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Keywords

mining, construction disaster, deformations, microgravity surveys, GPR surveys

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Abstract

The paper presents the analysis of the results of geophysical surveys conducted in the mining area located in Bytom – Karb (USCB, Poland) in the aspect of identifying the causes of significant damage to the complex of inhabited tenement houses which occurred in 2011. The surveys were carried out by microgravimetric and GPR methods. The construction disaster was caused by the exploitation of one of the hard coal seams at a depth of about 800 m along the mining longwall running underneath the settlement. The terrain deformation parameters exceeded the forecasted values, and in several places discontinuities took linear forms along the diagonal directions to the front lines of the longwall. In addition to the sliding movement, the rotational movement appeared in the ground. As a consequence of spatially complex ground movements, some buildings suffered significant damage. The extent of the damage turned out to be catastrophic and immediate relocation of the inhabitants and demolition of the buildings became necessary. The article is an attempt to explain the nature and the causes of excessive terrain deformations in relation to those modeled on the basis of analysis and interpretation of geophysical data from the current measurements as well as archival maps and geological and mining cartography data.

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1. Introduction

Underground coal mining with longwall systems causes a significant transformation of the rock mass structure and its properties in the zone between the depth of exploitation and the terrain surface [4]. Numerous publications can be found in the world literature on the problem, presenting the analysis of land surface subsidence caused by mining (in particular longwall one), which is based on the results of measurements of displacements of points on the surface of the terrain and modeling [1,18,19,23,27]. Such measurements are conducted during exploitation in the form of constant geodetic monitoring, and the size and extent of subsidence basins are constantly updated. In contrast, in this paper, the authors focused on the geophysical imprint that can be left by the deformation and transformation of the underground rock mass physical parameters caused by the overlapping mining exploitation of various mineral resources in exceptionally complex geological and mining conditions.

As a result of the deformation of the strata caused by longwall mining, the surface is subjected to vertical and horizontal movements. Analytical and numerical methods in the vast majority of the cases allow for an accurate prediction of terrain surface deformation parameters for the assumed geometrical model of the coal longwall before the start of the mining operations [7,15–17]. Modeling and forecasting of the impacts of exploitation on the ground surface assume the continuity of the deformation of the rock layers lying between the exploited seam and the surface and immediate transfer of the deformation to the ground level after extraction of the coal seam – without time delay. It happens however, that the estimated parameters exceed the forecasted

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values when the layers building the overburden deform discontinuously. In the conditions of the Upper Silesian Coal Basin (USCB) in Poland, this particularly occurs in coal mining carried out in deposits covered by a series of Triassic strata. The coal extraction performed in the part of the USCB called the Bytom Basin creates a major threat of harmful changes in the terrain relief and in the building infrastructure located in it. This extraordinary threat is caused by the particular geological structure of this area (Fig. 5). Its characteristic feature is the occurrence of a series of Triassic deposits in the overburden of the Carboniferous containing the coal seams. Locally these strata are covered with clay-sandy sediments of the Quaternary of fluvio-glacial origin. The Triassic deposits are represented by a concise dolomitic-limestone complex of rocks, different in physical and mechanical properties than the Carboniferous strata. Their structure has been transformed by the impact of the Quaternary glaciers pressure in the past. To what extent the glacier has influenced the setting and continuity of the geological strata can be observed in brown coal deposits occurring in the Tertiary sediments in northern Poland [12]. Hence, it can be stated that in the process of transmission of the deformations from the Carboniferous deposits to the surface of the terrain, this complex deforms more fragile. In the zones where the Triassic formation is exposed on the surface, discontinuous deformations take the linear forms of thresholds and crevices of unprecedented dimensions than in the other areas of the USCB, where the Carboniferous strata are outcropping on the surface or are covered with Quaternary sediments [22]. The described terrain deformations are more devastating for the building structures than the deformations of the continuous type. It can therefore be concluded that the manner in which the terrain surface deforms is in this part of the USCB determined by the way in which the Triassic formations deform. A thin layer of the Quaternary deposits only duplicates the Triassic forms and shape.

Linear discontinuous deformations also appear in areas where the Triassic deposits are not present [3,11,14,24–26]. The analysis of the cases in which they occurred in the areas of underground coal mining in the USCB shows that in each case in which the horizontal deformations of the mining area exceed the value of 3 mm/m (the limit of category III of the mining field), the probability of their occurrence is very high [13]. However, this type of deformation is causing much more damage to the building structures in areas where Triassic deposits are found in the Carboniferous overburden.

This article attempts to explain the type and causes of the deformation of the terrain lying within the Bytom Basin in the Karb district of Bytom in Poland (Fig. 1). In the south-eastern part of the district in 2011, under a complex of inhabited tenement houses, the exploitation of one of the coal longwalls in the 504 seam at a depth of 800 m caused significant damage to residential buildings. In the region, a few coal seams lying higher were previously extracted, and additionally, the mining was carried out in one lower-lying seam by the so-called relaxation longwall. As a result of the building extent damage, it was necessary to completely demolish them and relocate tenants to temporary accommodation flats.

The geophysical surveys described in this paper were partly performed at the request of the mining entrepreneur and partly for the project COMEX purposes [2].

The effects of coal extraction for the urbanized area of the analyzed part of the Karb district are illustrated by satellite maps from Google Earth resources (Fig. 2). They show the land development of the area before the construction disaster and two years after its occurrence.

The structure of shallow geological layers constituting the basis for damaged buildings was the subject of recognition by geophysical measurements performed by gravimetric and georadar (GPR) methods. These measurements were carried out in two field series. The first one was conducted during the ground motions, which caused the construction disaster in September 2011. The second series of measurements were made after the cessation of the ground movements in July/August 2013. Fig. 3a shows the timeline with the described events at the Karb disaster area highlighted chronologically.

The deep mining in the studied area induces seismic tremors of high energy [30]. Four events with magnitudes exceeding $M = 3$ have occurred in close vicinity of the study area in the period from 11 January 2011 to 21 November 2012 (Fig. 3a,b). The hypocentres of those tremors were located below the depth of mining operations [21]. The recorded peak acceleration of ground motion in epicenter zones of these events has exceeded the value of 1 m/s^2 (> 0.1 g, where g is a gravity acceleration). Therefore, it can be assumed that these shocks caused relatively large dynamic loads on the rock mass in the overburden of exploited longwall. They could also initiate the defragmentation of the overburdened strata.

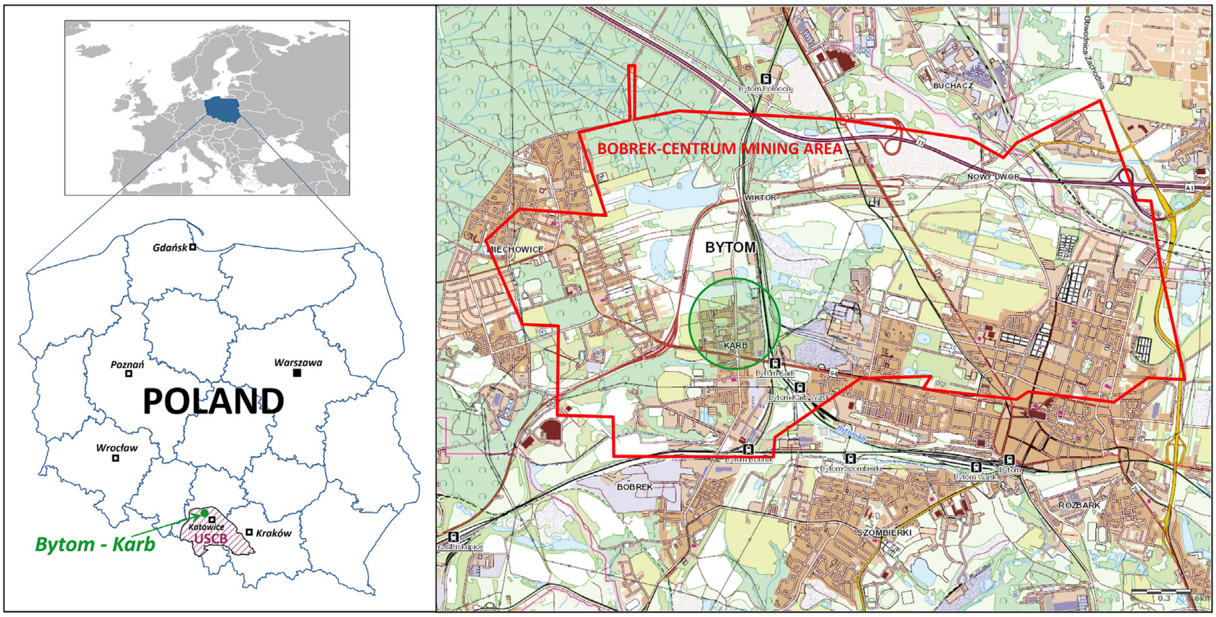


Fig. 1. Localization of Bytom-Karb district and operating Bobrek-Centrum mining area on the city plan [28].

2. Geology and mining

In the geological structure of the analyzed area, the Quaternary, Triassic and Carboniferous deposits are involved. The Quaternary strata have a thickness of several to several dozen meters. They are mainly represented by glacial and fluvial-glacial clays. Triassic deposits are assembled in the form of flat layers of limestone and dolomites with marl inserts, altogether about 180 m thick. In the Triassic sediments at a depth of about 80 m, deposits of zinc and lead ore are present, which were the subject of exploitation at the turn of the 19th and 20th centuries. The Carboniferous strata occur below the Triassic deposits. In these sediments, a deposit of monocline dipping hard coal seams is documented. Stratigraphically, they occur in the Upper Silesian sandstone series (Rudzkie and Siodłowe layers) in the form of the seams lying at different depths between layers of sandstones interleaved with shale and mudstones. In the tectonics of the region adjacent to the analyzed area, dislocations of the W—E and NW—SE directions, formed during the Variscan and Alpine orogenesis, are dominating. The extent of cracking in the rock layers duplicates these directions. One of the tectonic dislocations crosses the coal longwall field, the extraction of which caused a construction disaster. Directly in the analyzed region, the flat-parallel retention of the Triassic layers is disturbed by the dislocation of glacial genesis pressing the Quaternary deposits into the Triassic ones and, through them, deeper into the Carboniferous strata. This form has the shape of a syncline and is called the “Karb washout”. Its width varies in the range of 800—1500 m in the W—E direction.

a) b)

Fig. 2. Satellite images of the study area (in red) before (a) and after (b) the catastrophic event [29].

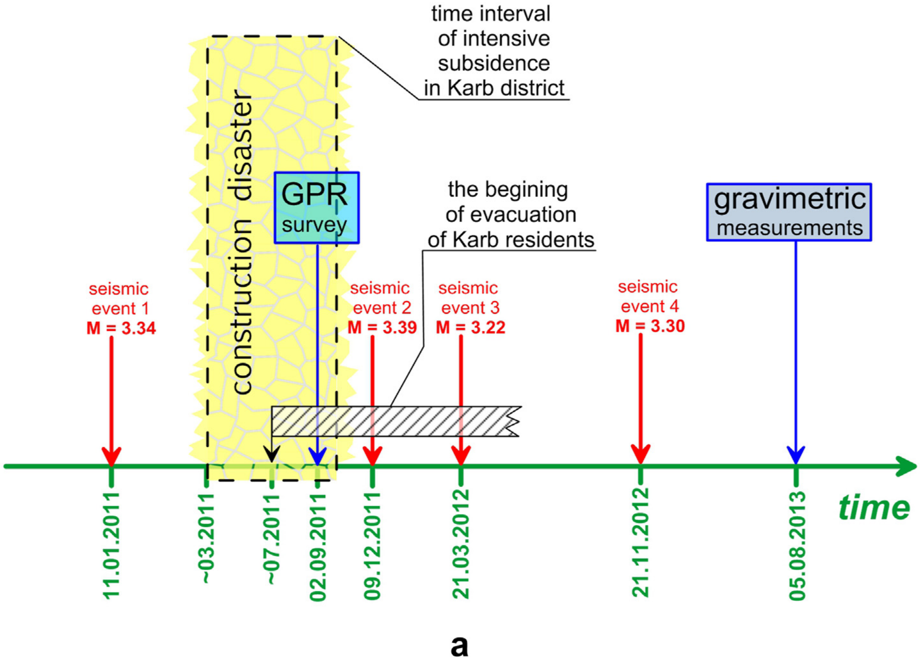


Fig. 3. (a) Timeline of the 2011–2013 events in Bytom-Karb, and (b) seismic events recorded in Karb district 7.01.2010–10.09.2013.

The geological structure of the region is illustrated in the German archival structural map from 1941 [28] (Fig. 4). A vertical image of rock mass structure to a depth of about 900 m and its transformation by the exploitation of hard coal and ores in the study area is shown in Fig. 5. The location of the area of geophysical surveys is indicated in both figures.

There was no documented ore mining in the Triassic sediments directly below the damaged buildings. There are also no deep boreholes showing the geological structure and mineralization of the Triassic series in this region. Information about the lack of mineralization comes from two exploring galleries, performed at a depth of approximately 80 m (Fig. 5). Those openings left a large part of not explored rockmass between the faces of galleries. It leaves the possibility of occurrence of not discovered, mineralized rocks with a

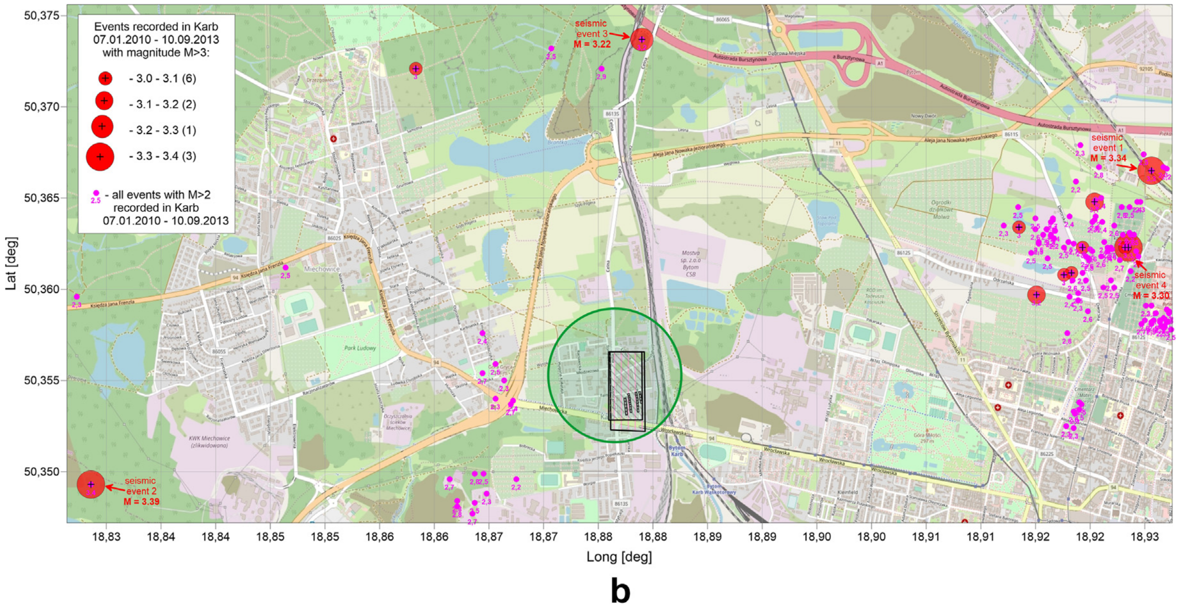


Fig. 3. (Continued).

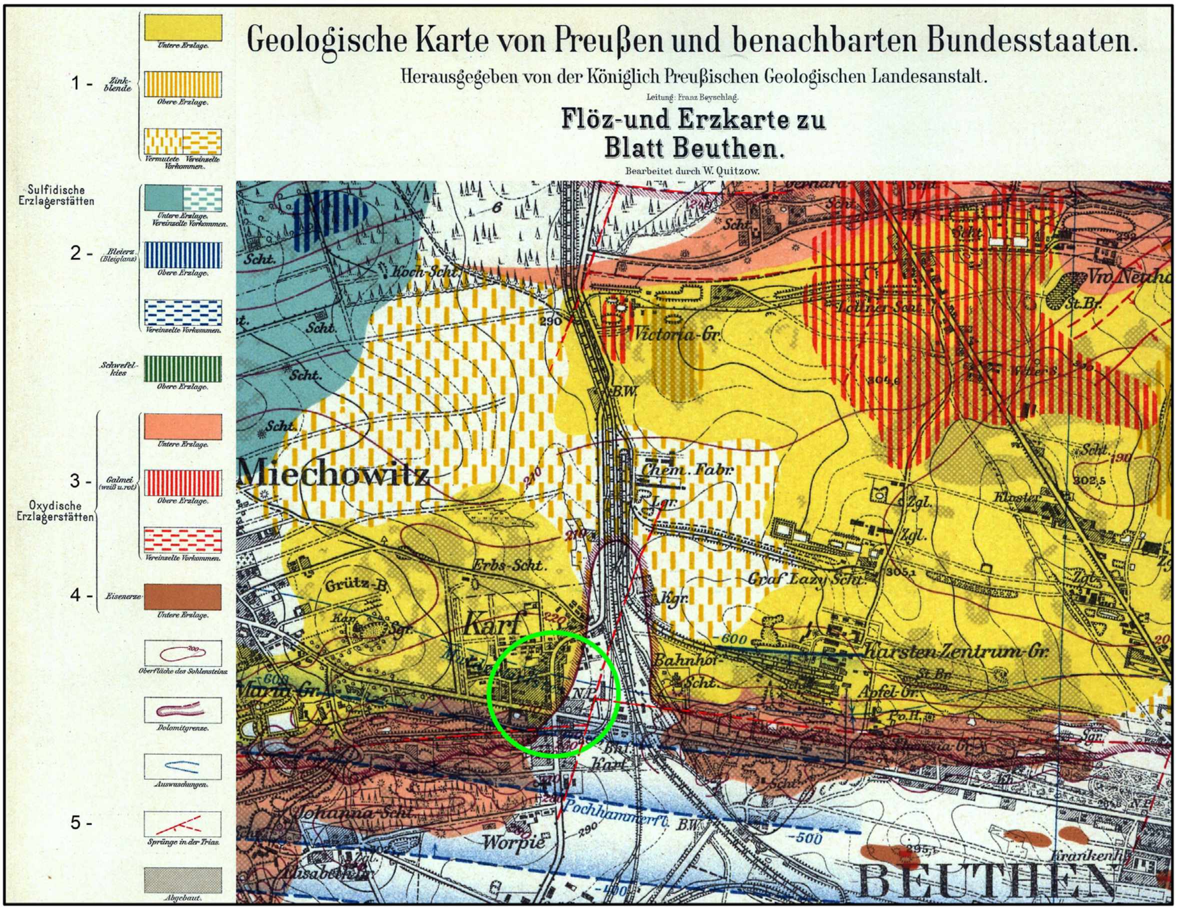


Fig. 4. Fragment of "Geological Map of Prussia and neighboring lands (Bytom Card)" from 1941 [5]; in green – disaster area. 1 – zinc ore deposits, 2 – lead ore (galena), 3 – galmanine, 4 – iron ore, 5 – tectonics in Triassic.

high bulk density (such as galena) in this area. In the Carboniferous deposit in the period from 1942 to the time of the construction disaster, mining was carried out in 13 coal seams (405, 407, 409, 412, 414, 418, 419, 501, 503, 504, 507, 509, 510) of the total thickness of the extracted coal equal to 25–28 m. Due to that fact, the near-surface soils and rock strata building the overburden were repeatedly deformed. A comparison of elevations of the disaster terrain in 1941 (Fig. 4) and 2013 (Fig. 9a) indicates that it has subsided about 20 m through that time, and that amount is the total effect of coal exploitation.

The events described in this article occurred during the running of the LP1 longwall in the 504 seam in 2011. In this seam, coal was extracted by a layer of 3.3 m thick. Five years earlier, coal in the 503 seam was extracted in this region. This longwall had the same designation (LP1) as the longwall in the deeper coal seam –504. The edges of the mining in the 504 and 503 seams projected on the terrain surface were located near the planned ending of the LP1 wall in the 504 seam. The seam 503 occurs 20 m above seam 504. The mining in this seam caused the formation of cracks in the rock mass ceiling. They outcrop in the NW part of the studied area, adjacent to the projection of the edge of the long wall on the surface. These cracks are visible as lineaments in the hillshade image of the numerical relief model (www.geoportal.pl) in a zone about 50–100 m wide (Fig. 6). Presumably, there are discontinuities of tectonic genesis in the Triassic as well as structural disturbances of sedimentary or glacitectonic origin in the Quaternary deposits in this region, visible also in the upper center area of Fig. 4 (marked with cyan arrow).

3. Geophysical surveys

Shortly after the largest ground deformations and damages of the buildings in the area of the streets: Pocztowa, Falista, Techniczna, and Konstytucji in Bytom-Karb, geophysical surveys were performed within the disaster area. In this first approach, the surveys were carried out by the GPR method to determine the structural features of subsurface soils and, in particular, the homogeneity of near-surface geotechnical layers. These features have a

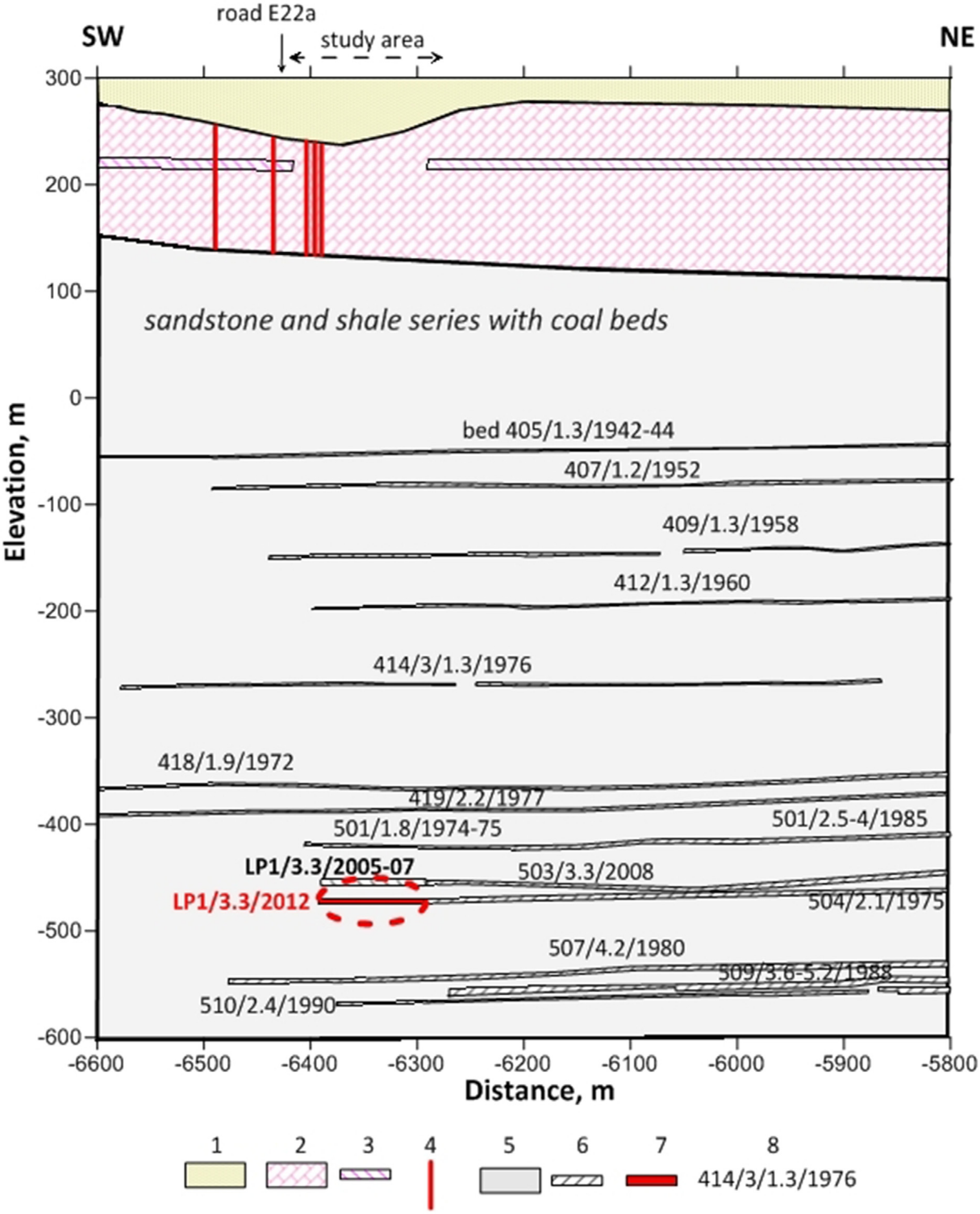


Fig. 5. Geological cross-section of the surveyed area with mining work-outs. 1 — quaternary, 2 — triassic, 3 — abandoned ore gobs, 4 — fissures in Triassic series, 5 — carboniferous series, 6 — abandoned coal gobs, 7 — longwall panel driven before the catastrophe, 8 — coal bed no/thickness of coal extracted in the year of extraction.

significant impact on the deformability of the layers in the foundation level of damaged buildings. Also they could provide data about the reasons for the rock mass, noncontinuous deformations.

3.1. GPR survey (2011)

GPR profiling with the *SIR-3000* apparatus manufactured by the *Geophysical Survey Systems Inc.* and

Fig. 6. Lineaments in the region of one of the Triassic fault visible in the hillshade image of the numerical relief model [28] after extraction of coal by the LP1 longwalls in 503 and 504 seams. 1 – lineaments, 2 – tectonic faults in Triassic, 3 – tectonic faults in 503 and 504 coal seams, 4 – panel LP1 in 503 seam, 5 – panel LP1 in 504 seam, 6 – damaged building segments.

100 MHz antenna (400 ns time window) was carried out on September 2, 2011, in the area of the largest damages in masonry houses. The measurements were conducted on a total of 10 profiles; their runs are indicated in Fig. 7 and marked by symbols P1–P8 (longitudinal – red) and R9-R10 (transverse – magenta).

Field data were processed and analyzed using GSSI Inc. RADAN7 software. The propagation velocity of radar pulses in the strata was determined by the method of multiple hyperbola migration trials. The analysis showed that the velocity of radar waves in the examined medium had vertical and horizontal zonation. In the top parts of the

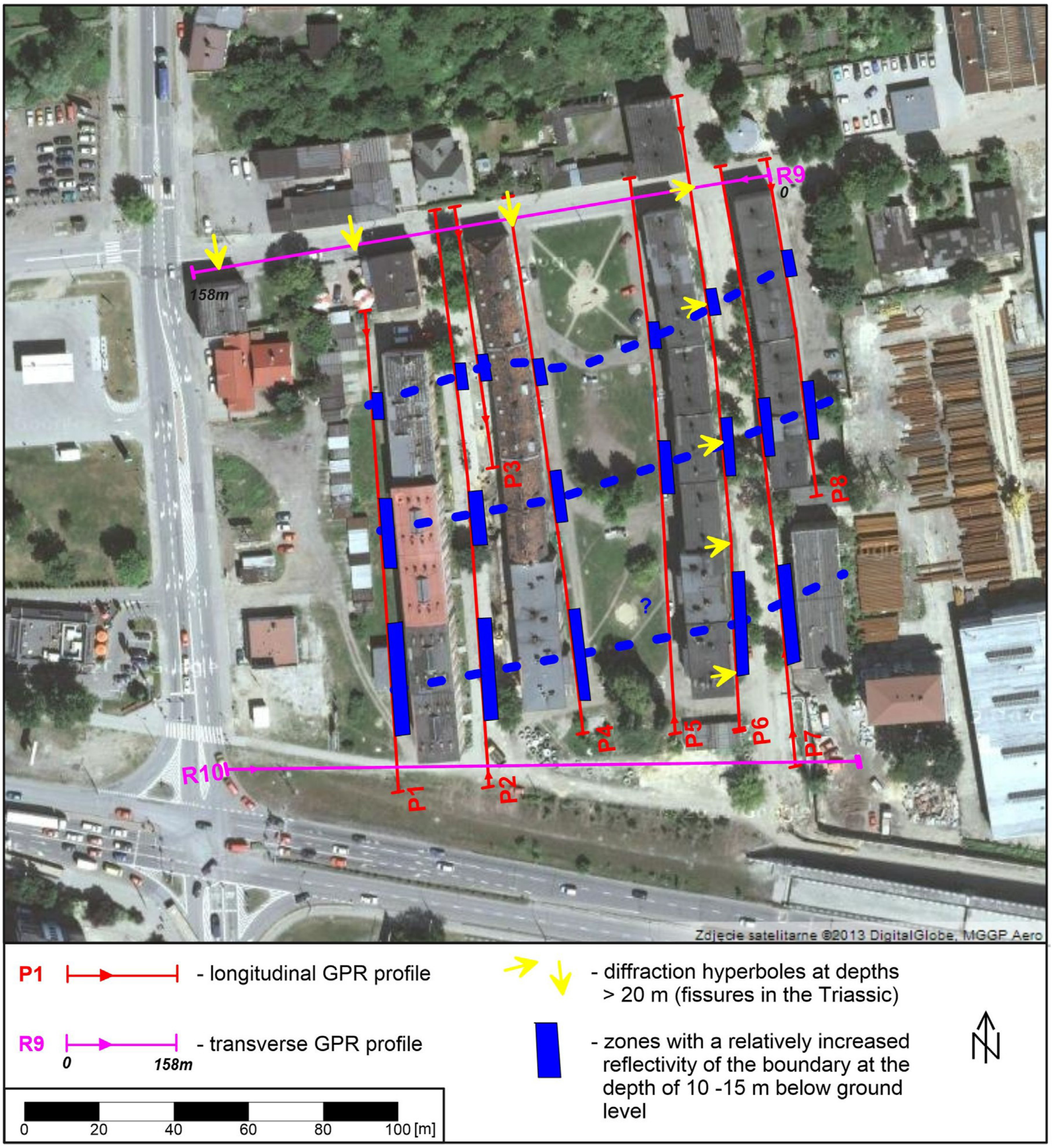


Fig. 7. GPR profiles location and geophysical survey results — September 2011 [29].

echograms, wave velocity exceeds $2 \cdot 10^5$ km/s. In the lower parts of the section, the effective speed in some places was high, in the order of $1.5 \cdot 10^5$ km/s, and in others nearly three times lower, reaching only the order of $0.5 \cdot 10^5$ km/s. High velocity values of EM waves are characteristic for soils with low water content. Low velocity values can be associated with the presence of water-saturated soils such as sands or liquefied clays. Considering that in the geological structure of the studied area in terms of depth penetrated by georadar, mainly clay with low humidity is present, the effective velocity of wave propagation in the strata $V = 1.56 \cdot 10^5$ km/s was adopted for the transformation of the radar time sections into depth ones. This value corresponds to the dielectric constant of the strata $\epsilon = 3.6$.

After data processing, an image of the subsurface structure was obtained, in which the flat-parallel system of three reflection horizons dominates. They divide the subsurface strata into four geophysical layers. To determine the geological model for the interpretation of the radar data, profiles of archival

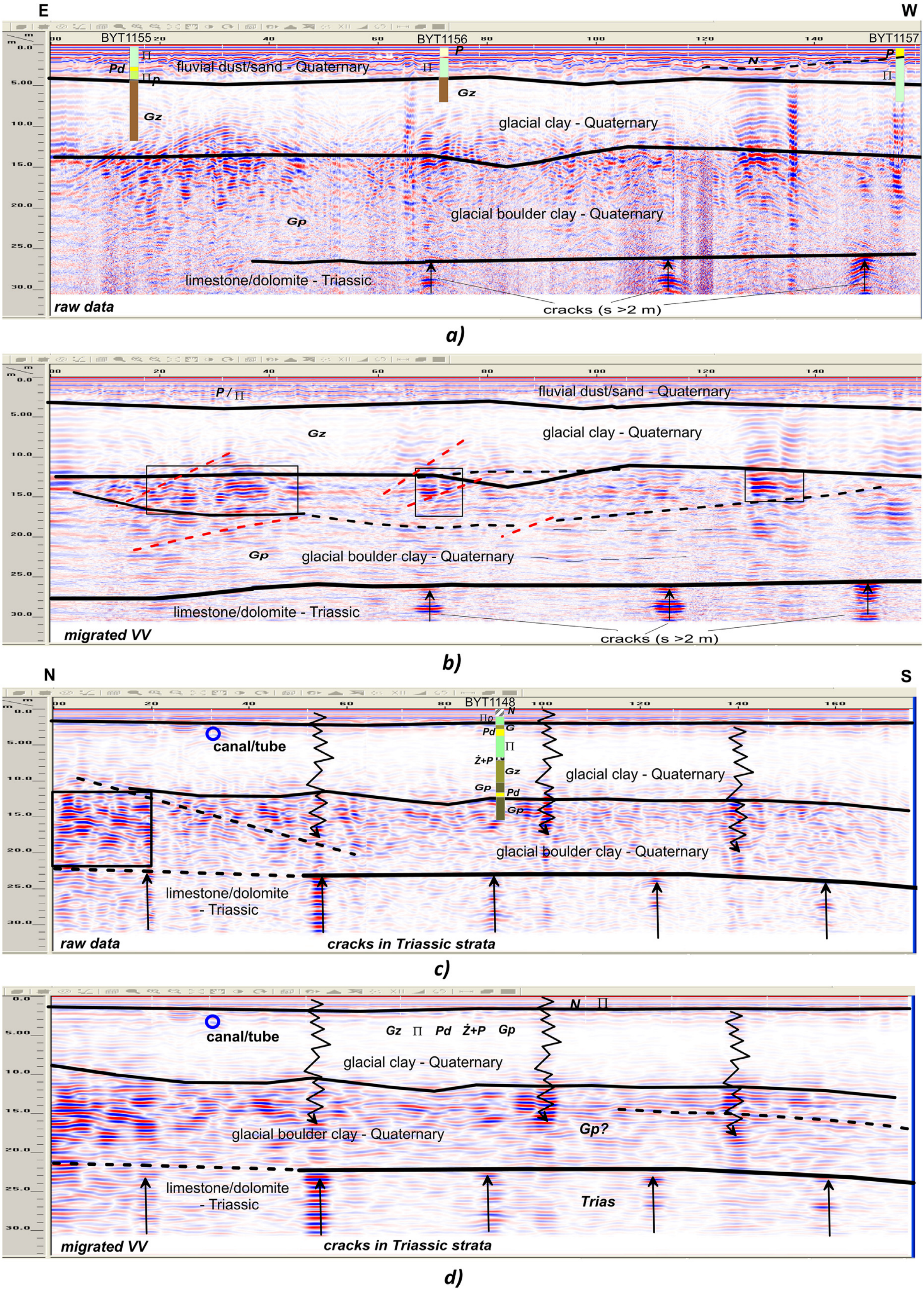


Fig. 8. Geologically interpreted GPR depth sections of R9 and P6 profiles in the image of raw data (a, c) and data processed by the hyperbolic migration algorithm (b, d) and P6.

geological-engineering wells from the research area were used (Fig. 8a).

The radar sections analysis results indicate that the subsoil has horizontal and vertical divisibility. Horizontal divisibility is associated with the lithologic and stratigraphy boundaries in the Quaternary formation. Vertical divisibility was observed from a depth of about 10–15 m. It could be associated with the structural transformation of the strata lying at this depth (sandy clay) caused by mining-induced stresses. Analysis of strong hyperbolic reflections of the radar waves from the heterogeneity located at a depth exceeding 20 m showed that they come from gaps and fissures with a large aperture (> 2 m) in the Triassic formation. The correlation of the zones recorded on individual profiles in which the amplitude of reflections reaches the highest values at the top of the geophysical layer identified as boulder clay is shown in Fig. 7 (blue rectangles).

The zones of highest energy of reflections from subsurface features are generally arranged in a direction similar to the extent of the front of longwall LP1 in the 504 coal seam (W–E). Nevertheless, it can be observed that the line-correlating anomalies is not straight and deviates slightly to the north at the east end. It suggests uneven over time, deformation of the subsurface strata, and the possibility of its rotation. The distances between anomaly zones range between 30 and 40 m. That spacing can be associated with the structural transformation of the Quaternary sediments on the lines of Triassic blocks movements in the rock mass. Along these lines of the rocky blocks movement, wide gaps and probably also steps were created, which affected the way the Quaternary strata deformation. Such forms were recorded on profiles R9 and P6 (Figs. 7 and 8). It can be therefore assumed that Triassic sediments were defragmented into blocks of horizontal dimensions of 30–40 m. Block-type deformation of the Triassic strata may be the reason for the irregular deformation of the Quaternary sediments. It could cause the occurrence of slippage at the lithological boundaries in the Quaternary, directly resulting in the damage of the constructions on the ground level. These types of processes are suggested by the GPR image of the shallow subsoil in the area of the most damaged building at Pocztowa St.

From the point of view of the usefulness of the radar data to understand the construction disaster in Karb, the most important appears to be the GPR image of the top part of Triassic strata lying below the depth of 20–25 m. The transverse profile along the eastern part of Falista St. – R9 turned out to be particularly interesting. In this depth section, high energy diffraction spots were recorded in the deepest geophysical layer, as seen in the raw data image (Fig. 8a). Similar spots were recorded on profile P6 (Fig. 8c). Data processing by migration algorithm with the constant speed have flattened diffraction hyperbolas to objects in the shape of rectangles with a width of 2–3 m (Figs. 8a and c). The model of the geological structure of the ground requires that these objects should be interpreted as wide fissures (splits) in the Triassic strata mentioned earlier.

Comprehensive analysis of radar data and the structural image of the rock mass mapped with GPR suggests that in September, 2011, the process of deformation of the Triassic strata under the influence of longwall LP1 exploitation has not yet ended at that time. In particular, this applies to the southern part of the research area. Because the 2011 GPR survey covered only a small fragment of the surface over the extracted longwall in the 504 seam an extended survey with the microgravimetric method was performed nearly two years later, between July and August of 2013. This study covered a much larger area than the geo-radar survey.

3.2. *Microgravity survey (2013)*

The gravity survey covered the area bounded to the east and west by the Karb glacitectonic washout boundaries, from the north by the northern beltway of the city of Bytom, and from the south by Miechowicka St. The measurements were conducted using CG-5 SCINTREX Autograv gravimeter in the orthogonal grid of 470 points (Fig. 9a). The spacing between them was approximately 20 m. Points were stabilized in the ground, and their coordinates X, Y, and Z were determined by means of the GPS technique. The set of geodetic measurements allows to calculate the topographic corrections to gravity measurement data as well as allows to determine the terrain relief during geophysical surveying. The relief is presented in Fig. 9a as a contour map of the study area. It is shaped in the form of an open and tilted toward the north hutch. Its longitudinal axis is similar to the course of the meridian. Elevation of the points located in the region nearby the southern border of the area of measurements is about 277 m a.s.l., in the center of the basin located near the northern border of the research area – 269.5 m a.s.l. and near the eastern and western boundary of the study area the elevation is rising to around 278 m a.s.l.

The point with the number 1000 was adopted as the reference for calculations of the short-time drift of the instrument. The detailed methodology of the measurements and gravimetric data processing is analogical to authors' earlier research [8–10]. As a result of the gravimetric survey, a set of differential

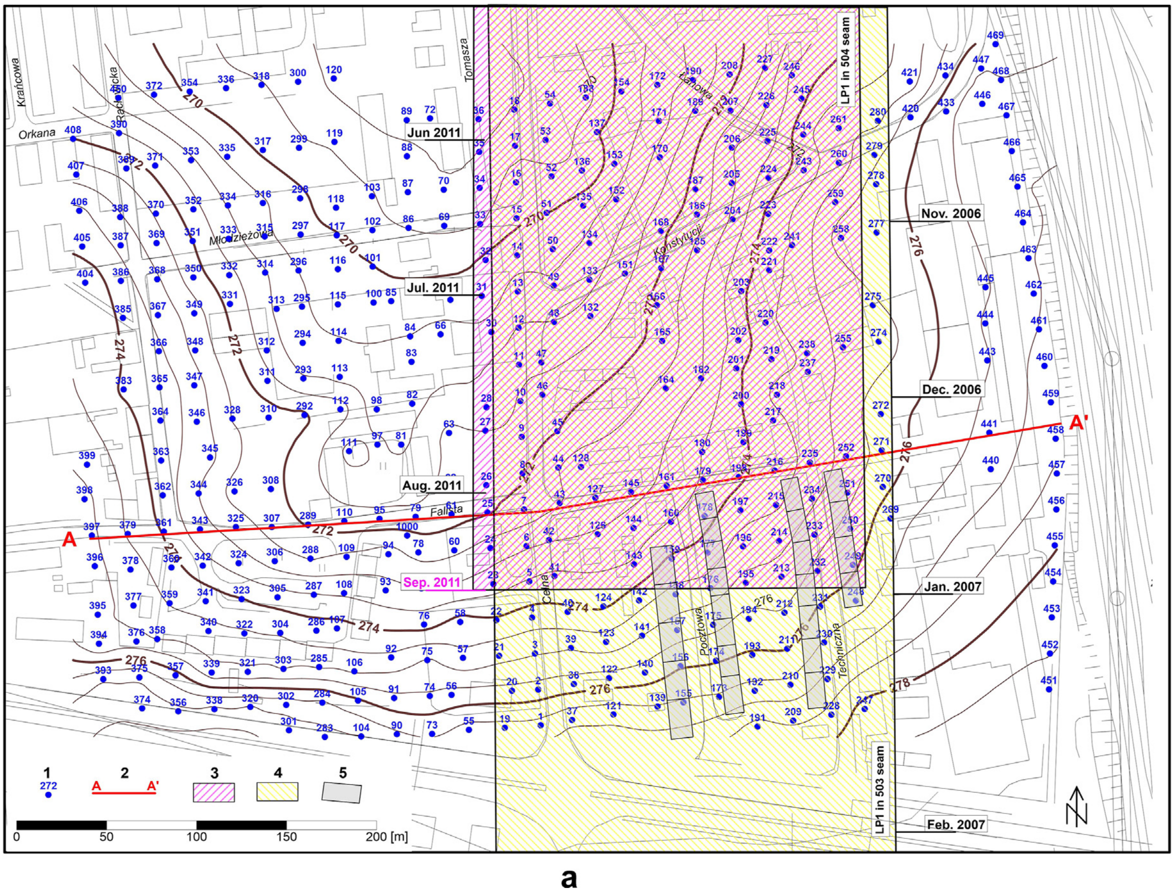
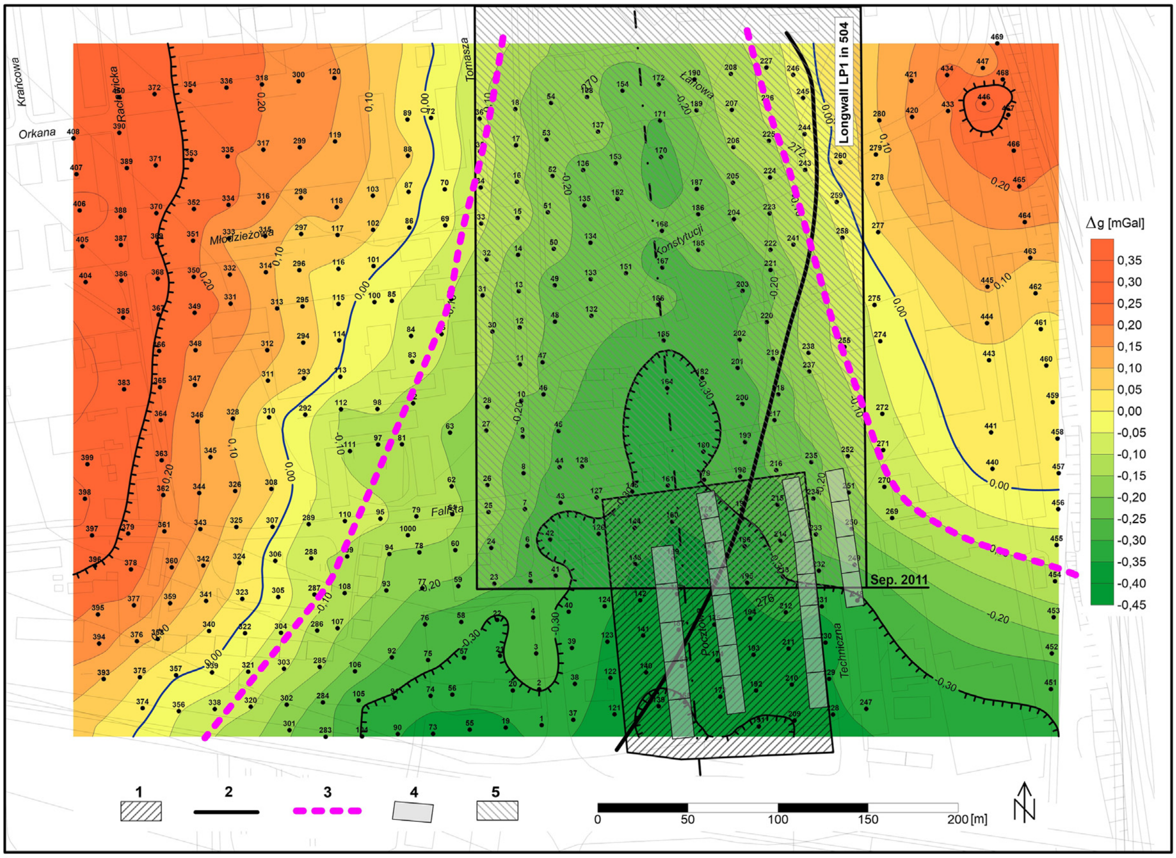


Fig. 9. Location of the gravity points on terrain elevation map (a) and Bouguer anomaly distribution map (b) in August 2013. 1 – area of demolished buildings, 2 – western range limit of ore-bearing dolomites based on Fig. 4, 3 – borders of the washout zone according to the interpretation of gravimetric data, 4 – building segments, 5 – LP1 in 504 position for August 2011.

values of the vertical component of the gravity field between a particular point and the reference point was obtained. From those data, the gravity anomalies in the Bouguer reduction were calculated for all of the grid points. The bulk density of 2.0 g/cm^3 was used in Bouguer reduction as a background density of the rock mass. This value is usually applied in processing gravimetric data from the USCB area and is confirmed by gravity measurements in several mining shafts in the region [20]. The interpolated map of the distribution of the Bouguer anomaly is shown in Fig. 9b.

The Bouguer anomaly map turns out to be generally an inverted image of the terrain relief. The lowest values were recorded in the vicinity of the southern border of the area. They reach there the values of the order of −0.40 mGal. The highest values of Bouguer anomaly (+0.35 mGal) were recorded in the west and northeast parts of the area. The characteristic feature of the map is the low values anomaly zone extending from south to north in the bell-shaped figure. The longitudinal axis of this zone runs approximately parallel to the Celna/Konstytucji St. approximately 70 m to the east. In the southern part of the study area, its course coincides with the Pocztowa St. The area of surface deformation which has led to the demolition of buildings appears on this map as a region of the lowest values of the Bouguer anomaly (−0.45 mGal). This suggests that in this zone, the bulk density of the rock mass is the lowest, which may be caused by the transformation of the rock structure in the overburden as a result of repeated coal mining at different depths. In general, the shape and distribution of the anomaly reflect the "Karb washout" geological structure.

The image of the Bouguer anomaly map is not compatible with the existing knowledge of the washout structure and its spread in the Triassic sediments. The black line on the map marks the extent of the western boundary of ore-bearing dolomite, as it is drawn on Fig. 4. The lines in pink mark the boundaries of the zone that is characterized by the reduction of the gravity field (anomalous zone). This feature allows assuming that the Triassic



b

Fig. 9. (Continued).

sediments, characterized by high bulk density – due to the presence of metallic minerals, fill the form in deeper Carboniferous formation. The form has the shape of gutter – an undulation of the Carboniferous strata surface. The amplitude of the anomaly values within this structure decreases to the north, which probably indicates that its thickness is reduced there. In Fig. 9b, the area in which several buildings were demolished in 2011 due to terrain deformations is also shown. The western border of this area is the Celna/Konstytucji St. The northern border determines the Falista St. The eastern border of the area is parallel to the Techniczna St.

3.3. Modeling the density structure of rock mass from gravity data

Large inconsistency between the geophysical data interpretation concept and existing views of the geological structure of the substrate was the reason for carrying out the modeling of the Bouguer anomaly in line A–A' (Fig. 9a) using the 2D inversion method. The primary task of modeling was to estimate the density distribution of rocks deposited in the overburden of longwall 504 in relation to the existing assumptions of the geological structure and their possible verification by data from gravity measurements. The second aim of the simulation was to estimate how the previous extraction of coal seams changed the density of rock mass and, thus, the weight of the overburden. Both of these factors could have influenced the errors in forecasting subsidence and horizontal deformations. Modeling was performed using the Gravmodeler software developed by LaCoste & Romberg.

The simulation algorithm involves inversion of the 2D structure in which in a block of unlimited size and constant bulk density, objects of limited size (polygons) that have different bulk density values than the block are embedded. For a given A–A' cross-section and adopted differential values of density between the block and embedded objects, the response of the gravity field on the terrain surface was calculated. By changing the shape and position of the objects on the cross-section one can look for a model for which the theoretical response of gravity fits the best to the measurement data.

The planes along which Triassic sediments fill the undulation in the carboniferous strata ceiling have steep dips. They form natural surfaces along which the upper parts of the rock mass can move during the subsidence of terrain due to mining operations carried below them. The best fit of measurement data points curve to the theoretical density model of the substratum was obtained for a structure with the vertical, rectangular block with a relatively lower density than the surrounding rocks inserted into the Carboniferous strata. This block simulates a zone in the overburden transformed by multiple subsidence processes caused by mining in the coal deposit (Fig. 10).

In the studied model, this zone has a lateral spread similar to that of longwall LP1 in 503 and 504 seams. It extends from the seam 503 roof to the bottom of the Triassic sediments. The best fitting of the model response to the data points was obtained when the assumed bulk density of the vertical object is equal to 1.84 g/cm^3 (red block in Fig. 10). It corresponds to the difference of porosity values between the object and background rock of 8%. It can be assumed that this value reflects the influence of all exploitations performed in the coal deposits below Falista St. on the overburden in density terms. According to the field data, the total subsidence of a terrain surface has reached 12 m here. It means that at least a 15 m thick layer of coal has been extracted from the coal bed in various seams and depths.

The arrangement of density blocks in the model can be assigned to the following geological strata (colors corresponds to Fig. 10):

- alluvial sediments, sandy clays, and clayey sands characterized by a density of 2.0 g/cm^3 (yellow),
- moraine soils, clays with limestone boulders with a density of 2.8 g/cm^3 (green),
- in the eastern part of cross-section, the Triassic marls of density 2.1 g/cm^3 (blue),
- Triassic ore-bearing dolomites characterized by varying densities: 5.12 g/cm^3 in the western part (magenta), 5.20 g/cm^3 in the central part (purple), 5.12 g/cm^3 in the eastern part of the cross-section (magenta); in the model these sediments fill the undulation in the cap of the Carboniferous strata along steep planes,
- stratified Carboniferous sediments (shale, mudstone and sandstone beds with coal seams) with an average density of 2.0 g/cm^3 (grey).

The upper part of the model, composed of Quaternary and Triassic sediments, was adopted to determine the geometry and the type of rocks selected for modeling the impact of dynamic loads caused by mining tremors on the stability of the voids left in the ore body by historical mining [2]. The results of modeling of density distribution indicate that the discrepancies in the subsidence predictions could have been influenced by both the variable weight distribution of the overburdened rocks of the younger sediments (Quaternary and Triassic) in the longwall area and the change in the weight of Carboniferous rocks as a result of earlier coal mining in this area.

4. Discussion on geophysical survey results

The analysis of geophysical images of the rock mass in the study area indicates that its structure between the Carboniferous floor and the terrain surface is highly heterogeneous. This heterogeneity is caused by the following elements:

- Variation in the thickness of the Quaternary deposits in the W–E direction,
- Variable volume density of the Triassic deposits and the resulting pressure on the Carboniferous strata. Presumably, the maximum bulk density of this series is achieved at the site of a construction disaster, and it results from the presence of zinc and lead ores in the substrate not detected by previous surveys.
- The presence of disturbances in the structure of the Triassic strata of tectonic and glacial tectonic origin.

These features were not revealed by shallow geotechnical drilling performed to a depth of about 10–12 m at the time of the first damages spotted in the buildings because they were too shallow. Up to this depth, the ground is built of a series of glacial tills in a compact state, covered with sands and clays of young origin of the river age (valley of the Bytomka River). It should be noted that the fitting of the density model of the rock mass to measured gravity data was obtained assuming very high values for ore-bearing strata in the Triassic series. Those inflated values are probably caused by the presence of galena within them, which is characterized by high specific gravity in the range of 7.4–7.6 g/cm^3 [6].

The distribution of the microgravimetric anomalies (Fig. 9b) apparently indicates the diminishing volume density of the rock mass formation to the south. On the other hand, the results of numerical modeling indicate that, in reality, this relationship is inverse and caused by the shift of the mineralized Triassic rocks towards the south. The consequence of this fact is the change in the weight of the overburden over the moving longwall LP1 front in 504

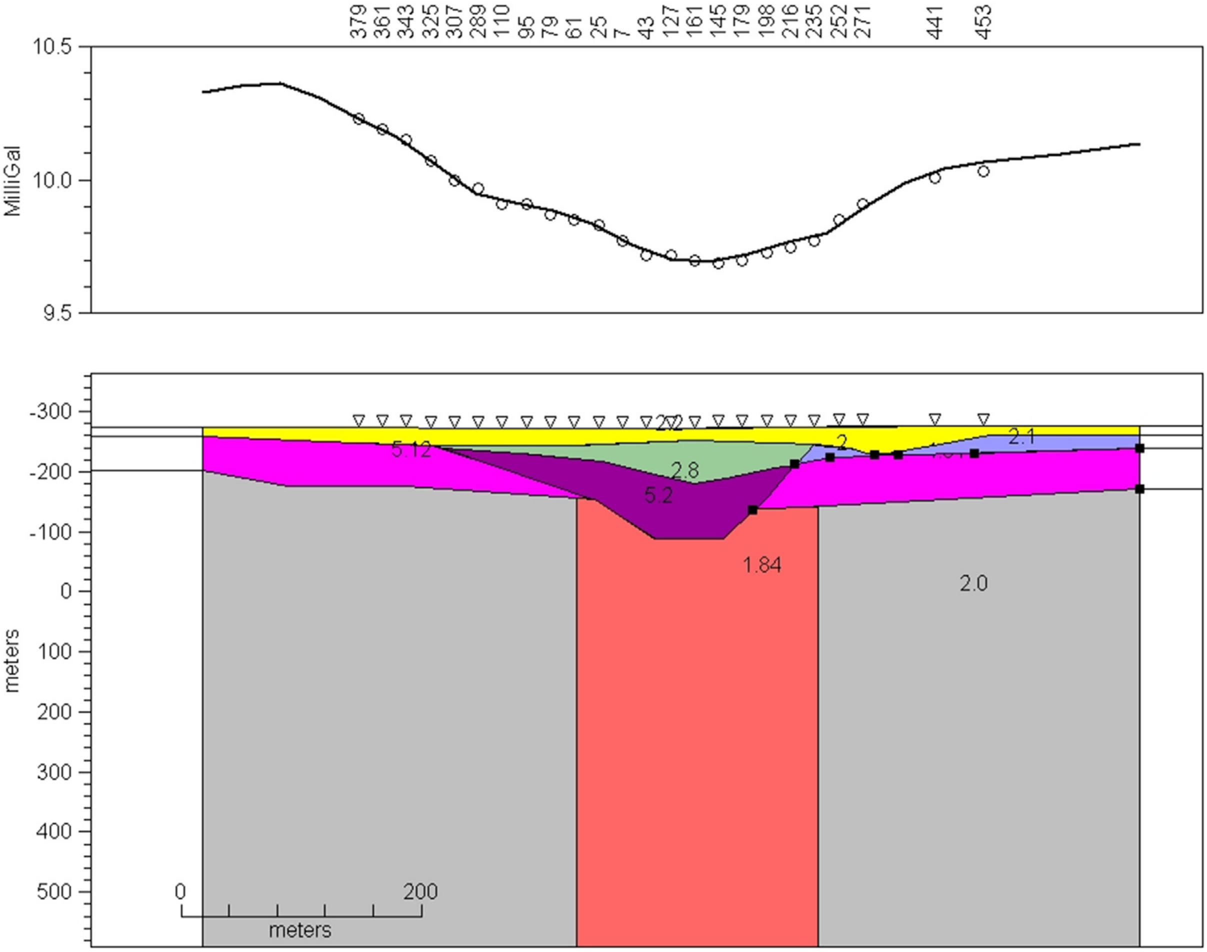


Fig. 10. Density model of strata and its theoretical response fitting to the observed Bouguer anomaly curve in the A–A' line (Falista St.) shown in Fig. 9a.

seam in a direction parallel to it. This factor caused a variation in the velocity of the rock mass deformation due to longwall movement in a direction parallel to the front of the longwall and the transfer of influences towards the surface on which the buildings were founded.

The movement of the blocks in the rock strata lying in the overburden of the exploited coal longwall depends on their natural structural divisibility (stratification, joint) and mining divisibility (width of caving zones). Under given conditions, the blocks of the Triassic layer in the tectonic disorder zone are trapezoidal, in which oblique sides are parallel to the tectonic or glacitectonic discontinuities. When these blocks move down, torsional movements may occur, which confirms the shape of the line correlating the centers of GPR anomalies registered in 2011 (Fig. 7). This line does not duplicate the projection of the longwall front on the terrain surface and deviates from it northerly in the eastern part of the analyzed area. This may indicate that the western part of the longwall overburden subsided faster than the eastern part. This movement was transferred to the Quaternary formations causing stresses and peripheral deformations of a rotational nature.

According to the numerical approximation of mining-induced surface deformations [15], during the movement of LP1 in 504 seam, the lateral strains varied between −12 mm/m and +6 mm/m. They were twice as high as the maximum forecast values corresponding to the 5th category of mining terrain according to the rules given by Kwiatek [16]. For a longwall panel 200 m wide, it means that in the case of block movement and concentration of strain along a single plane (discontinuity in the near-surface strata), the spread of the crack in the geological strata could range between 1.2 and 2.4 m. A very similar result was obtained from the interpretation of the GPR data.

5. Conclusions

The interpretation of the results of geophysical surveys described in chapters 3.1 and 3.2, presented in chapter 4 indicates the existence of a geophysical trace of the deformation in the rock mass caused by mining operations. In the presented geophysical images from the GPR and gravimetric methods, changes in physical properties (density and eclectic conductivity of subsoil formations) caused by discontinuous subsidence of the land surface, directly related to the exploitation of minerals in the past, are noticeable. Geophysical research has also provided data supplementing the knowledge about the structure of the geological strata lying in the subsoil of the buildings which suffered catastrophic damage in the Karb district. The survey results indicated that the geological structure of the Triassic and the Quaternary in the study area is strongly disturbed by mining and not sufficiently recognized. Gravimetric data reveal that it is highly probable that lead and zinc-bearing minerals have been displaced from a place of their origin to the south by the glacier movement. This could be a reason for the large variation of the coal longwalls overburden weight within the research area. Also, high energy seismic tremors which have occurred in the district in the recent past may originate in the overburden heterogeneity. The Quaternary and Triassic sediments, lying in the overburden of a hard coal deposit, are characterized by high variability of structural and mechanical features, which means that the geological and engineering conditions are highly complex. Forecasting the exploitation impact on the terrain surface in such areas requires the adoption of wider safety factors for predicted parameters of the surface deformation. Geophysical surveys can be helpful in this task, provided that they are done before the beginning of mining operations. Unfortunately, in this case, the research described in this article was carried out after the termination of mining due to rock mass movements larger than predicted ones.

Ethical statement

The author states that the research was conducted according to ethical standards.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of interest

The author declares no conflict of interest.

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