DOI 10.4467/21995923GP.20.008.13073 GEOINFORMATICA POLONICA
19: 2020

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IRREGULARITY OF POST MINING DEFORMATIONS AS INDICATOR REVEALING EFFECTS OF PROCESSES OF UNKNOWN ORIGIN IN AREA OF BOCHNIA

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Keywords: neotectonics, salt deposit, salt mining, vertical displacements, Chebyshev polynomials

Abstract

The presented work deals with the problem of terrain surface and rock mass deformation in the area of the Bochnia Salt Mine. The deformations are related to natural causes (mainly the tectonic stress of the Carpathian orogen) as well as anthropogenic ones related to the past mining activity conducted directly under the buildings of the town of Bochnia. The discussed characteristics of land surface deformation are important from the point of view of threats to surface features and contribute to spatial development. Particularly anomalous zones of observed subsidence basins are examined as places of second order deformation effects. The author presents a method of determinations of these anomalous areas and he discusses their origins.

NIEREGULARNOŚĆ ODKSZTAŁCEŃ POGÓRNICZYCH JAKO WSKAŹNIK UJAWNIAJĄCY EFEKTY PROCESÓW O NIEZNANYCH PRZYCZYNACH W REJONIE BOCHNI

Słowa kluczowe: neotektonika, złoża solne, górnictwo soli, przemieszczenia pionowe, wielomiany Czebyszewa

Abstrakt

Przestawiona praca dotyczy problematyki deformacji powierzchni i górotworu w rejonie Kopalni Soli Bochnia. Deformacje te związane są zarówno z przyczynami naturalnymi (głównie nacisk tektoniczny orogenu karpackiego), jak i antropogenicznymi związanymi z minioną aktywnością górniczą prowadzoną bezpośrednio pod zabudową miejską Bochni. Omówione charakterystyki deformacji powierzchni terenu są istotne z punktu widzenia zagrożeń dla obiektów powierzchni oraz są elementem planowania przestrzennego. Szczególnie przeanalizowane zostały strefy anomalne niecki obniżeniowej jako efekty drugiego rzędu deformacji. Autor przedstawił sposób ich wyznaczania oraz omówił genezę ich powstania.

1. INTRODUCTION

Bochnia is best known for its historic salt mine, which dates back to 12th century. The Bochnia Salt Mine was established probably in 1247, what makes it one of the oldest companies in the world. However, the mine ceased producing salt in 1990, it is still active as a tourist attraction. The object is outstanding due to its mining history but impressing geological setting too. The Bochnia salt deposit is situated at the front of the Carpathian overthrust. The very geological image of the deposit stirs the imagination and gives an idea of the collision of great tectonic units, where the role of the ram was played by a salt deposit, tectonically deformed in an extreme way. Mining operations carried out in this complicated geological environment had to face technical problems as large tensions activating convergence of underground passages and chambers. This process was the reason of terrain surface deformations and still observed subsidence is a remnant of old mining activity in Bochnia. Long time surveying measurements provided distribution of vertical displacements, which form subsidence basin. However spatial distribution of the displacements has not been varying much in many years, the decrease of their annual rates is noticeable. The distinctive feature of temporal vertical displacement distribution is certain irregularity of the subsidence basin geometry. So, vertical displacements demonstrated by benchmarks of the mine leveling network were analyzed. The aim was to determine zones of anomalous subsidence, which probably reveal combination of mining and other source influences. Analytical tools for separation of mining and natural (geological) influences are proposed by the author.

2. GEOENVIRONMENT

The area of the study is situated on the river Raba, in the Babica stream valley, at the boundary of the Carpathian Foothills and Sandomierz Basin and at the boundary of two geological units: the Outer Carpathians and the Carpathian Foredeep.

The geology of the salt deposit in Bochnia is well recognized due to long-time mining activity. It was widely discussed in numerous papers (Poborski, 1952; Poborski and Skoczylas-Ciszewska, 1963; Garlicki, 1968; Garlicki, 1979; Wiewiórka et al., 2006; Wiewiórka et al., 2008; Wiewiórka et al., 2009). The most significant feature of the area is complicated tectonics, whose recent tectonic activity was already discussed by Liszkowski (1982) or Toboła and Bezkorowajny (2006).

The Bochnia salt deposit is just situated in a narrow belt of folded Miocene strata, called the allochthonous unit, which spreads along the northern boundary of the Carpathians (Fig. 1).

Uplift of the deposit was related to overthrust movements of the Flysch Carpathians over the strata of the Carpathian Foredeep. Due to these movements, the salt series were thickened and uplifted towards to the surface (see: Poborski, 1952; Poborski and Skoczylas-Ciszewska, 1963; Garlicki, 1968; Garlicki, 1979). Investigations on recent tectonic movements of the Outer Carpathians have been ongoing for several de-

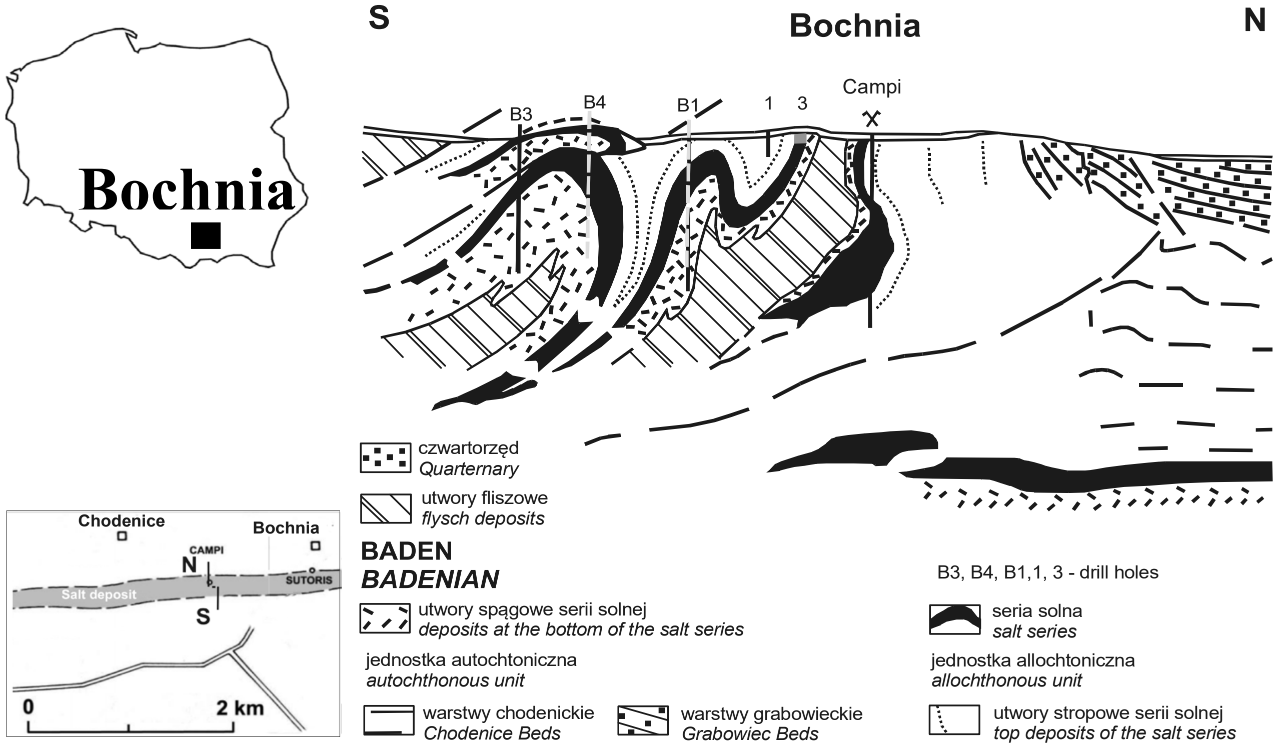

Fig. 1. Bochnia. Geological cross-section through the salt deposit (after Garlicki, 1968)
Ryc. 1. Bochnia. Przekrój geologiczny przez złoże soli (wg Garlicki, 1968)

cades, involving successive generations of researchers. According to Zuchiewicz there are several uplifted tectonic zones, with similar uplift intensities, rates and durations in different parts of the orogen (Zuchiewicz, 2001). These zones are aligned subparallel to the Carpathian belt, and the Bochnia area is one of them.

Tectonic setting reflects actions of geological forces in the past and probable recent stress distribution that has probably been preserved from the Miocene to the present day. Furthermore, they may be the forces that currently manifest in the form of movements of the rock mass and the terrain surface or more precisely: they disturb the characteristics of the deformations caused by old mining operations. The noticeable tectonic deformations and the observed by geodetic methods movements of the rock mass have 3 sources (Poborski 1982):

- tectonic – tectonic stress of the Carpathians,
- mining – the effect of plastic (most often) convergence of underground excavations,
- halotectonic (pushing salt masses upwards).

Tectonic activity of the area has been a subject of widespread interest of successive generations of scientists. According to Liszkowski (1982) effects of geological processes observed nowadays: as suffusion, land mass movements (as landslides) observed at the front of the Carpathians are manifestations of their neotectonic activity. There are numerous landslides in

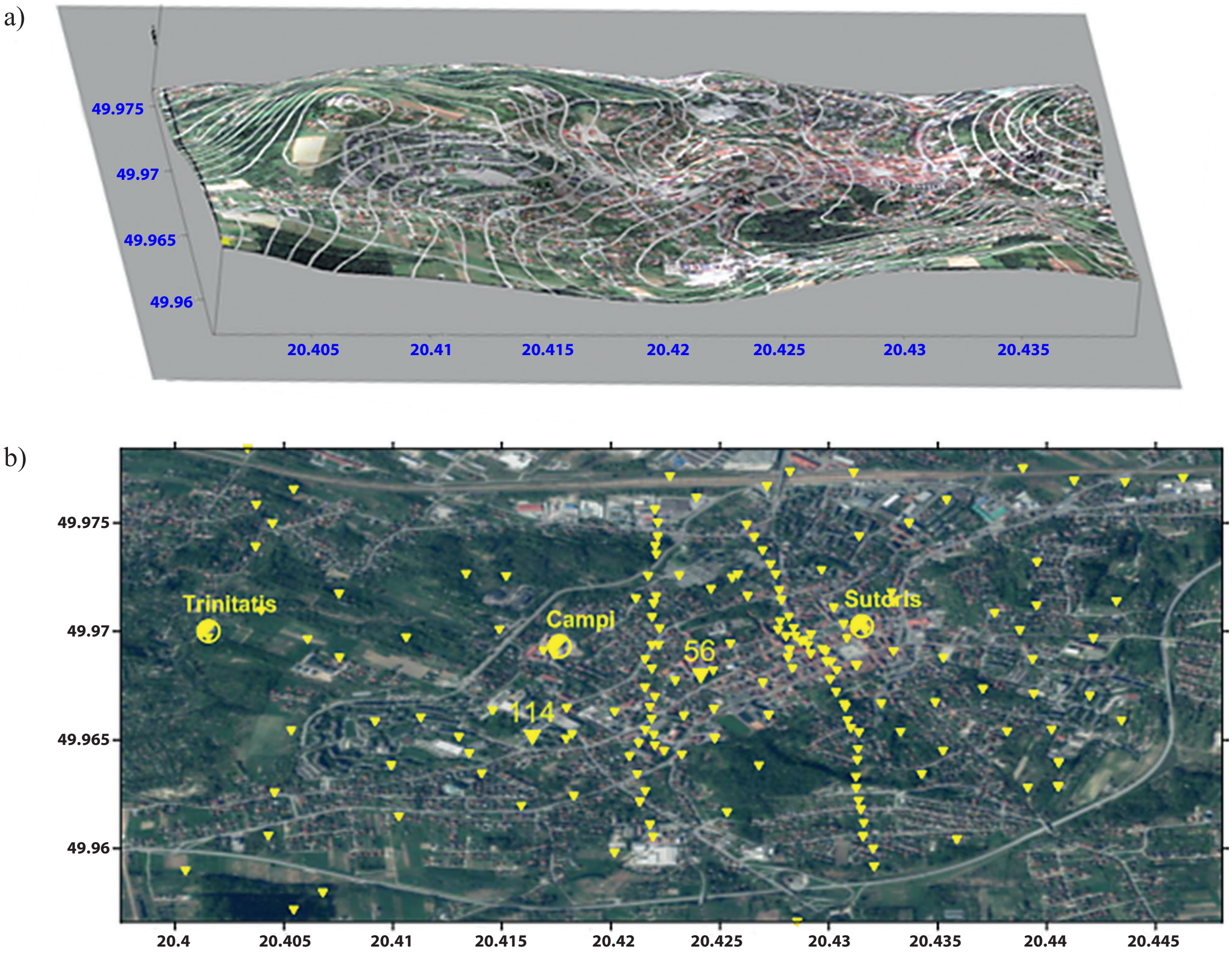

Fig. 2. Bochnia. Situational map of the area with locations of benchmarks and mining shafts: a – aerial view with topographic contour lines; b – base maps from Google Maps (September, 2020). Horizontal coordinates: latitude, longitude

Ryc. 2. Bochnia. Mapa sytuacyjna terenu z lokalizacją reperów i szybów górniczych: a – widok z lotu ptaka wraz z warstwicami; b – na podkładzie mapy pozyskanej z portalu Google Maps (wrzesień, 2020). Współrzędne horyzontalne: szerokość i długość geograficzna

Bochnia (active, periodically active, inactive) and areas exposed to landslides. The landslides in Bochnia cover quite large areas: in total, approximately 26.8 ha of urban area are within the range of active and periodically active landslides (Bereś and Olbromska-Matusiak, 2020). Geomorphologic conditions, characterized by steep slope gradients favor the landslide hazard in Bochnia (Fig. 2).

Some more geological manifestations of tectonic stress in underground, within the salt deposit after its final formation are discussed in (Toboła and Bezkorowajny, 2006). Underground galleries and passages of the Bochnia Salt Mine are usually N-S oriented i.e., in a direction perpendicular to the strike of the salt deposit and parallel both to the general movement of the Carpathians and to the orientation of the stress field, as estimated by Jarosiński (1998). Observations in the Bochnia mine show differences in the convergences of mining excavations in some areas of the rock mass according to their orientations to the deposit's strike and to the margin of the Carpathians (Toboła and Bezkorowajny, 2006).

Orientation of the historical excavations reflects stress field in underground: being oriented in that way they are usually well preserved and they are considered to be stable in the long term (Toboła and Bezkorowajny, 2006; Szczerbowski et al., 2016). This existing stress and its northward orientation may be evidence of recent movements of the Carpathians.

Results of some geodetic measurements show also effects of tectonic stress (Szczerbowski et al., 2016). Outline of the terrain surface deformations shows effects that are not related to observation errors or benchmarks instability, as they are observed in certain zones. The method of their determination, their localization, and an attempt to explain their origin are discussed in the further part of the work.

3. SURVEYS

Geodetic underground measurements are usually devoted to practical problems in mining or tunnel engineering. Mine surveying methods are also carried out in the Bochnia mine for engineering purposes as determination of displacements of control points. Detailed examination of the data was performed by the author to detect additional effects induced by geological processes. Geodetic monitoring of historical excavations was involved in efforts to preserve the Bochnia mine as object of outstanding universal value, hence it was entered on World Heritage List. It "illustrates the historic stages of the development of mining techniques in Europe from the 13th to the 20th centuries: both mines have hundreds of kilometers of galleries with works of art, underground chapels and statues sculpted in the salt, making a fascinating pilgrimage into the past" (according to https://whc.unesco.org/en/list/32).

Mine surveying in the Bochnia Salt Mine has a long history, addressing geological, mining, networking (cartographic) matters. The historical documents devoted to mine surveying survived through the ages, but the geodetic infrastructure itself (control points, benchmarks) as well, so they are still of use today. It is essential to monitor still existing deformations caused by compression of old excavations as a response of surrounding rocks to loads. Fortunately, plasticity of rock salt is the main "damper" in the cave-in process (Jeremic, 1994), so the old excavations in the Bochnia Salt Mine are still maintained.

The mine's surface leveling network consists of both wall and ground benchmarks (only about 25% of total number of control points), and the network itself is mainly dispersed. The exception is the group of benchmarks forming the B-B line (ground benchmarks), which passes through the area latitudinally (Fig. 2).

The spread of benchmarks is quite uneven and many, unfortunately, lack them. However, taking into account the relatively small differentiation of the distribution of vertical displacements and the stability of their changes over time, it can be concluded that their number is sufficient for determination of subsidence basin. Unfortunately, a gradual decrease in the number of these benchmarks is noticeable. They are damaged or destroyed mostly due to renovation works of buildings in Bochnia.

Leveling measurements carried out over the years in the mining area of the Bochnia Salt Mine covered area of 7.6 km^2 (approximately 5 × 1.5 km) maximally (Fig. 2). However, the most of the benchmarks are placed in the area of 3.5 × 1.5 km (approx. 5 km^2). Although the first benchmarks were established in 1952 (about 20), and the next ones in 1972 (about 40), the first useful information about the movements of the city's terrain surface was obtained only in the 1980s.

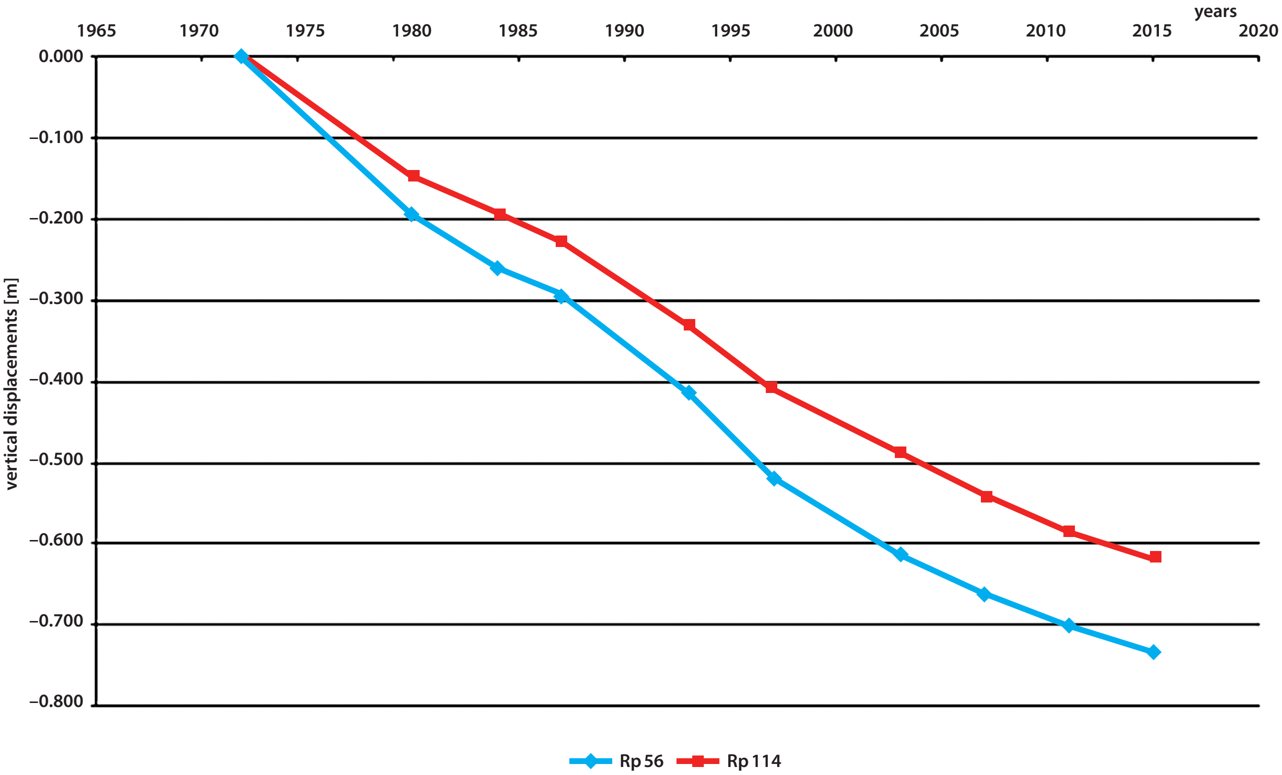

Fig. 3. Vertical displacements of Rp56 and Rp114 benchmarks from 1972 to 2015
Ryc. 3. Przemieszczenia pionowe reperów Rp56 i Rp114 w latach 1972–2015

In that time, an observation network with a satisfactory number of points was established. Therefore, heights of benchmarks determined by measurements carried out in 1980 were assumed as reference in the next analysis. Then the number of benchmarks was 135 and they covered a large part of the studied area. Thus, temporary vertical displacements from particular years were analyzed in relation to 1980, and vertical displacements for the period 1980-2015 were assumed here as total vertical displacements.

Temporal vertical displacements observed in the area by years are outlined by plot on Fig. 3. There are height changes of benchmarks Rp 56 and Rp114 located in the central part of the subsidence basins (Fig. 2). Presented displacement performance in successive year is typical and temporal changes demonstrated by the other benchmarks are similar.

Deformations and their changes in time can be expressed by another parameter – annual velocity of vertical displacements. This is much comparable for vertical displacements evaluated in different time intervals. So, in the further analysis just the annual rates of vertical displacements of the benchmarks are analyzed and their distribution in the area of Bochnia. Then the next figure shows average annual velocities of vertical displacement of the Rp56 and Rp114 benchmarks between 1980 and 2015 (Fig. 4).

As it shown the annual rates have been decreasing successively, although the decrease has been getting slower and slower. It outlines a process observed in the area: the clear majority of benchmarks show decrease of subsidence rates. However, there is a group of benchmarks whose characteristics of subsidence are out of this trend. They show uplift or increased values of subsidence. It is possible that in the case of such points there are measurement errors or local effects, e.g. of landslide origin. Anomalous vertical displacements of a larger group of benchmarks may have geological (e.g. drainage) or mining causes (impact of a group of shallow workings of the old mining operation). Identification of such anomalous regions may be possible based on the appropriate analysis, which is presented below.

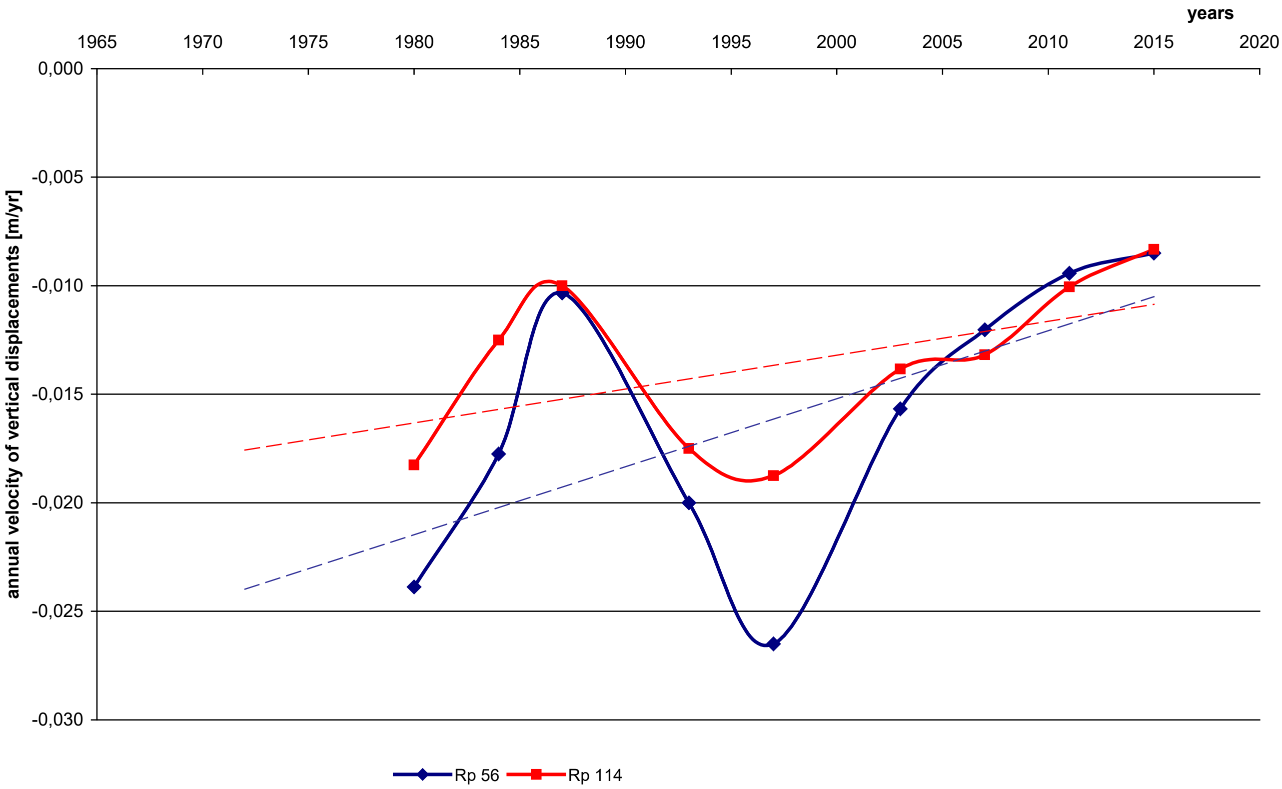

Fig. 4. Annual rates of vertical displacements (with linear trends) of Rp56 and Rp114 benchmarks between 1972 and 2015
Ryc. 4. Roczne prędkości przemieszczeń pionowych (z trendem liniowym) reperów Rp56 i Rp114 w latach 1972–2015

3. NUMERICAL ANALYSIS OF SPATIAL DISTRIBUTIONS OF VERTICAL DISPLACEMENTS

The main goal of the study is separation of deformations caused by old salt mining in Bochnia and the other effects, mainly resulted from geological factors such as drainage, subrosion etc.

In mining practice, theories of mining influences are based usually on the Gaussian distribution of mining influences, which are expressed in the form of so called influence function with empirically determined parameter values. In Poland the most popular approach in modelling and calculating ground movement, however basically applied for coal mining areas, is the influence-function method by Knothe (Knothe, 1959; Knothe, 1969; Knothe, 1970, Knothe, 1984).

In the analyzed case the Gaussian distribution of the effects of salt mining is assumed but the parameters of influence function are unknown. The determination of "theoretical" model of subsidence basin is based on scattered data – annual rates of vertical displacements evaluated by leveling surveys of benchmarks of the mine's network in Bochnia. This theoretical model is a smoothed surface, which geometry can be described by polynomials approximating acceptably close influence function based on Gaussian distribution of deformations (vertical displacements) induced by mining (Szczerbowski, 2001). In practice, the 6th degree polynomial satisfactorily approximates the subsidence basin, which is geometrical distribution of subsidence data, or precisely: the Budryk-Knothe function that describes it (Szczerbowski, 2001). In order to obtain the most reliable results of this modeling, the following steps were performed:

- geometric analysis of distributions for different periods – modeled and observed values,
- approximation with the use of Chebyshev polynomials: 3rd, 4th, 6th and 10th degrees – the polynomials were assumed as sufficient to approximate subsidence distribution,
- comparative analysis of modeled subsidence (resulted from polynomial approximation) and de-

termined discrepancies between the theoretical and the vertical displacements determined by measurements (residuals of the approximation by polynomials),
- estimation of differences between observed and the modeled values of subsidence were residual values. They formed zones of negative or positive deviations (residues),
- interpretation of evaluated zones of anomalous vertical displacements.

It was assumed that subsidence that should be revealed on terrain surface is a result of summation of mining effects (caused by compression of underground workings), which can be approximated by Chebyshev polynomials and the others, which interference the direct effect of mining. This approximation of spatial distribution of vertical displacement distribution allows a determination of disturbances in spatial data – zones of anomalous vertical displacements.

Assuming these disturbances resulted from effects of natural processes taking place in the rock mass (not related to mining), the presented approach identifies areas, where their effects occur. This is important for separation mining, i.e., primary and secondary effects, especially in a case, where influence of mining workings on terrain surface is impossible to be modeled (as in the case of the Bochnia Salt Mine).

The method was applied before for vertical displacements observed in Inowrocław, another already historical salt mining area in Poland (Szczerbowski, 2005).

So, in the first stage of the displacement analysis, distributions of subsidence were determined for the periods: 1980–1984, 1980–1987, 1980–1993, 1980–1997, 1980–2003, 1980–2007, 1980–2011, 1980–2015. These displacements formed temporary subsidence basins, i.e. which were formed between particular years in the period 1980-2015. (Fig. 5) presents vertical displacements in Bochnia evaluated in chosen periods in the form of contour maps and spatial maps for selected periods, respectively.

As it is shown the subsidence basin has an oval shape and it is latitudinally extended, what corresponds to the orientation of post mining excavations. Another distinct feature is it asymmetry: northern and eastern parts of the basin are more inclined than their opposite sides. In the period 1980–2015, the highest rate of vertical displacements was demonstrated by Rp133 benchmark – 0.018 m/year. This benchmark, together with a fairly large group of benchmarks is concentrated in a small area of approx. 500 m^2 which is situated in the center of the subsidence basin. It is approx. 300––400 m southeast of the Campi shaft. All of the above benchmarks showed average annual subsidence of over 0.015 m/year.

The first obvious observation was certain variability of geometry of particular basins. It is a paradoxical fact, considering that the temporal distributions of vertical displacements of individual benchmarks presented before are characterized by high stability. However, as already mentioned, the high variability of the number of benchmarks involved in levelling measurements in particular years, as well as their loss combined with the reestablishment of new points is the main cause of varying in time geometry of the determined contour lines (isolines) outlining vertical displacements.

Variability in the time-spatial distribution of vertical displacements of terrain surface in Bochnia does not affect clear regularities:

- the center of the subsidence basin is located in a narrow strip roughly between the Campi and Sutoris shafts,
- the subsidence basin is stretched latitudinally, which is justified in the mining situation,
- moreover, the subsidence basin is characterized by an outstanding lack of symmetry and local variations, including temporary uplifts.

The general picture of temporary vertical displacements of the terrain surface also includes local disturbances in the geometry of individual subsidence basins. They take the form of local subsidence basins, surprising sudden changes in the course of the isolines, which is not justified in the mining situation due to the considerable depth of mine workings. This irregularity in the image of individual subsidence basins was just the reason for presented application of polynomial approximation of height change distributions.

The distributions of mentioned above temporary subsidence of time intervals of 1980–2011 and 1980––2015 were approximated by Chebyshev polynomial with two variables of: 3rd degree, 4th degree, 6th degree, 10th degree (Fig. 6 and Fig. 7). Two time intervals and the significant number of applied polynomials were chosen to outline differences in obtained results. As it is shown in various time intervals distribution of areas of

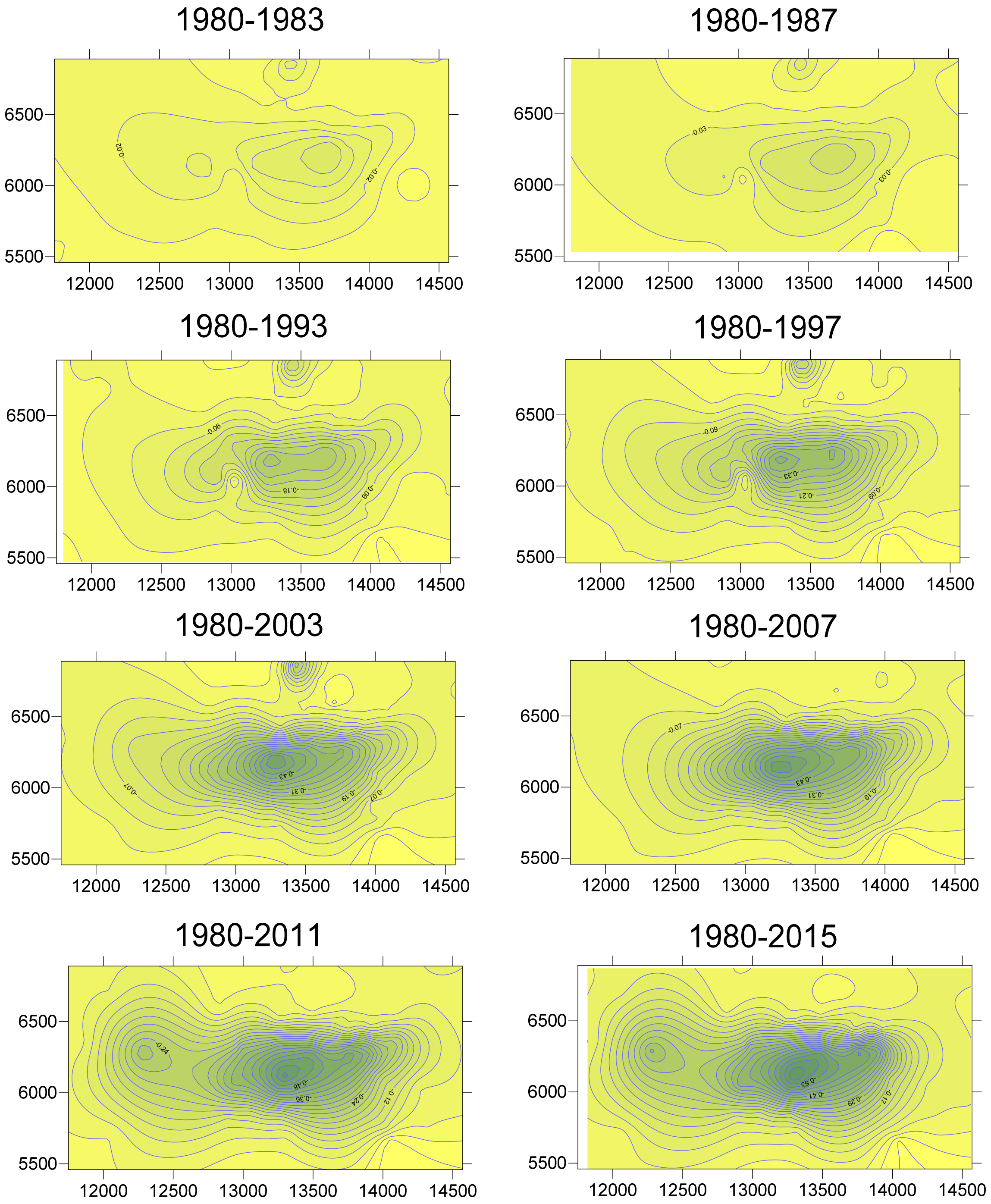

Fig. 5. Bochnia. Temporary vertical displacements [mm] in time intervals. Local coordinate frame
Ryc. 5. Bochnia. Okresowe przemieszczenia pionowe [mm] w latach. Lokalny układ współrzędnych

positive and negative residues don't differ very much. Fig. 6 and Fig. 7 present modeled distribution of subsidence as well: contour lines are more smoothed (more or less dependably on degree of polynomial applied for approximation) but mentioned features are maintained, especially in case of approximation of higher degree polynomials. It's worth remarking that the residues occurred more or less closely in the same areas in all

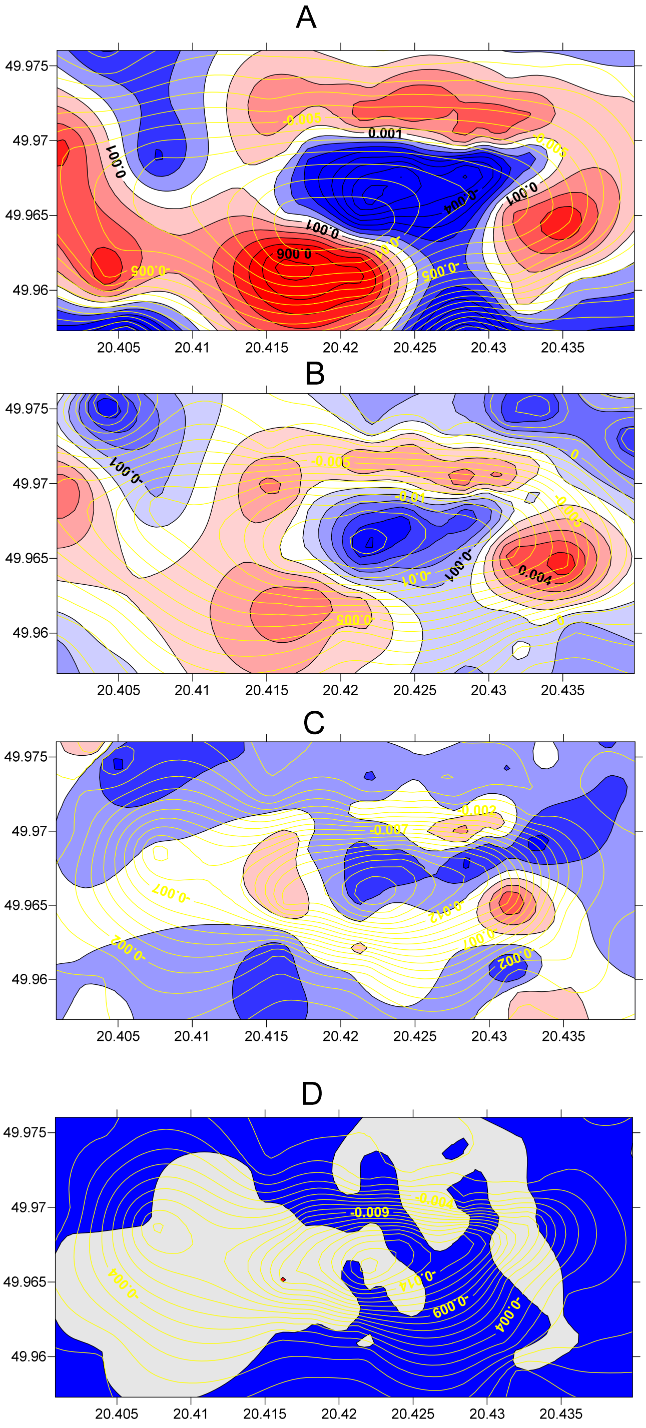

Fig. 6. Approximation of annual rates of vertical displacements in the period of 1980–2011. Modeled rates (yellow contour lines) and their residues (color map; negative values in blue, positive values in red) based on approximation by Chebyshev polynomials of: A – 3rd degree, B – 4th degree, C – 6th degree, D – 10th degree. Horizontal coordinates: latitude, longitude

Ryc. 6. Aproksymacja rocznych przemieszczeń pionowych w latach 1980–2011. Modelowane wartości (zaznaczone żółtymi liniami) i ich rezydua (mapa kolorów; wartości ujemne w kolorze niebieskim, wartości dodatnie w kolorze czerwonym) na podstawie aproksymacji wielomianami Czebyszewa: A – 3. stopnia, B – 4. stopnia, C – 6. stopnia, D – 10. stopnia. Współrzędne poziome: szerokość i długość geograficzna

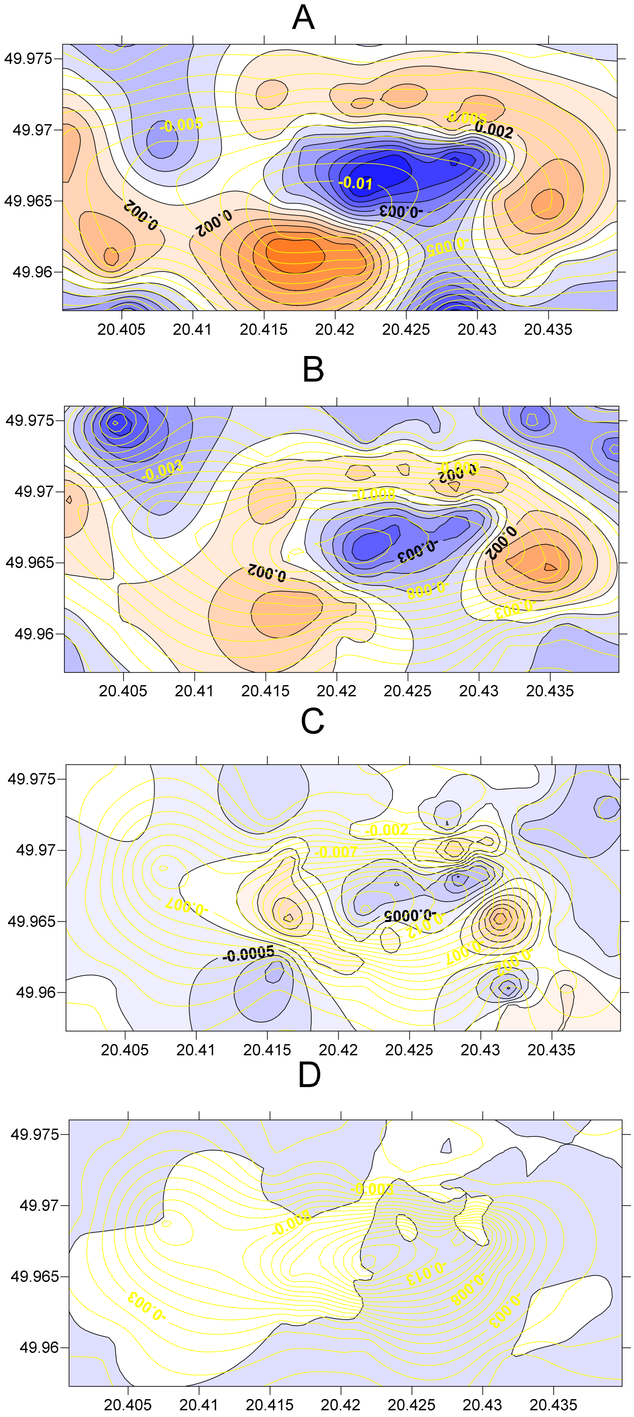

Fig. 7. Approximation of annual rates of vertical displacements in the period of 1980–2015. Modeled rates (yellow contour lines) and their residues (color map; negative values in blue, positive values in red) based on of approximation by Chebyshev polynomials of: A – 3rd degree, B – 4th degree, C – 6th degree, D – 10th degree. Horizontal coordinates: latitude, longitude

Ryc. 7. Aproksymacja rocznych przemieszczeń pionowych w latach 1980–2015. Modelowane wartości (zaznaczone żółtymi liniami) i ich rezydua (mapa kolorów; wartości ujemne w kolorze niebieskim, wartości dodatnie w kolorze czerwonym) na podstawie aproksymacji wielomianami Czebyszewa: A – 3. stopnia, B – 4. stopnia, C – 6. stopnia, D – 10. stopnia. Współrzędne poziome: szerokość i długość geograficzna analyzed time intervals and in a particular polynomial approximation. This means that the irregularity was somewhat "inscribed in" the distribution of vertical displacements and it resulted from non-mining reasons. And locations of certain zones of anomalous vertical displacement rates do not seem to be accidental.

Due to the use of various polynomials – more or less precisely fitting into the distributions of the analyzed vertical displacements, anomalous zones are obtained with different area size. So: fitting with a 4th degree polynomial results in residuals appearing in larger areas. They could be called 1st degree residuals (and the corresponding anomalous zones – 1st degree zones). For a 6th and 10th degree polynomials these are respectively 2nd degree residuals (zones) and 3rd degree residuals (zones). 10th degree polynomial very good fits into the vertical displacement distribution and areas of anomalous zones is wide spread but values of residue is not significant. The zones in this case are not very useful for investigation of additional effects in outline of deformations.

The obtained residuals could be random but considering their replicability in successive periods that seems pretty unlikely. On the other hand, the 1st order anomalous zones could be considered as resulted from inadequacy of the 4th degree polynomial fit into the geometry of an atypical geometry of subsidence basin, formed also by shallow, abandoned and not documented old galleries. In the case of 3rd degree polynomial fitting values maximal/minimal residues (several mm) is about 40% of maximal/minimal value of subsidence rate, in the case of 4th degree polynomial fitting – about 30%, in the case of 6th degree polynomial fitting – about 20% and in the case of 10th degree polynomial fitting the value of maximal residues is about 5% of maximal/minimal value of subsidence rate.

As it was mentioned Chebyshev's polynomial of 6th degree was accepted as sufficient to approximate the distribution of subsidence (or rather Budryk-Knothe's function describing it). So, differences between values determined by measurements and values modeled on the base of polynomial fitting (residues) should be minimal and their distribution should be random. Otherwise the obtained residues convey information about a phenomenon causing additional vertical displacements distorting deformations caused by mining. The higher degree polynomials produce filtered information; however it still can be significant and useful.

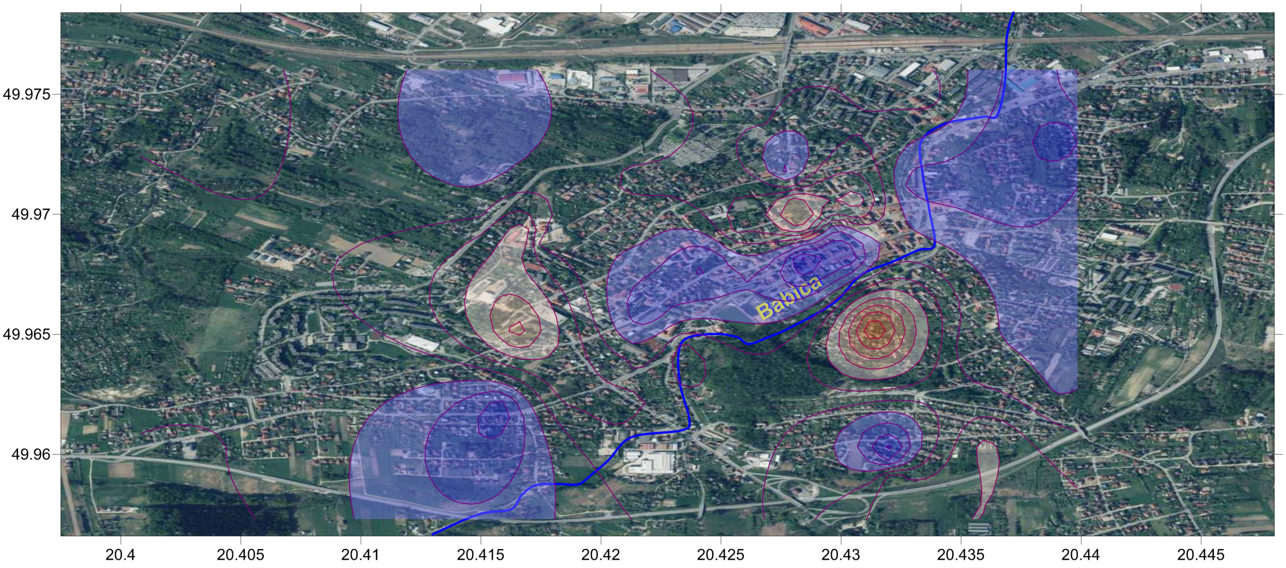

Fig. 8. Bochnia. Zones of anomalous vertical displacements observed in the period of 1980–2015 determined on the base of 6th Chebyshev approximation (areas of negative rates in blue and areas of the positive rates in red). Base maps from Google Maps (September, 2020). Horizontal coordinates: latitude, longitude

Ryc. 8. Bochnia. Strefy anomalnych przemieszczeń pionowych obserwowanych w latach 1980–2015 wyznaczone na podstawie aproksymacji wielomianów Czebyszewa 6. stopnia (obszary współczynników ujemnych w kolorze niebieskim i obszary współczynników dodatnich w kolorze czerwonym). Na podkładzie mapy pozyskanej z portalu Google Maps (wrzesień, 2020). Współrzędne poziome: szerokość i długość geograficzna

The significant anomalous zones are exposed by overlaying on situational base map for better identification of their locations. Fig. 8 presents the zones determined on the base of 6th Chebyshev approximation of subsidence of terrain surface in Bochnia between 1980 and 2015. They are presented on Fig. 7C as well. In this outline the contour lines are removed. As it is shown there are 5 zones of "smaller values" of subsidence rates than modeled values, i.e., they are areas where subsidence is affected by other sources than mining. They increased the subsidence rates – as it was mentioned – about 20%. The south western zone is situated on steep hillside of the Carpathians and the probable reason of anomalous vertical displacements is downhill creep. Another zone of the negative values of residues is in the eastern part of the area. Its western part is affected by documented landslides. The next one, situated central part of the city is extended along the Babica stream. Geometry of this zone of negative residue values and its placement suggests influence of the stream. However, this zone is situated between the Campi and the Sutoris shafts and it may be resulted from the specific effects of old shallow, abandoned and not documented workings of the mine. Another zone of the negative values is located on hill in the north western part of the city. The probable reason of anomalous vertical displacements there is downhill creep.

There are 3 zones of "too high values". So, annual rates of vertical displacements (subsidence) are much smaller than modeled values there. Their area size is rather small on this model of residues determined on the base of approximation of 6th degree polynomials. But they occur in the other models as a significant area size of the city. There is no credible explanation of the zones of positive residue values. They could be a numerical effect of polynomial fitting (result of asymmetric distribution of subsidence values). The only physical explanation of the reason of decreased subsidence values is an uplift factor. The only one in the area is halotectonic movement of salt structure towards the surface. This problem should be explained with the use of other methods.

4. CONCLUSIONS

In the area of Bochnia, subsidence as an effect of old mining is still being observed. Distributions of the long-term vertical displacements demonstrated atypical geometry of temporary subsidence basins. Specific variability of the course of isoclines (lines of constant vertical displacement rate) depicting subsidence suggests that the deformation processes are under additional influence (not related to effect of convergence of old mining galleries and chambers). Polynomial approximation of subsidence basin was proposed here to determine the area of anomalous vertical displacements. The author assumed 6th degree polynomial as sufficient for approximation of influence function and he applied it as a tool for numerical separation of deformation caused by mining and the other sources. The residues between observed and modeled values were presumed as anomaly in deformations, which amounted maximally to 20% of maximal influence of convergence caused by documented excavations of the Bochnia Salt Mine. Values of the residues are of negative and positive character, which in practice means too low (decreased) or too high (increased) subsidence.

The zones of negative values of anomalies are usually situated on a steep hillside and between the main shafts of the mine, where mining operations were concentrated since 13th century and many old shallow workings were situated. Currently, they are abandoned, collapsed and not documented. This zone is surrounded by the area of subsidence of anomalously decreased values (zones of positive residues). Their origin is to be investigated by other methods.

Although the presented analysis is based on numerical method of approximation spatial distribution of data (subsidence values), it is not a quantitative analysis. It should be considered as a proposal to determine areas of atypical deformations that should be investigated further with application or it provides initial identification the causes of the phenomenon (anomalous vertical displacements).

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