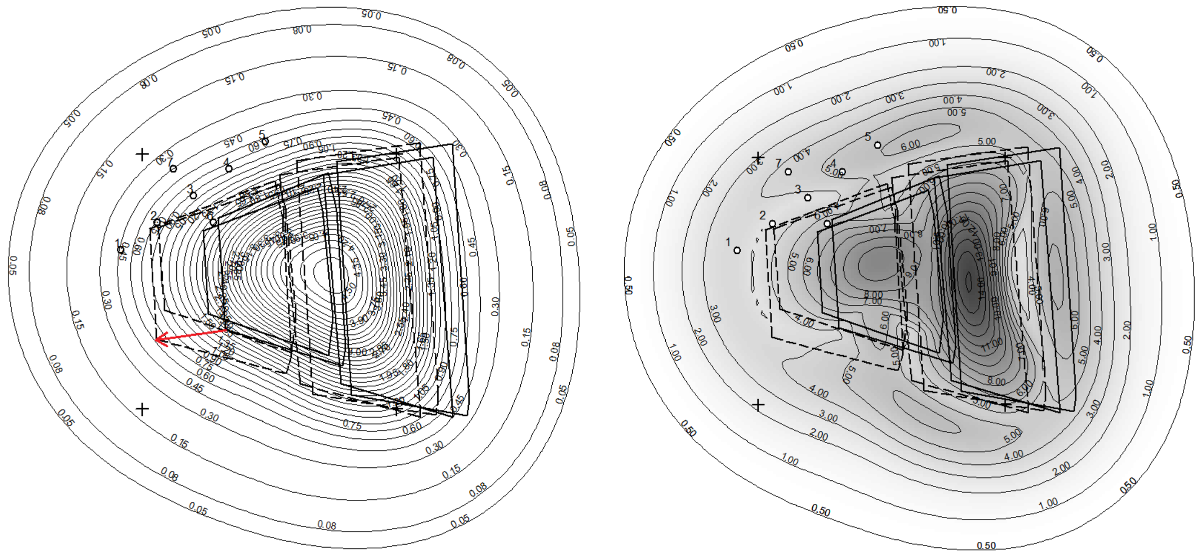
Maps of distribution of deformations indicators values on terrain surface have been made. On the maps the mining terrain categories from 1st (insignificant impacts) to 5th (significant impacts) have been marked. Reforecasts also in seven points representing the fault zone have been done. Arrangement of these points within the borders of discontinuous deformations area at the Figure 2 has been shown.

3.1. Subsidence reforecasted values

From the Figure 3a results that after an exploitation end of the 1/II and 2/II longwalls in the 404/3 and 404/5 hard coal seams, maximum value of subsidence should be equal to 4.5 m and should occur in the middle of an exploitation area. In the points which characterize location of the fault zone, subsidence shouldn't exceed 1.0 m. It can reach a value of 1.8 m only in a point number 6 (Table 4).

At the Figure 3a a movement maximum vector of real edges of the 2/II longwall in the 404/5 bed towards a seam declination has been shown (a red arrow). It has 135.8 m of length and a south-western direction. Because of that the fault zone points are located almost above the 2/II longwalls edges (especially a point number 2). That explains a formation of the longest fault (224.8 m) which has 30 cm of height and it's located parallel to a main road / the moved exploitation edges.

Subsidence velocity (Figure 3b) is the largest above the 1/II longwalls and equals to 15 mm/day. Values of subsidence speed calculated in the 1 ÷ 7 points amount from 3 to 6 mm/day (Table 4) and don't rather have a significant influence on discontinuous deformations occurrence.



a) Subsidence S [m] b) Subsidence velocity V_S [mm/day]

Figure 3. Reforecasted isolines of subsidence and their velocity above real edges of the longwalls (continuous lines) and their theoretical edges moved towards a seams declination (dotted lines)

Table 4. Deformations indicators values in the characteristic points of fault zone

Point number	Subsidence S [mm]	Subsidence velocity V_S [mm/day]	Inclinations I [mm/m]	Inclinations category C_I	Horizontal strains ε [mm/m]	Strains category C_ε
1	-467	3	5.4	3rd	5.2	3rd
2	-782	3	7.8	3rd	-4.6	3rd
3	-953	4	9.8	3rd	5.7	3rd
4	-849	5	9.6	3rd	8.2	4th
5	-653	6	7.6	3rd	9.4	5th
6	-1764	6	14.3	4th	-8.2	4th
7	-459	4	5.3	3rd	6.6	4th

3.2. Inclinations reforecasted values

According to a made reforecast of mining exploitation influences, the maximum values of inclinations should occur above a middle of the 1/II longwalls (25 mm/m) and above the edges which start and end exploitation of the 2/II longwalls (20 mm/m). Mining terrain is classified to the 5th category in these areas (brown colour at the Figure 4). The minimum values of inclinations can occur above a middle of exploitation field and around the borders of subsidence trough (less than 2.5 mm/m). In these areas occurs the 1st category of mining terrain which by yellow colour at the Figure 4 has been marked.

As indicates the Table 4, a mining terrain in almost all points of the fault zone (with an exception of the point number 6) belongs to the 3rd category (red colour at the Figure 4). In the 6th point inclination is equal to 14.3 mm/m and this is the 4th mining terrain category (purple colour).

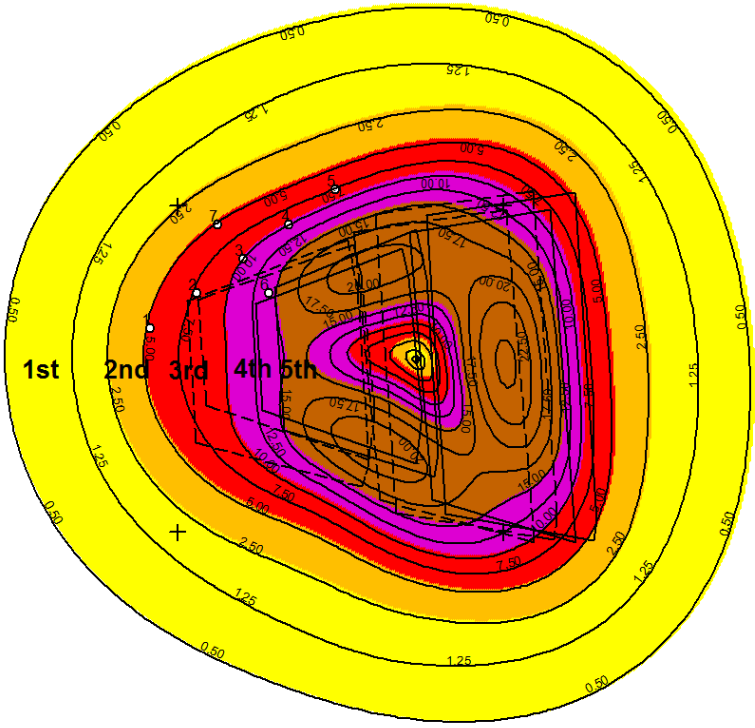


Figure 4. Reforecasted isolines of inclinations above real edges of the longwalls (continuous lines) and their theoretical edges moved towards a seams declination (dotted lines), and the mining terrain categories due to the inclinations

3.3. Horizontal strains reforecasted values

In made reprognosis the maximum values of horizontal strains occurred above the all longwalls (compressive strains), the real edges of the 1/II longwalls (tensile strains) and along the starting and ending exploitation edges, above hard coal deposit (tensile strains). They achieved a value greater than 9 mm/m and in these areas a mining terrain is classified to the 5th category. The greatest strains have a value of 20 mm/m and are located in a southern part of the 1/II longwalls (Figure 5).

The horizontal strains have the values from -8.2 mm/m (the 4th category in the 6 point) to 9.4 mm/m (in the 5 point – the 5th category) in the fault zone. Ground was only compressed in the 2 and 6 points. In the other points a ground was stretched (Table 4). Moreover, the tension-compression area around the longwalls theoretical edges moved in a seam decline direction has been arisen. The points, which characterize the fault zone, were located in this area (Figure 5). It can be the main cause of a discontinuous deformations formation.

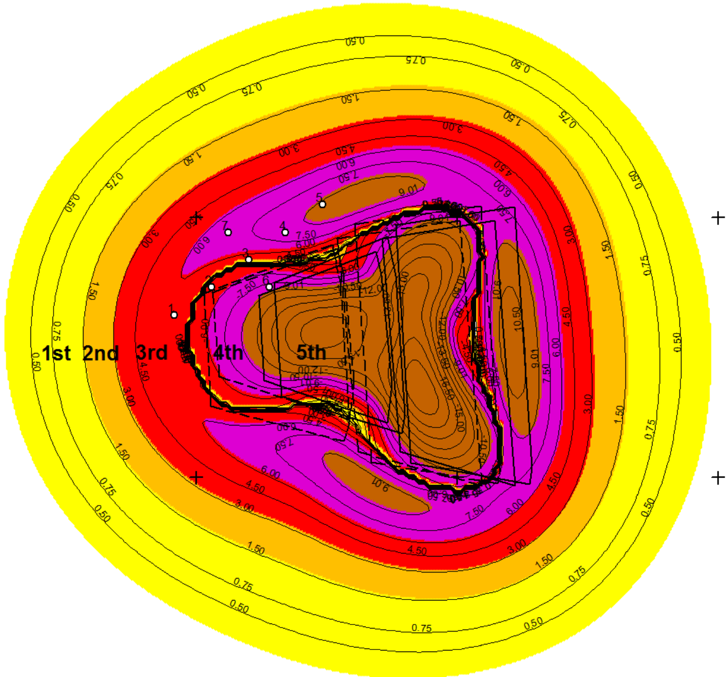


Figure 5. Reforecasted isolines of horizontal strains above real edges of the longwalls (continuous lines) and their theoretical edges moved towards a seams declination (dotted lines), and the mining terrain categories due to the horizontal strains

4. Summary and conclusions

In the article an example of underground mining exploitation of the hard coal deposits has been presented. Coal extraction in two seams by use of the longwall system with a roof rocks cave-in has been conducted. The hard coal seams had a:

- big thickness (over 7 m);
- location small depth (around 500 m);
- large declination (average value equals to 19°).

Probably an exploitation caused the discontinuous deformations of a linear type (faults, ground steps) on terrain surface which is located in a north-western part of exploitation area (north of exploitation edges).

The causes of a fault zone formation are:

- an unfavorable geometry of mining excavations (an overlap of exploitation edges);
- the difficult, geological – mining conditions of exploitation (especially a seams declination);
- a displacement of the longwalls real edges towards a seams declination (the fault zone above the theoretical exploitation edges has been arisen);
- a formation of the tension-compression area around the longwalls theoretical edges in which the characteristic points of the fault zone have been located.

Made reforecasts of mining exploitation impacts on a terrain surface indicate that the buildings which are located in the fault zone should be resistant to exploitation effects. Most of them have the 4th resistance category and terrain generally has also the 4th category. But for sure it should be taking into account an adverse effect of discontinuous deformations on buildings construction which doesn't contain prognosis. So forecasts of continuous deformations of a terrain surface (values of the deformations indicators such as subsidence, inclinations, curvatures [12-14], horizontal displacements and strains) should also be analyzed taking into account an occurrence possibility of discontinuous deformations.

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