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Results of the Ground Surface Deformation Measurements in the Zone of Commencing the Roof Caving Exploitation and the Assessment of Its Impact on Buildings

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Abstract

The article presented the results of periodic geodetic measurements, which embraced both the land surface and buildings in the zone of commencing mining exploitation. Classical geodetic measurements (levelling and tachymetric) were carried out in order to determine the size and nature of the mining ground deformation, the pace of change and their impact on the existing building development. The final results of the surface deformation were also compared with the forecasts prepared by the mine. The measurements lasted 13 months. During that period 19 measurement cycles were performed.

Keywords:

1. Introduction

Land surface in the place of commencing roof caving exploitation is a hardly predictable zone which can be characterised by its high dynamics of change in geometry. It is potentially very dangerous for the building development. A serious danger to such located buildings is also the fact that after depletion of coal the land surface will remain deformed in that place. Therefore, the impact on the building structures in that case will be of continuous and not temporary nature, as in case of buildings situated inside the exploited coalfield [4]. Horizontal deformations and curvatures, which appeared in the land surface, are the most dangerous for the structures of buildings, because they create deformations of structures, what results in appearance of additional internal forces. Figure 1 illustrates diagrammatically the zones of the biggest threat to the buildings in the place of commencing the mining exploitation.

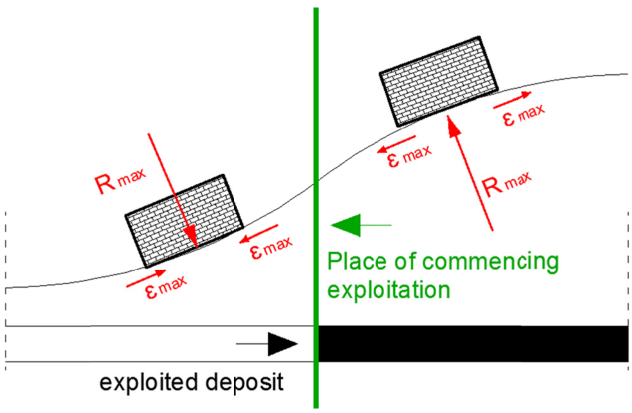

Fig. 1. Ground surface deformation in the place of commencing exploitation and its impact on a building (*Source:* own elaboration)

Knowledge of dynamics, size of displacements and final rates of surface deformation is essential for the assessment of danger to buildings posed by the zone of commencement of mining [8]. Possibility to monitor changes in geometry of the ground surface is provided by properly planned and periodically conducted geodetic measurements. The obtained results are extremely important for the assessment of the impact of potentially occurring post-mining deformations on the appearance of the so-called mining damage [10].

In order to inspect how the deformed land surface in the place of mining commencement will affect the technical condition of building development, a series of geodetic measurements of the land surface and the buildings was carried.

2. Location of the monitored area and buildings in relation to the longwall as well as operational data

For the purposes of the conducted research in the place where mining was commenced, it was planned to carry out geodetic measurements of buildings and the ground surface. The research was done in the area of Świerkowa street in the city of Marklowice in Śląskie Voivodeship. The site selection was based on two decisive aspects:

1) Mining works were carried out there at a depth of 330 m and it was one of the shallowest that was scheduled for 2014. Three-meter thickness of the seam exploited with roof caving resulted in the predicted significant deformations, classified even as the 4th category ones.
2) Location selected for the research was a built-up area. In the Świerkowa street area in Marklowice the building development is typical for agricultural holdings. There are both residential and utility buildings. After analysing the ground conditions, it was decided to monitor three different buildings:
   - two-storey residential building – at 1 Świerkowa Street,
   - one-storey utility building with a usable attic – at 4 Świerkowa Street,
   - two-segment (residential and utility) building – at 6 Świerkowa Street.

Three wall benchmarks were installed on each of the selected walls of buildings (Fig. 2) marked with double red-line in order to be able to monitor, apart from subsidence and tilt, the potential deformations of building structures.

Mining exploitation in the area subject to monitoring was commenced on 22.10.2014. At the beginning the progress of mining works was slow. After achieving the whole length of the wall, the exploitation was conducted significantly faster (Fig. 2).

Fig. 2. Location of monitored buildings in relation to the exploited longwall and exploitation progress in time (*Source:* own elaboration, based on data from the Marcel Coal Mine)

3. Characteristics of the monitored buildings

Three buildings described below were subject to geodetic measurements included in the research:

– **residential building – at 1 Świerkowa Street**

No. 1 is a two-storey building with a basement 14.2 × 9.4 m in size. It was constructed in 1930's using the traditional brick-and-mortar technology with wood ceilings and roof, and with the brick foundation. In the past it was damaged many times and then repaired as a result of mining activity [source: Marcel Coal Mine]. In 2009 the building was strengthened by means of a reinforced concrete band with a cross-section of 70 × 100 mm at the foundation level – fixed along the whole perimeter. The strengthening element is visible in the photos (Photo 1).

Photo 1. East and south wall of the residential building at 1 Świerkowa St.
(*Source:* own elaboration)

Six benchmarks in total were fixed at the level of +0.5 m (3 on the south wall and 3 on the east wall – Photo 1), which were used to perform periodical height measurements.

– **utility building at 4 Świerkowa Street**

No. 4g is a one-storey building with an attic. It was built in brick-and-mortar technology with dimensions of 10.1 × 6.6 m in horizontal projection.

Photo 2. West wall of the utility building at 4 Świerkowa St.
(*Source:* own elaboration)

In order to carry out geodetic monitoring of the building, 3 benchmarks were fixed on the west wall at the level of +0.3 m (Photo 2). The shorter wall of the building was not monitored because in case of such short sections it is difficult to observe deformation of a building by means of geodetic methods. It is affected by measurement errors, which in case of small distances between benchmarks can achieve significant values.

– **residential and utility at 6 Świerkowa Street**

No. 6 is a building consisting of two separate parts, a residential and a utility one. The first one with dimensions of 10.0 × 9.0 m in horizontal projection and the second one 3.95 × 11.43 m respectively. The residential part has a basement and utility attic. The utility part of the building has not got a basement. In this building the exterior wall, which is common to the both parts, was monitored. It is visible in the photo (Photo 3).

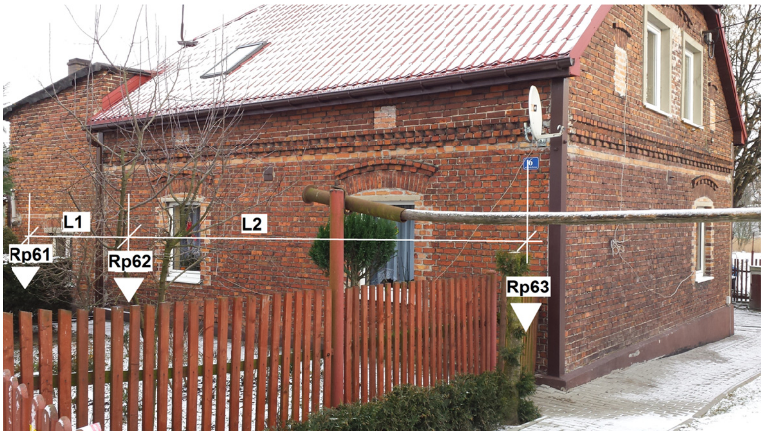

Photo 3. West wall of the building at 6 Świerkowa St. (*Source:* own elaboration)

3 benchmarks in total were fixed on the western wall of the building at the level of +0.5 m. Two of them are on the residential segment and the third one on the utility one. Monitoring of vertical movements for this building was planned in order to examine how the deformation of the building will be influenced by the fact that it was provided with an expansion joint.

4. Geodetic monitoring of the ground in the zone of commencing the roof caving exploitation

In order to determine the ground surface deformation of the observed terrain two models of benchmarks were stabilized: as a line and a rosette. In order to determine the inclination and curvature of the ground a measurement line was used, which was composed of 9 field points (no. 1-9) at a mutual distance of 25 meters (Fig. 3). The line is situated over the middle of the exploited field and is approximately perpendicular to the exploitation front. In order to determine horizontal deformations of the ground three additional

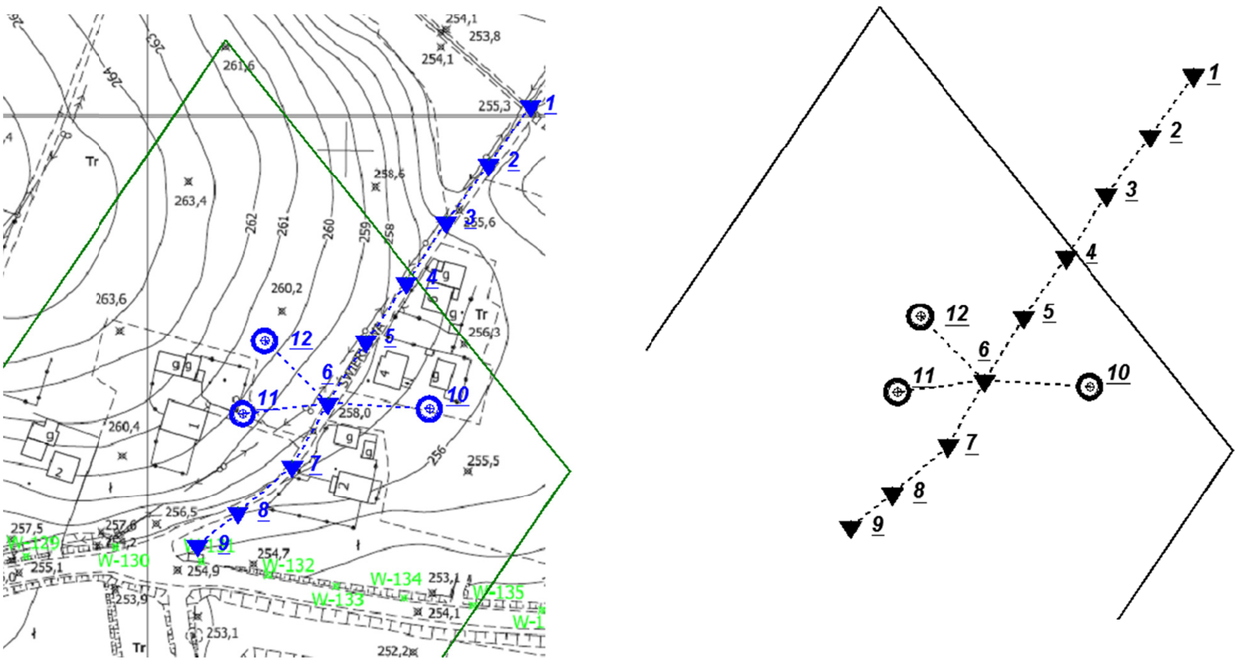

Fig. 3. Location of points representing the land surface (*Source:* own elaboration, based on data from the Marcel Coal Mine)

points were also stabilised in the direct vicinity of the line. Points no. 6, 7, 8 (Fig. 3) are common to both the measurement line and the rosette. Stabilization of all points was performed on 16.09.2014. Each installed geodetic field mark is a steel rod set at a depth of 1.3 m below the surface on the concrete foundation. Holes around the rods needed for execution of the concrete foundations were filled thoroughly with native soil in accordance with guidelines [9].

In order to monitor lowering of points on the measurement line: 1-9 periodical measurement of geodetic height was carried out by means of the *Sokkia SDL 50 Digital Level*. The first, so-called '*zero reference measurement'* took place on 11.10.2014. Then at the interval of about two – three weeks subsequent periodical measurements were carried out to the day of 25.10.2015. The chart (Fig. 4) presents the dates of all field activities.

Additionally, parallel to the levelling work, changes in the sides of the rosette were measured in order to determine the horizontal deformations. It was done with *the TOPCON GPT 3107N* tachometer + prism on a tripod.

5. Results of the research of the land surface deformation

5.1. Vertical deformations

Measurement line stabilized approximately along the axis of the exploited field in Marklowice is subject to deformations during the mining exploitation. The result of the periodical measurement for the points on the line was presented in the chart (Fig. 4). The major objective of the measurements was to determine the land surface deformations and consequently to assess what danger to the building development they entail. Therefore, the chart (Fig. 4) was drawn up assuming simply that point 1 is permanent and it is not subject to vertical movements.

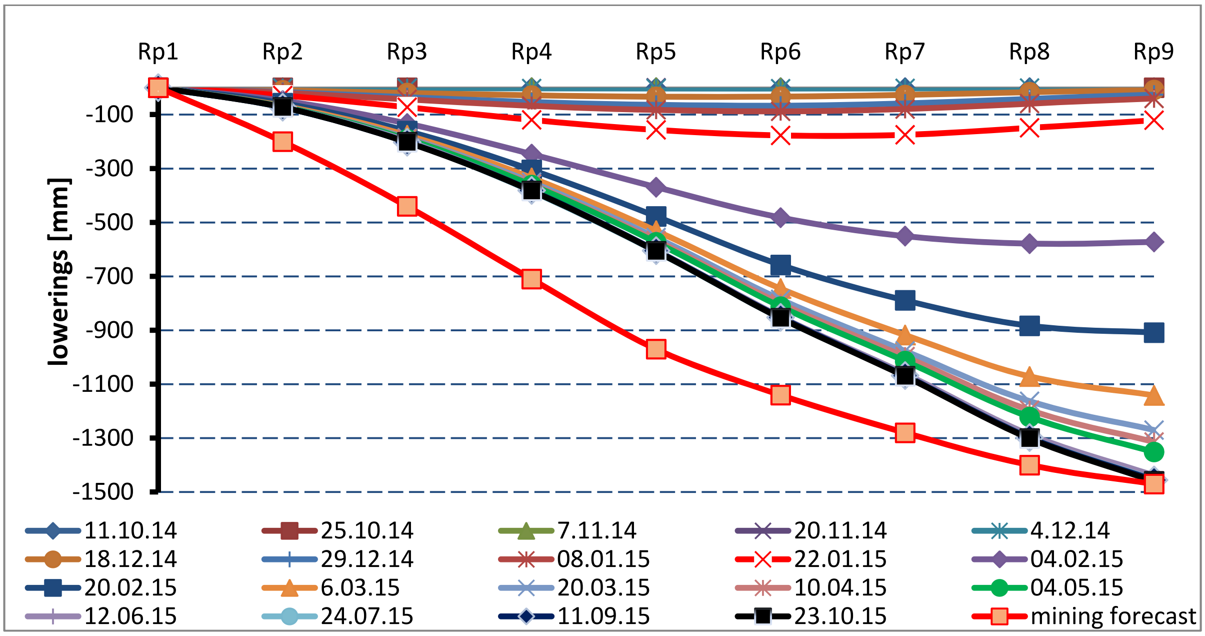

Fig. 4. Vertical deformations of the main terrain line (*Source:* own elaboration)

The first slight subsidence amounting to –3 mm was observed on 4.12.2014, over a month after the commencement of exploitation. After almost two months, on 18.12.2014, the first significant lowering of points on the measurement line was observed. In the first phase of deformation the ground surface deflected in the form of a concave curvature along the whole observation line, which amounted to about 193 m. Such tendency maintained till 22.01.2015. Then a sudden increase in the subsidence took place and the formation of the final subsiding trough started. Such a state maintained for the period of 2 months. On 20.03.2015 gradual extinction of further changes was observed. Observations were carried out until 25.10.2015, that is a year after the commencement of monitoring. It was decided to finish monitoring because the differences in subsidence between particular measurements were already not bigger than 1 mm. Actually, from July till October 2015 no further changes were observed. Anticipated final deformations were also presented in the chart (Fig. 4), which was drawn up by the Coal Mine Marcel (Fig. 5).

Fig. 5. Forecast trough of subsidence caused by exploitation of the W-5 longwall with marked location of the terrain line (*Source:* Material prepared by the Marcel Coal Mine)

The measured difference in subsidence between the extreme benchmarks of the terrain measurement line is close to the forecast value. On the other hand, the shape of the predicted edge of the subsiding trough diverges slightly from the real one, which was determined on the basis of the field measurements.

5.2. Tilts

Analysing further the results of the measurements, changes in the values of tilt were determined for particular sections of the surface line (Fig. 6)

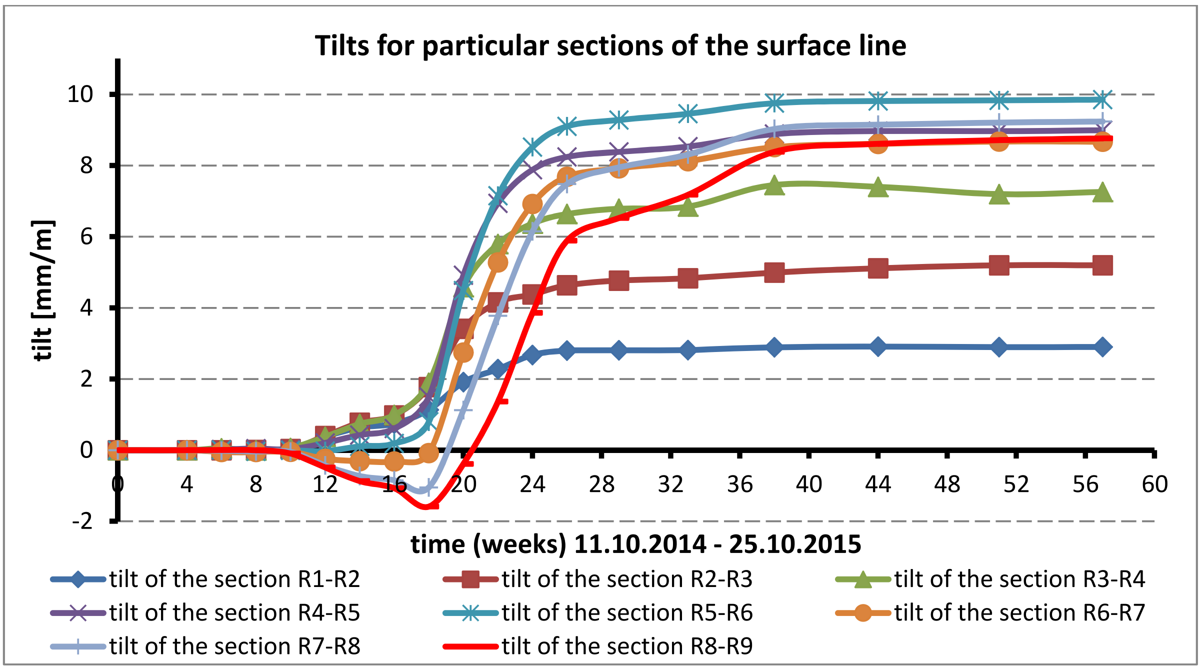

Fig. 6. Chart of the tilt for particular sections of the surface line (*Source:* own elaboration)

The biggest final tilts was observed in the central sections of the line. The smallest tilts were observed in the section between points 1 and 2 as well as 2 and 3, which are located farther from the edge of the exploited field. Two different natures of deformation of the monitored ground surface can be seen in the chart (Fig. 6). In the first instance, when a partial concave trough was formed over the initial exploitation edge, the tilts of sections 6-7, 7-8 and 8-9 located inside the exploited field had the opposite sign. Then, together with the progress of ground deformation, a sudden forming of a subsiding trough took place, the shape of which was similar to the final one. It resulted in the same, with regard to the sign, tilts of all sections of the monitored terrain line. Maximum tilt in the section between points 5 and 6 is about 10 mm/m. The results of the measurement indicate that the 4th category tilt was not obtained in any of the monitored sections of the line.

5.3. Curvatures

Local terrain curvature (Fig. 7) was also determined at each of benchmarks of the terrain line.

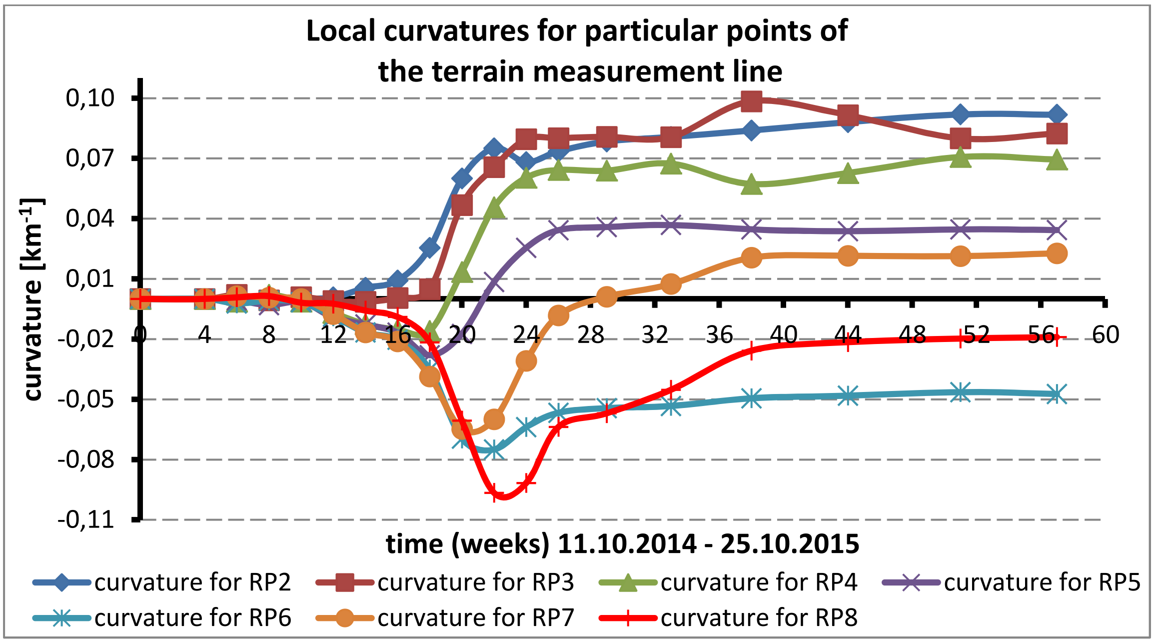

Fig. 7. Chart of local curvatures for particular points of the terrain measurement line
(*Source:* own elaboration)

At the beginning, the curvature of the land surface was increasing slowly. Till the moment an incomplete trough was shaped in the place of exploitation commencement, a slight concave curvature was observed in almost all points of the terrain line. Benchmark no. 2 was an exception, at which the curvature was convex from the very beginning. Together with the formation of the subsiding trough, the shape of which was similar to the final one, that is about 4 months from the commencement of exploitation the values of the curvature began changing dynamically. The biggest convex curvature was measured at points no. 2 and 3. Moving gradually away from the exploited field the value of the analysed parameter decreases till the moment an opposite sign is obtained. It means that at the benchmarks 6 and 8 there is a concave curvature. At point no. 7, in spite of initially formed concave curvature the convex shape was finally observed. The results are the confirmation of the thesis that locally the terrain curvature is a parameter which is variable and difficult to forecast [7]. The maximum curvature with a radius of about 10 km was observed at the benchmark no. 3, which corresponds to the 3rd category of mining damage.

5.4. Horizontal deformations of ground

Simultaneously with the surface subsidence observed on measurement lines, the sections of the measurement rosette were changed in length. Selected measurement results were presented in the Table 1.

In the initial phase of deformation, shortening of all five arms of the monitored rosette was observed. During the period from 22 October till the second half of January 2015, that is three months from the com-

Tab. 1. Selected measurement results for the sections of the rosette

Sections of the rosette	Horizontal deformations ε [mm/m]								
	Dates of the measurement								
	29.12	**22.01**	**5.02**	**20.03**	**10.04**	**04.05**	**12.06**	**24.07**	**25.10**
d5-6	–0,80	–1,67	–2,51	–1,91	–0,88	–0,52	–0,16	0,32	0,24
d6-7	–0,68	–1,97	–3,75	–4,16	–2,66	–2,54	–1,97	–1,57	–1,57
d6-10	–0,73	–1,38	–1,58	–1,20	0,17	0,51	0,65	0,76	0,87
d6-11	–0,94	–1,78	–3,16	–2,92	–1,75	–1,41	–0,81	–0,47	–0,50
d6-12	–0,39	–1,31	–3,44	–4,42	–5,84	–6,00	–6,27	–6,27	–6,30

Source: own elaboration

mencement of exploitation, horizontal deformations took approximately similar values at the level of about –1.4 to –2 mm/m in the whole rosette. Then the diversity between them started to diminish. Maximum horizontal compressive deformations for each side of the rosette were marked in red (Tab. 1). Their culmination fell on 5.02 when the change in the nature of the surface deformation took place along with the formation process of the subsiding trough in the shape similar to the final one. The moment of change in the nature of deformation was marked in yellow. It was observed on the basis of the previously mentioned levelling results. Maximum positive deformation was marked in blue. The highest and also final value of horizontal deformations was observed in the section 6-12. The amount of –6.3 mm/m, in the area the 4th category of mining hazard category (6-9 mm/m) [1]. Deformations at the other sides of the measurement rosette are much smaller. Large diversity of horizontal deformation can be observed within a small area covered by the measurement rosette. Negative effects of horizontal ground deformation on the elements of the ground-based infrastructure within the measured area were presented in the photos (Photo 4 and 5).

Photo 4. Damage to the drainage trough at building No. 4g, which increases in time
(*Source:* own elaboration)

6. Impact of the ground surface deformation on the buildings in the zone of commencing mining activities

6.1. Tilts

Together with the appearance of surface tilt the monitored buildings also started to incline. Building no. 1, which was situated about 90 m from the original exploitation edge inwards the exploitation field (Fig. 2),

Photo 5. Pavement surface damage at the main street in Marklowice
(*Source:* own elaboration)

leaned, in the initial phase, slightly to north-east in the direction of the initial location of the exploitation edge. Then, together with rapid growth of ground deformation the building started to incline in the opposite direction (Fig. 8,9). The change in the tilt direction is associated with the fact that the exploitation front ran below the building. At the beginning, it was located to the northwest of the building and then moved southwest.

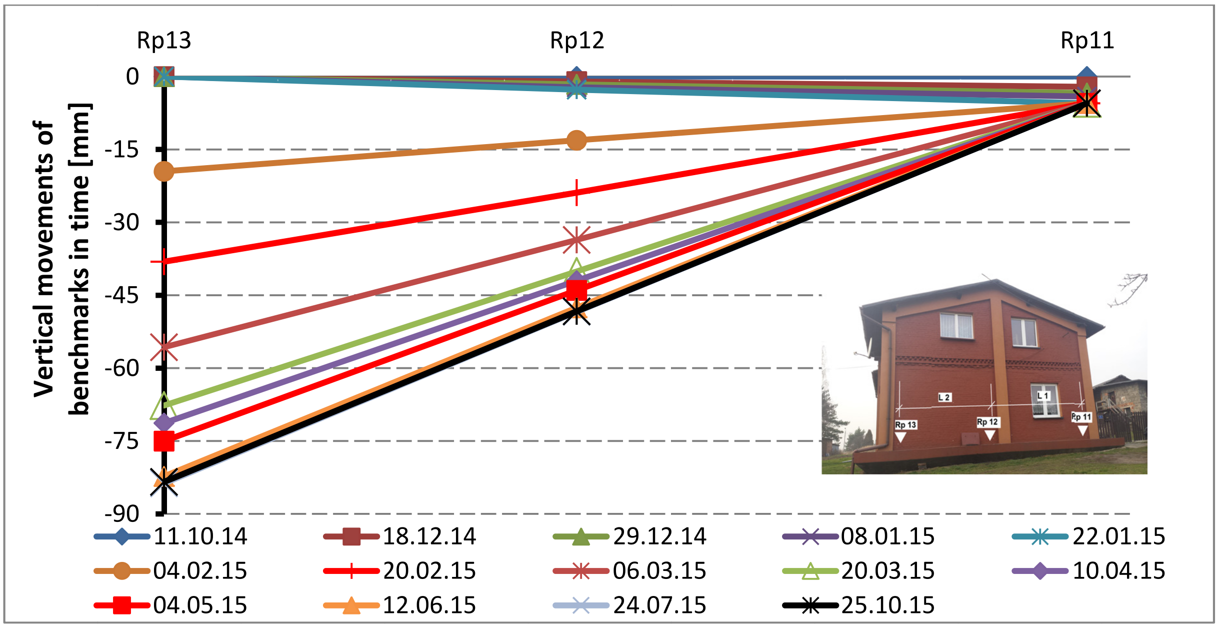

Fig. 8. Vertical movements of benchmarks on the east wall of Building No. 1
(Source: own elaboration)

The other two buildings (no. 4g and no. 6) which were situated approximately over the initial edge of exploitation were leaning all the time in one direction only – inwards the exploitation field (Fig.10, 11). After performed exploitation all buildings remained leaned.

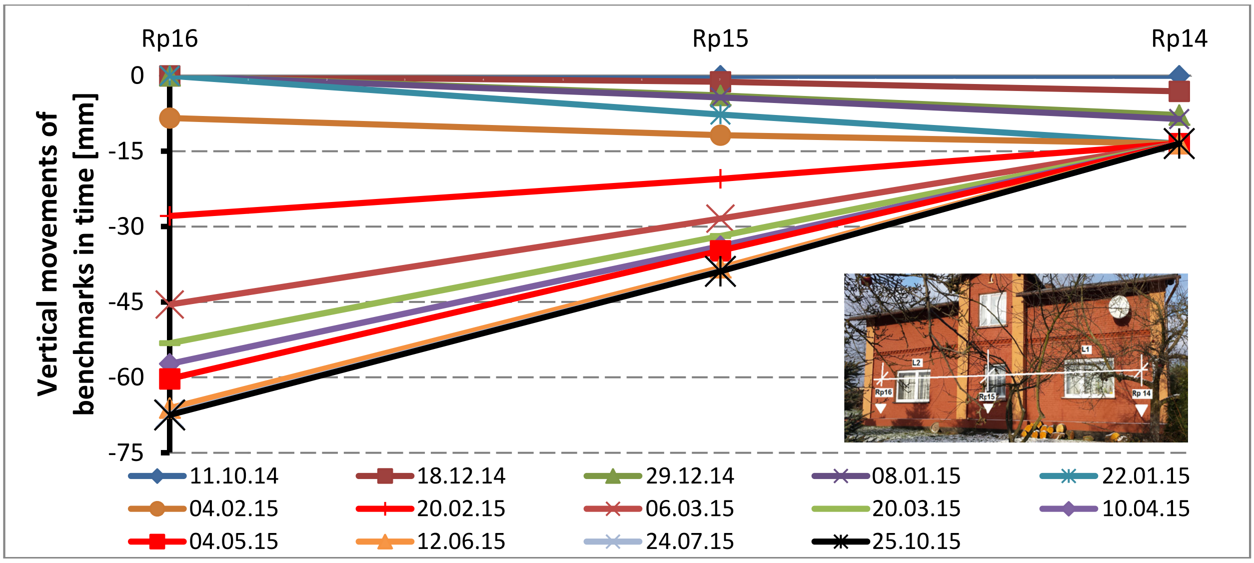

Fig. 9. Vertical movements of benchmarks on the south wall of Building No. 1
(*Source:* own elaboration)

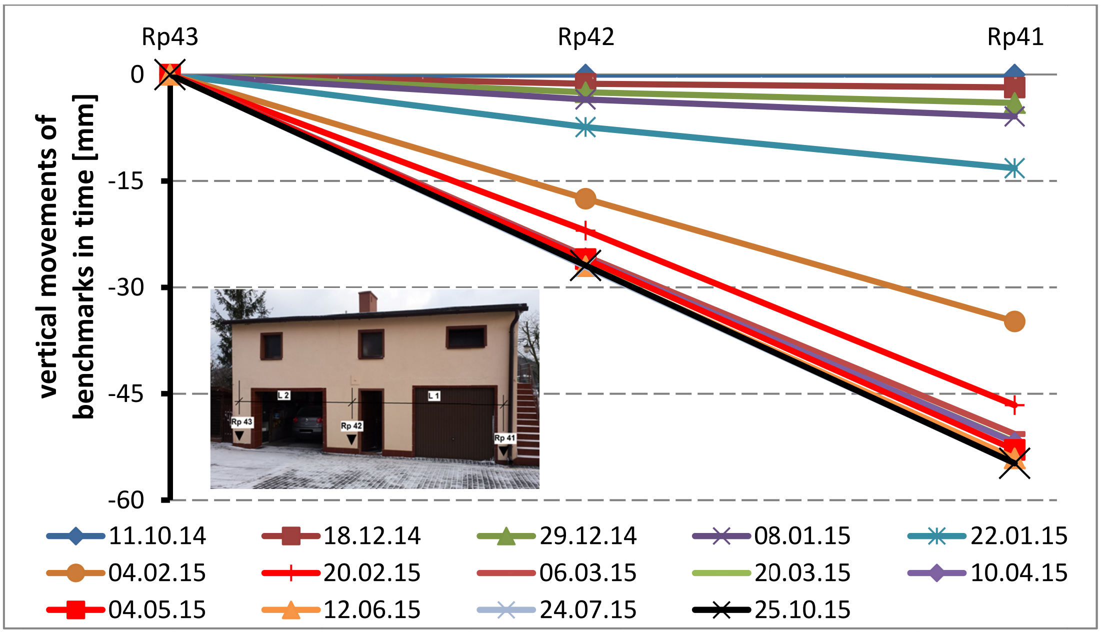

Fig. 10. Vertical movements of benchmarks on the west wall of Building No. 4g
(*Source:* own elaboration)

6.2. Ground deformations

Installation of three wall benchmarks on each of the monitored walls of buildings makes it possible to register deformations of buildings, which could be characterised by uneven inclination of particular parts of the structure [3]. Analysing potential deformations in the first building (no. 1) a chart was compiled, which presented the tilt of particular parts of the east wall of the building (Fig. 12).

Except for changes in tilt of particular sections of the monitored wall (L1, L2), chart (Fig. 12) presents also changes in the ground tilt in the vicinity of the building, represented by a selected section of the terrain line (Rp7-Rp8 – Fig. 3).

The building used to lean in line with the ground movements in that place. In the first phase, a slight tilt was observed towards the first location of the exploitation front of nearly 1 mm/m. Then, along with the movement of the longwall under the building, a change in the tilt direction took place, which was of more dynamic nature. Finally, the building remained in the leaning position in comparison with the initial state of

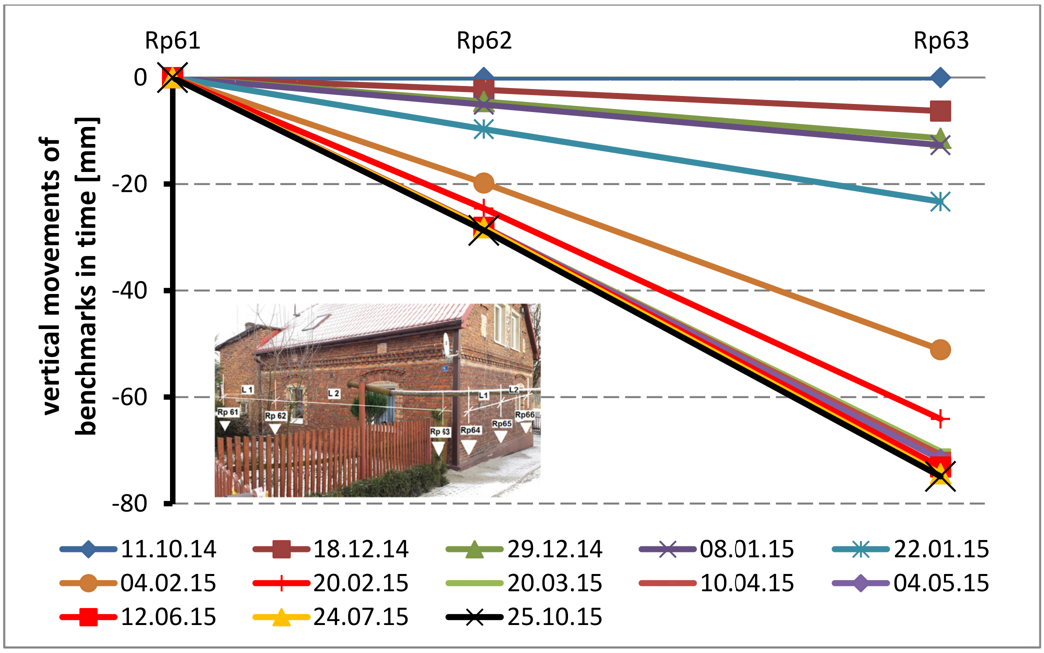

Fig. 11. Vertical movements of benchmarks on the west wall of Building No. 6
(*Source:* own elaboration)

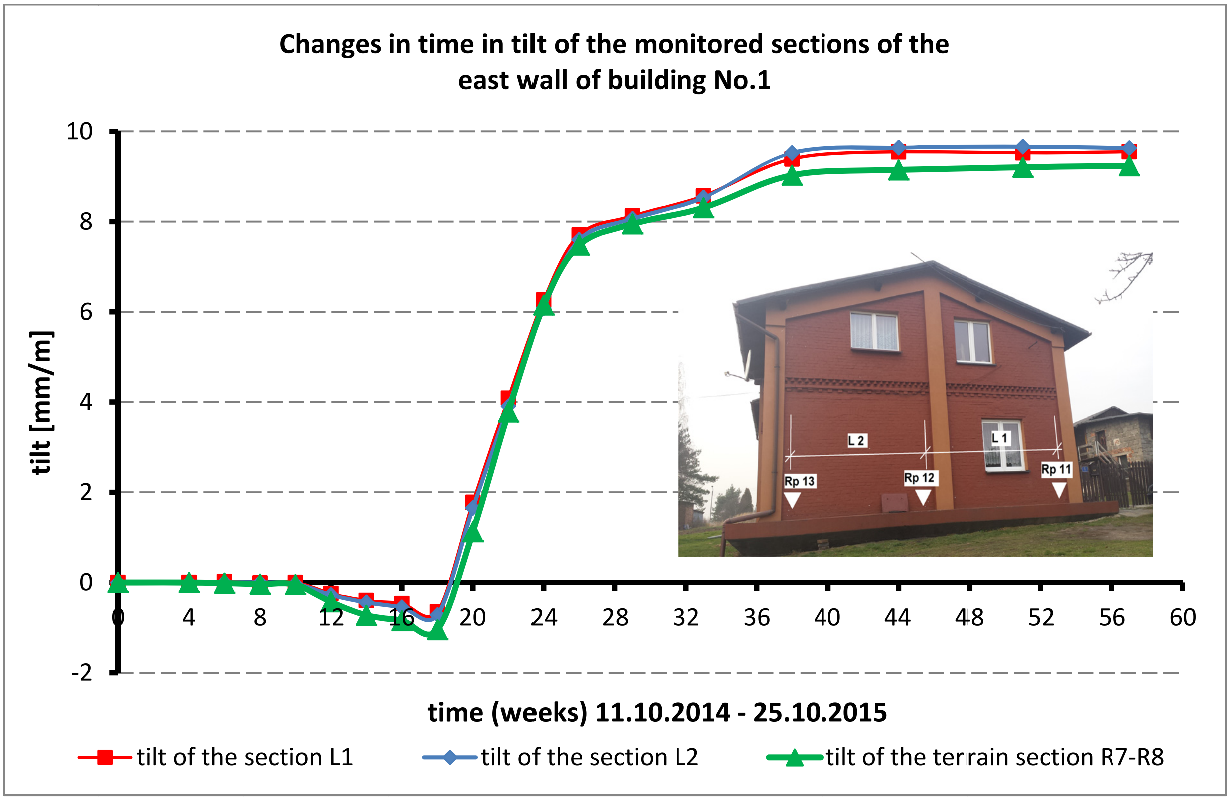

Fig. 12. Changes in time in tilt of the monitored sections of the east wall of Building No.1 along with changes in the ground inclination in the direct vicinity of the building
(*Source:* own elaboration)

about 10 mm/m, towards the inside of the exploited field. It is worth noting that the tilts of lines L1 and L2 do not run along the same track. It can be connected with the limited accuracy of geodetic measurements, but on the other hand, it can also signify the occurrence of the building deformation. Damage to the building visible in the photos (Photo 6) confirms that thesis. It was taken after the exploitation front had passed in September 2015.

Photo 6. Technical condition of the monitored building after the exploitation front passed, September 2015
(*Source:* own elaboration)

Before the commencement of exploitation works the building was renovated. Its elevation had no signs of scratches and damage. When the exploitation front had passed cracks appeared. They concentrated mainly in the vicinity of window openings. It has to be borne in mind, however, that the building in question had been damaged many times in the past as a result of the mining activity. Each time actions were taken in order to repair the damage. It was not, however, insignificant for the rigidity of the building. The building was constructed in brick-and-mortar technology. Such types of building structures get significantly weakened after the first damage and it is difficult to restore them to their original stiffness [6].

Thus, compiling the chart for the building no.6 situated exactly over the initial edge of exploitation, it is possible to come to a conclusion that it was deformed to even larger extent than the building no. 1 (Fig. 13).

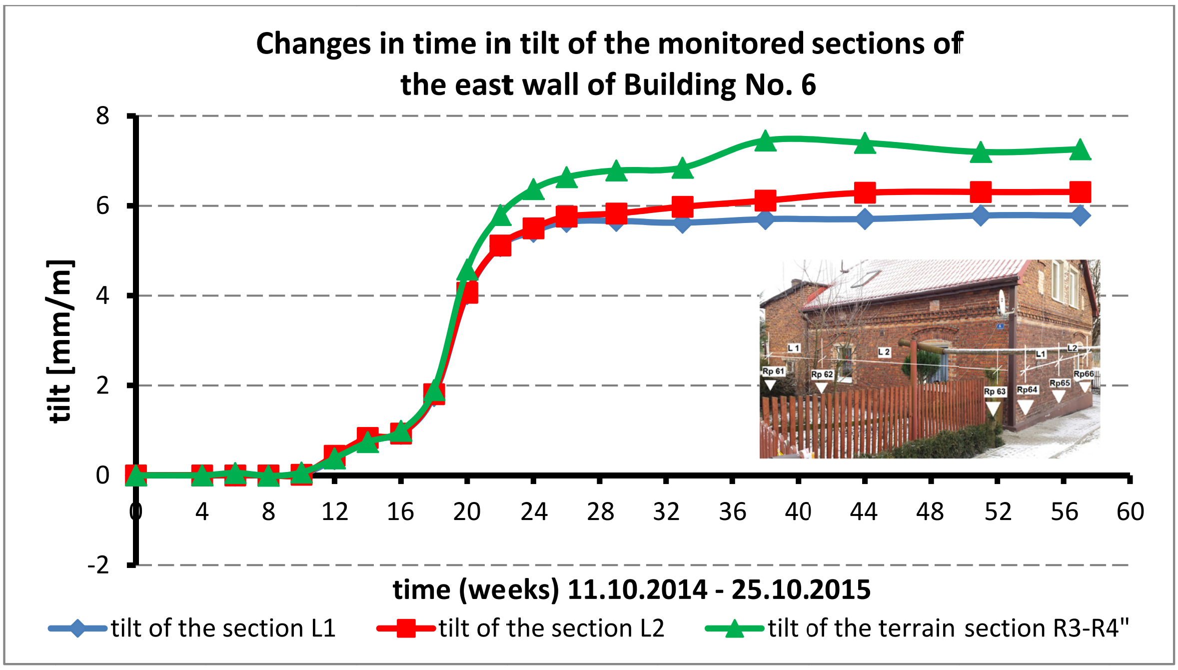

Fig. 13. Changes in time in tilt of the monitored sections of the east wall of Building No.6 along with changes in the ground inclination in the direct vicinity of the building
(*Source:* own elaboration)

It is easily visible here that the tilt of particular fragments of construction is different in size (curves L1 and L2). It should, however, be pointed out that it is a two-segment building. Increasing ground deformation could result in the opening of the expansion joint between the two independent parts of the building structure. As proof of such an actual state is the fact that during the conducted research no damage was found in the structure of the building no. 6. In that case, it is most likely that the expansion joint protected the building against the formation of scratches. The problem of building division in aim of decreasing of structures internal forces was considered earlier and published in [5, 4]. Results of that consideration were published in regulation [2].

7. Summary

Measurements carried out in Marklowice allowed to determine the dynamics and nature of changes in geometry of the ground and movements of the buildings. Finally, the land surface in the zone of commencement of exploitation remained deformed, which could have had a negative impact on the existing building development. The results of the measured surface deformations within the monitored zone were similar to the anticipated ones, defined in forecasts. Besides, they were not big enough to significantly endanger the structures of the observed buildings, the more so because these buildings were properly protected. The results of measurements of the buildings suggest that when the exploitation front had passed slight deformations in the structure of the walls of the buildings appeared and, therefore, small scratches, but they did not pose any major threat to the safety of the construction. They resulted only in decrease of usability (Photo 6). It should be noted here that when the exploitation front had passed the land surface in the zone of commencement of exploitation remained deformed, so the influence of the deforming surface on the building structures is of permanent nature, what can be justified by the fact that the buildings did not regain their initial location and shape. After termination of mining operations the buildings remained leaned, what undoubtedly has a negative impact on the comfort of use.

Acknowledgements

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