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Influence of Discontinuous Linear Deformation on the Values of Continuous Deformations of a Mining Area and a Building Induced by an Exploitation of Hard Coal Seam

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Featured Application: Conducted research may allow us to predict the behavior of a mining area, in a particular building located in an area of discontinuous linear deformation of a terrain caused by the underground mining of hard coal and determine the real values of their inclinations and curvatures. The method of removing a building's deflection depends on its inclination values.

Abstract: In this article, the impact of a ground step on a residential building and a mining terrain has been presented. Influence of a discontinuous linear deformation by the changes of the inclination and curvatures' values (continuous deformations) has been observed. Discontinuous and continuous deformations have been caused by an exploitation of the 405/1 hard coal seam, located at a depth of 550 m. Extraction was carried out with the use of the longwall system to the south of the building. A discontinuous linear deformation occurred parallel to a north wall of the building and had a height of 0.2 m. The inclination and curvatures' values have been calculated on the basis of the results of the geodesic surveys. Vertical displacements and horizontal distances between the measuring points in the ground and on the building's walls have been measured. Points in two perpendicular directions (parallel and perpendicular to a ground step) have been stabilized. The observational network consisted of 12 points (3 points in each direction, in the ground and on the walls). Research has shown that inclinations and curvatures have different values on a terrain's surface and in buildings, which means that a deformation process takes place in a different way in the ground and a building. The obtained results indicate that an occurrence of a discontinuous linear deformation near the building reduces the values of inclinations and curvatures of a terrain surface and a building in a parallel direction to its longitudinal axis, and it increases the values of the continuous deformations in the direction perpendicular to it.

Keywords: discontinuous linear deformation; ground step; residential building; mining area; continuous deformation; inclination; curvature; underground hard coal exploitation

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1. Introduction

The extraction of hard coal from underground deposits is always connected with negative effects on humans, environment, technical infrastructure [1], and land development. On the terrain's surface, and in objects, continuous deformations (e.g., subsidence, inclinations, curvatures, horizontal strains, and horizontal displacements) [2–4] and discontinuous deformations (e.g., faults, ground steps (linear deformations), and sinkholes (surface deformations)) can occur [5–11].

The process of the formation of discontinuous linear deformations is not fully known, unlike the process of formation of discontinuous surface deformations, which has been described in many papers [7–9,11].

Discontinuous deformations in mining areas are usually caused by improper technical, geometric, and geological conditions of operation (a chamber or a pillared-chamber exploitation system, not liquidated inactive mining shafts, overlapping of the edges of the excavations located in several overlying seams, too small dimensions of an exploitation field, too shallow depths of operation, weakly concise rocks upbuilding a direct roof above excavations) [8–12].

Discontinuous deformations can also be an effect of a collapse of an escarpment's slope (a landslide) [13], earthquakes [14–16], cracking of a land surface due to excessive drying of the soil, leaching of a part of the soil by rainwater [17], water drainage from underground water reservoirs, etc. They can occur at every latitude and climate (especially in places where heavy rainfall is recorded periodically [18]), thus they are a global problem.

Deformations of the subsoil, on which the object is located, cause vertical and inclination deviations. It is a very serious problem in mining areas where the underground exploitation of hard coal deposits is conducted, e.g., in China, Russia, the United States of America, India, the Republic of South Africa, Australia, Indonesia, Ukraine, Kazakhstan, Germany, and Great Britain.

Similar problems occur in the southern part of Poland, in the Upper Silesian Coal Basin. It concerns various types of buildings: church elevators [19], historic brick [20] and wooden towers [21], churches [22], and residential buildings [23]. Inclinations can cause damage to objects with a load-bearing wall structure [24] and frame structure [25] and can increase the risk of operation of the object [26] as well as construction disasters [27]. In the case of tilted individual structural elements, they are stabilized in a new position [28]. In special cases, building elements [29,30] or entire buildings [31,32] are rectified. Elimination of deflection is based on tearing the structure apart on one floor level, usually the basement level, and then unevenly raising the building above the tearing plane using piston jacks [33].

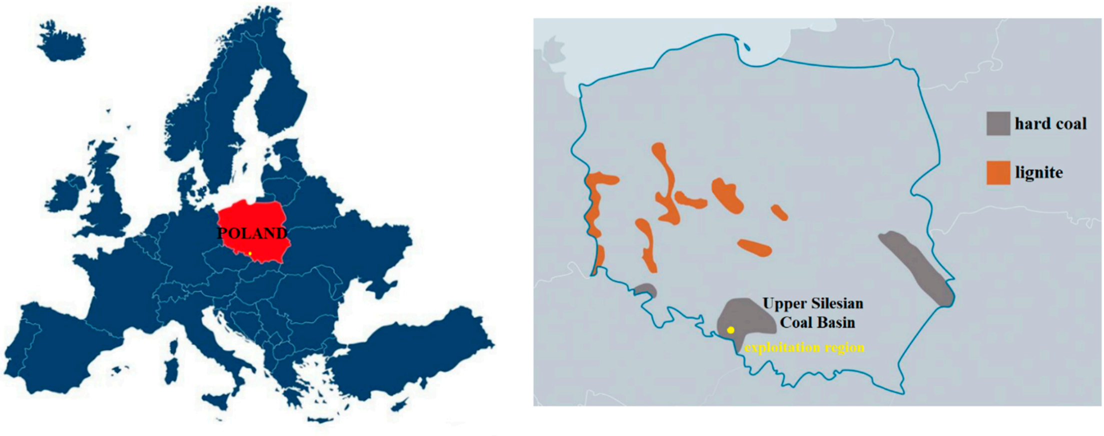
Excessive deviations out of vertical of buildings can cause inconveniences for their inhabitants (sloped floors, doors and windows, constant renovations related to the removal of damages inside and outside the building, inhabitants' fear of further damages) and may affect the deterioration of the technical condition of the building (scratches; fissures; cracks of ceilings and walls, which may pose a threat to the safety, health, and life of the residents) [5]. In exceptional cases, a building may collapse or can be deliberately demolished.

This work presents an example of the formation of discontinuous linear deformations of the ground due to a hard coal seam exploitation conducted on the south of a residential building. Coal extraction also caused the continuous deformations (inclinations and curvatures) of the terrain surface and buildings. Four stages of exploitation in the 405 hard coal seam and changes of the inclinations and curvatures values caused by each time-period of operation have been presented. In order to observe the inclinations and the curvatures changes of the terrain surface and a building, measuring points in a ground (six points: three points parallel to a ground step and three points perpendicular to it) and on a building (six points: three points parallel and three points perpendicular to a linear deformation) were stabilized. Geodesic surveys were carried out at two-week intervals on these points. The values of the inclinations and curvatures have been calculated on the basis of the results of the surveys conducted at different times.

Obtained results indicate that a building and its land work in a different way. The inclinations and curvatures achieve various values depending on the progress of exploitation with time and a considered direction. Moreover, a discontinuous linear deformation changes the values of continuous deformations.

2. Materials and Methods

The discussed case of hard coal exploitation is located in the Upper Silesian Coal Basin, in the southern part of Poland, near the town of Rybnik. The location of the exploitation region has been shown in Figure 1.



(**a**) (**b**)

Figure 1. Location of an exploitation region on a map of: (**a**) Europe; (**b**) Poland.

Exploitation of the 405/1 hard coal seam in February 2019, on a medium depth of 550 m and at a height of 1.7 m, has been started. The '1/II' longwall was conducted, and its deviation from the horizon was 18°. Extraction in a longwall ended in September 2019.

It is worth mentioning that the 404/3 and 404/5 hard coal seams exploitation had been conducted before the exploitation of the 405/1 hard coal seam started.

Exploitation of the 404 seam took place in the years of 2013–2018, and it was carried out with the use of the longwall system with a roof rocks cave in.

The 404/3 coal seam was exploited by use of two longwalls numbered '1/II' and '2/II'. The longwalls had a height of 4.0 m and 3.4 m, and their depth was from 410 m on the east to 575 m on the west. The seam dip had a value of 17°. The '1/II' longwall was conducted from May to December 2013 and the '2/II' longwall from August 2016 to February 2017.

Exploitation of the 404/5 coal seam started in November 2015 by the '1/II' longwall which was conducted at a height of 3.3 m and on a depth of 470 m. Extraction of a hard coal from this longwall finished in June 2016. The second longwall, named '2/II', was exploited from October 2017 to April 2018. The excavation had a height of 3.5 m and was located at a depth of 550 m. The inclination of this hard coal seam was 18.5°.

Basic information about the extraction of hard coal from the 404 and 405 seams has been presented in Table 1.

Table 1. Characteristics of exploitation of the 404 and 405 hard coal seams in the years 2013–2019.

Characteristic	The 404/3 Seam		The 404/5 Seam		The 405/1 Seam
Number of longwall	1/II	2/II	1/II	2/II	1/II
Time of exploitation	May 2013–December 2013	August 2016–February 2017	November 2015–June 2016	October 2017–April 2018	February 2019–September 2019
Depth of exploitation (m)	410–500	500–575	430–510	500–600	495–605
Height of longwalls (m)	4.0	3.4	3.3	3.5	1.7
Deviation (°)	17.0		18.5		18.0

In the area of this exploitation, a rock mass was formed by layers of overburden composed of sands, gravels, Quaternary clays, clays, and Miocene sands with a total thickness of approx. 220 m, and Orzesze layers formed in the form of a shale–sandstone facies with a definite predominance of shales.

Influences of exploitation were observed on the surface of the mining area and in the residential building.

The land development consists of loose single-family housing in the northern part of the region; arable fields, meadows, and escarpments in the central and the southern part; family allotment gardens in the south-western part, and technical infrastructure (roads, land utilities networks, poles of the medium-voltage power grid) in the whole area. Development of the terrain surface has been presented in Figure 2.

(a) (b)

Figure 2. A residential building: (**a**) on the background of the longwall's contours in the 404/3 seam—pink line, the 404/5 seam—green line and the 405/1 seam—orange line (yellow circle); (**b**) a view from north-eastern side.

The building is located to the north of the exploitation and in the fault zone, i.e., in the region where numerous discontinuous linear deformations have occurred (the yellow circle in Figure 2a). It has the shape of a square with a side length of 13 m, with a small cut in the south-eastern part. The building has one overground storey and is 9.5 m high. It was made with traditional technology from bricks and has a load-bearing wall structure. The entrance to the building is on the north side. Three garages are located perpendicular to the building (Figure 2b).

In order to observe impacts of mining exploitation conducted in the 405/1 hard coal seam on a terrain and in the object, an observational network consisting of 12 measuring points has been established. Geodesic measurements on the points stabilized in a ground (6 points named 'z09p', 'z10d', 'z11d', 'z56d', 'z57d', 'z58g') and on the building's walls (6 points numbered 's09', 's10', 's11', 's56', 's57', 's58') have been carried out. Points in two different directions: parallel and perpendicular to a discontinuous linear deformation have been located. They formed 4 observational lines consisting of 3 points each. Metal mandrels were dug into the ground at a distance of 2 m from the building's walls and about 3 m from each other. The wall points were made of metal buttons also located 3 m apart. The locations of the measuring points established in the ground (a brown color) and on the building (a pink color) are shown in Figure 3.

Figure 3. Location of the measuring points in a ground (a brown color) and on a building (a pink color) and a discontinuous linear deformation (a red line).

It should be emphasized that a ground step (0.2 m) in front of the north wall of the building, after the end of an exploitation in the 404 hard coal seam and during an extraction conducted in the 405 hard coal seam (in March 2019), has occurred (Figure 4). Therefore, the behavior observations of the terrain surface and the building under the influence of exploitation carried out in the 405 seam began.

Figure 4. Discontinuous linear deformation (a ground step) with a value of fault 0.2 m towards the south.

In the building (outside and inside), damage resulting from conducted exploitation has arisen. The eastern wall of the building was especially damaged with numerous scratches and fissures, as well as defects in the plaster. The fence was also damaged (Figure 5).

(**a**) (**b**)

Figure 5. Damage outside the building: (**a**) a scratch near window in the east wall; (**b**) a crack of base of the fence.

Damage to floors, walls, and ceilings were also noted in rooms located in the eastern part of the building (Figure 6).

It can be seen that the damage occurred in the rooms in the eastern part of the building located perpendicular to the longitudinal axis of the ground step. Minor damage to the rest of the building was observed. It should be kept in mind that the damage may increase if the exploitation in the area intensifies. In this case, the building should be protected against further damage.

The height measurements of the points by the use of a precise leveler with an accuracy of 0.1 mm (Figure 7a) at the time intervals of two weeks (4 March 2019, 19 March 2019, 3 April 2019, 17 April 2019, 10 May 2019, 28 May 2019, 19 June 2019) in a local altitude system were conducted. The height differences of the points observed between the next measuring cycles were determined. Based on those and the distances measured between the subsequent points (measured by the D510 electronic distance meter, made by the

Leica Geosystems, Warsaw, Poland with an accuracy of 1 mm—Figure 7b), the values of inclinations and curvatures of the ground and the building have been calculated.

(a) (b)

Figure 6. Damage inside the building: (**a**) a fissure in the wall of the living room in the south-east part of the building; (**b**) a crack in the wall and ceiling in the kitchen in the north-east part of the building.

(a) (b)

Figure 7. The measuring devices: (**a**) a precise leveler; (**b**) a distance meter.

According to the author, the innovation of the research lies in the fact that simultaneous measurements of the building and the terrain under the influence of the exploitation were carried out. In addition, it was possible to determine the influence of discontinuous linear deformations of the terrain on the building and the ground by observing changes in continuous deformations (inclinations and curvatures).

3. Results

In the article results coming from four observational cycles (1: 19 March 2019; 2: 3 April 2019; 3: 17 April 2019; 4: 10 May 2019) have been presented. These are the cycles that represent impacts caused by the next stages of an exploitation of the 1/II longwall in the 405 hard coal seam.

In Table 2, the differences of heights and the distances between the neighboring points noted in particular measuring cycles have been juxtaposed.

Table 2. The differences of heights and the distances between the neighboring points noted in the time period of March–May 2019.

Section	1–19 March 2019		2–3 April 2019		3–17 April 2019		4–10 May 2019	
	ΔH_1 (mm)	d_1 (m)	ΔH_2 (mm)	d_2 (m)	ΔH_3 (mm)	d_3 (m)	ΔH_4 (mm)	d_4 (m)
s09–s10	−177	3.95	−182	3.95	−179	3.95	−183	3.95
s10–s11	79	5.49	79	5.49	76	5.49	74	5.49
z09p–z10d	−161	3.68	−160	3.68	−162	3.68	−164	3.68
z10d–z11d	−222	5.49	−229	5.50	−234	5.50	−250	5.50
s56–s57	41	6.21	41	6.21	41	6.21	43	6.21
s57–s58	34	5.96	33	5.96	34	5.96	35	5.96
z56d–z57d	130	6.22	129	6.22	125	6.22	127	6.22
z57d–z58g	62	6.03	65	6.03	64	6.03	63	6.03

3.1. Inclinations

Inclination values in each observational cycle (T_n), as a quotient of a height difference (ΔH_n) and the distance between the subsequent measuring points (d_n), have been calculated [2]:

$$T_n = \frac{\Delta H_n}{d_n}. \tag{1}$$

Calculated values of inclinations and their changes (ΔT_{1-n}) observed between the first (T_1) and a particular measuring cycle (T_n):

$$\Delta T_{1-n} = T_n - T_1, \tag{2}$$

Table 3 and Figure 8 present the values of inclinations from March 19.

Table 3. The values of inclinations and their changes observed on the sections in the time period of March–May 2019.

Section	1–19 March 2019	2–3 April 2019		3–17 April 2019		4–10 May 2019	
	T_1 (mm/m)	T_2 (mm/m)	$\Delta T_{1\text{–}2}$ (mm/m)	T_3 (mm/m)	$\Delta T_{1\text{–}3}$ (mm/m)	T_4 (mm/m)	$\Delta T_{1\text{–}4}$ (mm/m)
s09–s10	−44.81	−46.08	−1.27	−45.32	−0.51	−46.33	−1.52
s10–s11	14.39	14.40	0.01	13.86	−0.53	13.49	−0.90
z09p–z10d	−43.75	−43.48	0.27	−44.02	−0.27	−44.57	−0.82
z10d–z11d	−40.44	−41.67	−1.23	−42.58	−2.14	−45.50	−5.06
s56–s57	6.60	6.60	0.00	6.60	0.00	6.92	0.32
s57–s58	5.70	5.54	−0.16	5.70	0.00	5.87	0.17
z56d–z57d	20.90	20.74	−0.16	20.10	−0.80	20.42	−0.48
z57d–z58g	10.28	10.78	0.50	10.61	0.33	10.45	0.17

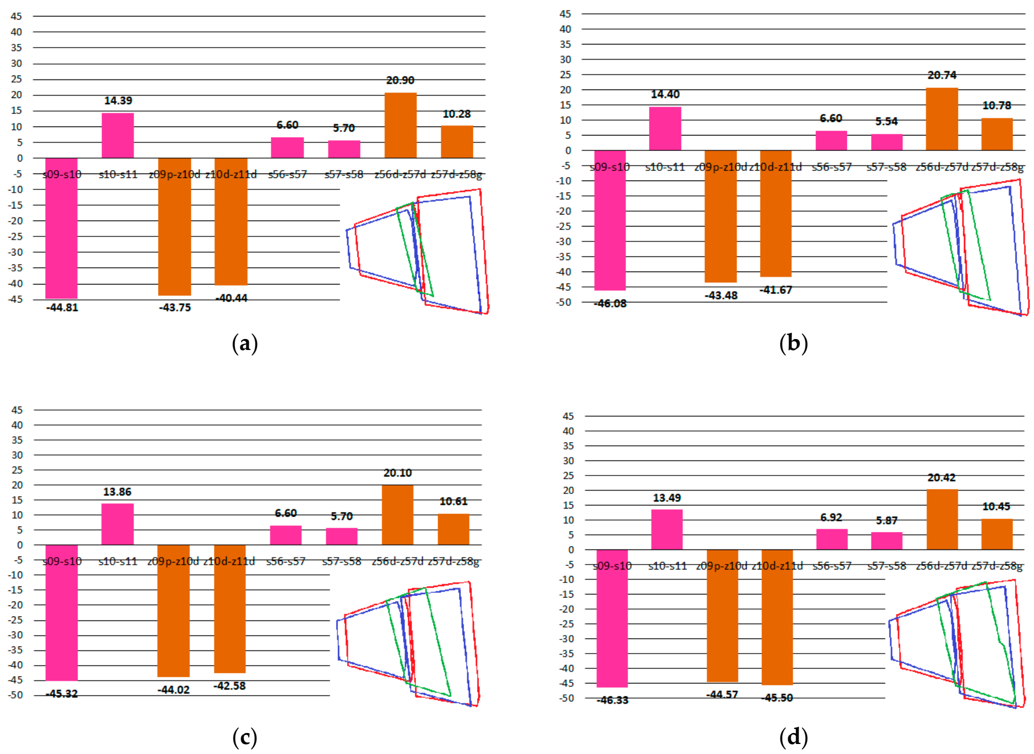


Figure 8. The values of inclinations (vertical axis) observed on the ground sections—brown color and the wall sections—pink color (horizontal axis) in the time period of March–May 2019, and the progress of the 1/II longwall in the 405/1 hard coal seam: (**a**) 19 March 2019; (**b**) 3 April 2019; (**c**) 17 April 2019; (**d**) 10 May 2019.

3.2. Curvatures

Curvatures values in each observational cycle (C_n), as a quotient of a difference of the inclinations observed on two neighboring sections (ΔT_{i-i+1}):

$$\Delta T_{i-i+1} = T_{i+1} - T_i, \tag{3}$$

and an average length of two neighboring sections (l_{aver}):

$$l_{aver} = \frac{d_i + d_{i+1}}{2}, \tag{4}$$

have been calculated [3]:

$$C_n = \frac{\Delta T_{i-i+1}}{l_{aver}}. \tag{5}$$

Calculated values of curvatures and their changes (ΔC_{1-n}) observed between the first (C_1) and a particular measuring cycle (C_n):

$$\Delta C_{1-n} = C_n - C_1, \tag{6}$$

Table 4 and Figure 9 present the values of curvatures from March 19.

Table 4. The values of curvatures and their changes observed on two neighboring sections in the time period of March–May 2019.

Sections	1–19 March 2019	2–3 April 2019		3–17 April 2019		4–10 May 2019	
	C_1 ($\times 10^{-3}$ 1/m)	C_2 ($\times 10^{-3}$ 1/m)	$\Delta C_{1\text{–}2}$ ($\times 10^{-3}$ 1/m)	C_3 ($\times 10^{-3}$ 1/m)	$\Delta C_{1\text{–}3}$ ($\times 10^{-3}$ 1/m)	C_4 ($\times 10^{-3}$ 1/m)	$\Delta C_{1\text{–}4}$ ($\times 10^{-3}$ 1/m)
s09–s10–s11	12.54	12.82	0.28	12.54	0.00	12.68	0.14
z09p–z10d–z11d	0.72	0.39	−0.33	0.31	−0.41	−0.20	−0.92
s56–s57–s58	−0.15	−0.18	−0.03	−0.15	0.00	−0.17	−0.02
z56d–z57d–z58g	−1.73	−1.63	0.10	−1.55	0.18	−1.63	0.10

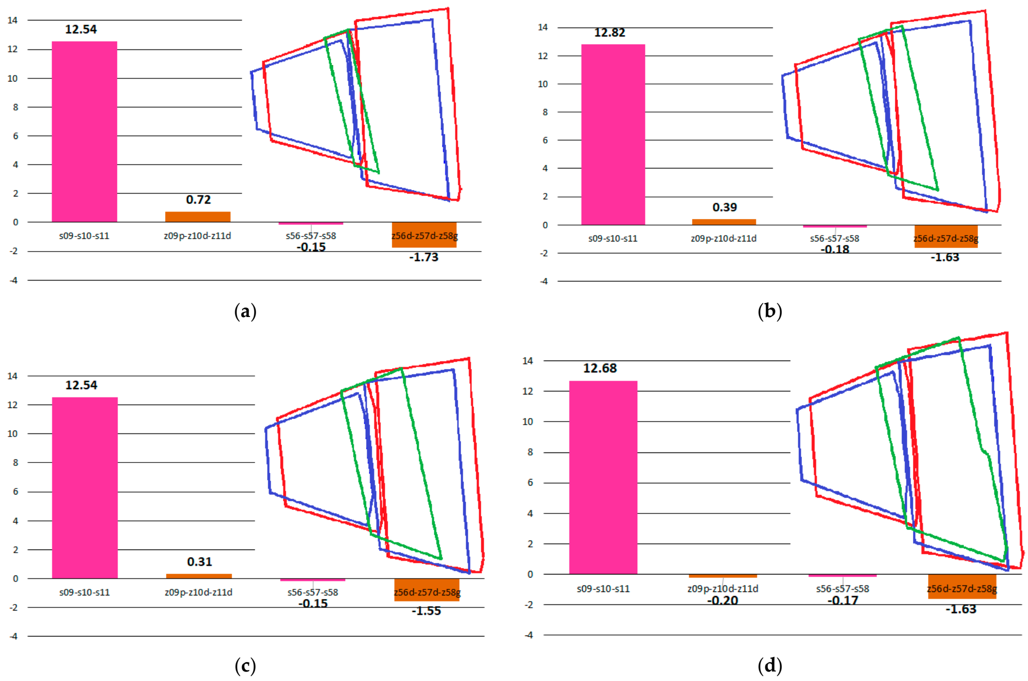


Figure 9. The values of curvatures (vertical axis) observed on two neighboring, ground sections—brown color and wall sections—pink color (horizontal axis) in the time period of March–May 2019, and the progress of the 1/II longwall in the 405/1 hard coal seam: (**a**) 19 March 2019; (**b**) 3 April 2019; (**c**) 17 April 2019; (**d**) 10 May 2019.

4. Discussion

This section contains a discussion on the results obtained for inclinations and curvatures observed on a terrain surface and in a building in 2019 from March 19 to May 10.

4.1. Inclinations

Data presented in Figure 8 and Table 3 indicate that the exploitation of the 1/II longwall in the 405/1 hard coal seam in the time period of 2 months changes the primal values of inclinations.

A maximum change for the ground points had a place in the case of the 'z10d–z11d' section (a section located closest to a linear discontinuous deformation and perpendicularly to it). This, consecutively, amounted to 1.2 mm/m, 2.1 mm/m, and 5.1 mm/m in the subsequent cycles. This means that an operation of the 1/II longwall in the 405/1 seam caused an increase of 12.5% in the inclination value.

A minimum change for the points stabilized in the ground had a place for the 'z57d–z58g' section (a section located parallel to a ground step). An increase in the inclination value in the subsequent measuring cycles of: 0.5 mm/m, 0.3 mm/m, and 0.2 mm/m (a diminishing increase) has been consecutively noted. That means that the exploitation of the 1/II longwall in the 405/1 hard coal seam caused an increase of 1.7% in the inclination value.

For the wall points, a maximum change took place in case of the 's09–s10' section (a perpendicular section to a linear discontinuous deformation). An increase in the values (1.3 mm/m, 0.5 mm/m, and 1.5 mm/m) has been generally observed. Extraction of a hard coal from the 1/II longwall in the 405/1 seam caused an increase of 3.4% in the value of inclination.

In turn, the smallest change in the inclination values in the building occurred in case of the 's57–s58' section located parallel to a ground step (0.2 mm/m, 0.0 mm/m, and 0.2 mm/m in sequence), which means an increase of 3%.

It can be generally said that a change in the inclination values observed on the sections located in the ground (a maximum value of 12.5%) is greater than it was noted in the wall sections (a maximum value of 3.4%). This means that the ground and the building work in a different way because the building walls have a greater stiffness than the subsoil and are less susceptible to deformations.

The inclinations of the sections (in the ground and on the walls) arranged perpendicularly to the ground step are bigger than the inclinations of the sections lying parallel to the deformation. It can be noted that a discontinuous linear deformation causes an increase in inclination values in a perpendicular direction to its longitudinal axis and a decrease in the inclination values along this axis.

4.2. Curvatures

Calculation results shown in Figure 9 and Table 4 prove that the operation of the 1/II longwall in the 405/1 seam in the time period of March–May 2019 changes the primal values of the curvatures.

The general increase in the curvature's values occurred on the wall sections 's09–s10–s11' and 's56–s57–s58'. This, consequently, amounted to 1.1% and 13.3%, relative to the initial values.

A decrease in the initial values of the curvatures in the case of the ground sections 'z09p–z10d–z11d' and 'z56d–z57d–z58g' (127.8% and 5.8% in sequence) has been noted.

It can be said that the curvature increases in the building and the decreases on the terrain's surface work in a different way.

The change in the value range of curvatures from 0.02×10^{-3} 1/m for the 's56–s57–s58' sections (a building wall parallel to a discontinuous linear deformation) to 0.92×10^{-3} 1/m (a maximum change) for the 'z09p–z10d–z11d' sections (the ground sections perpendicular to a ground step) has occurred.

The maximum value of curvature was 12.82×10^{-3} 1/m, and, on 3 April 2019, along the 's09–s10–s11' sections located on and perpendicular to the building wall, a discontinuous linear deformation was noted. The curvature had an about 40 times lower value (about 0.31×10^{-3} 1/m) along the 'z09p', 'z10d', and 'z11d' ground points stabilized in the same direction.

A minimum average value of the curvature as to the absolute value (about -0.16×10^{-3} 1/m) along the 's56', 's57', and 's58' wall points, located parallel to a ground step, has been observed. On the points 'z56d', 'z57d', and 'z58g', established in the ground in the same direction, the curvature achieved an about 10 times greater value (about -1.64×10^{-3} 1/m).

It can be generally noted that the curvatures achieved greater values in a perpendicular direction to a longitudinal axis of a ground step than in the direction parallel to it.

5. Conclusions

In this article, it has been shown that discontinuous linear deformation may affect the values of continuous deformations of the ground and buildings.

The conducted research sheds new light on the behavior of the building in the case of revealing inclinations and curvatures in it, and it shows the cooperation of the building with the subsoil.

This research can be considered unique as it simultaneously enabled the determination of the impact of a discontinuous linear deformation of the terrain on the building and the ground using the values of continuous deformations (inclinations and curvatures).

It is very important to know the real values of a building's inclinations in mining areas because the method of removal of a building's deflection depends on their values [34]. The research shows that a discontinuous linear deformation occurring near the building can increase the inclinations' values in the direction perpendicular to it.

Taking into account the above considerations it can be concluded that:

- The next stages of an operation of the 1/II longwall in the 405/1 hard coal seam within a period of 2 months changes the primal values of inclinations and curvatures;
- the ground and buildings work in a different way;
- inclinations generally achieve greater values on the terrain's surface than those in the building. It has a greater stiffness than the subsoil and is less susceptible to the deformation process, in the case of inclinations in the building and the groundwork independently;
- curvatures generally have greater values in the building than on the ground because they are closely connected to the subsoils in which foundations are located. A deformation process passes from the ground to the building; thus, in this case, they work together;
- an occurrence of a discontinuous linear deformation near the building reduces the values of inclinations and curvatures of the terrain's surface and an object in the direction parallel to its longitudinal axis and increases the deformations in the direction perpendicular to it.
- despite the significant leaning of the building and its numerous minor damages, its technical condition can be described as satisfactory. However, minor ongoing repairs and continuous monitoring are necessary.

In the future, further observations of other buildings and engineering objects are planned in a similar way in order to confirm the thesis of increasing the values of continuous deformation indicators in the direction perpendicular to the longitudinal axis of the discontinuous linear deformation.

It will also be possible to modify the observation network by increasing the number of measurement points and changing the distances between the observation points, as well as their distances from the tested object. Changing the configuration of the network can improve the description of the studied phenomenon related to the increase in continuous deformations.

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