GOSPODARKA SUROWCAMI MINERALNYMI

Tom 25 2009 Zeszyt 3

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Impact of tectonics on ground deformations caused by mining activity in the north-eastern part of the Upper Silesian Coal Basin

Introduction

Mining and postmining areas are threatened with different kinds of terrain deformations. A character of those deformations depends on many factors like volume and type of exploitation, and geological and hydrogeological conditions. A continuous monitoring of ground deformations and analysing its results together with other data (e.g. geological and mining) can help to define the origin and mechanism of terrain displacements. It is very important in increasing the operational and public security in mining and post-mining areas.

In this work a correlation between values of ground deformations measured in PS (Permanent Scatterers) points and their locations (in relation to main faults) was studied. The studied region includes mining areas of seven coal mines: “Kazimierz-Juliusz”, “Sosnowiec”, “Saturn”, “Paryz”,”Grodziec”, “Jowisz”, “Porabka-Klimontow”, that are part of the Dabrowskie Coal Basin. Among the above-mentioned coal mines, only the “Kazimierz-Juliusz” mine is productive and the others are dormant mines. Despite the fact that exploitation was finished several years ago, it was found that mining areas still suffer from the subsidence. Small and long-period ground deformations were measured using PSInSAR (Permanent Scatterers Interferometry Synthetic Aperture Radar) technique, which is dynamically developed branch of satellite radar interferometry.

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1. An outline of geological structure of the study region

The studied region that includes mining areas of selected mines of the Dabrowski Coal Basin has a very complicated geological structure. It is a zone with fold-block tectonics (Idziak et al. 1999; Pilecka 2006). The dense net of faults is characteristic of the region. The throws of the faults range from several dozens to more than 350 m.

A main dislocation in this area is the Bedzinski fault with NW-SE strike. The throw values of this fault range from 50 m (SE) to 200 m (NW). The Bedzinski fault is crossed by many faults with meridional strike. In this work only faults with throws larger than 50 m were taken into account (Fig. 1.1).

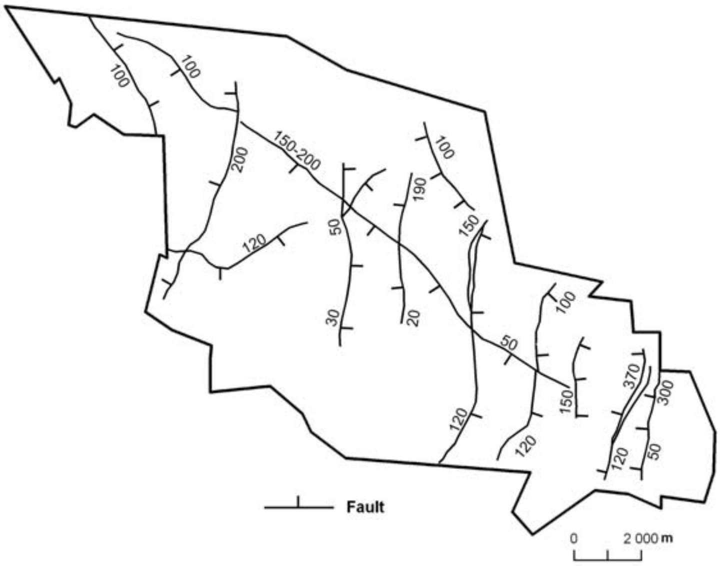

Fig. 1.1. Area of study with locations of main faults and values of their vertical displacements

Rys. 1.1. Obszar badań z zaznaczonymi głównymi uskokami oraz wartościami zrzutów uskoków

2. PSInSAR data

PSInSAR (Permanent Scatterers Interferometry Synthetic Aperture Radar) technique is an improvement of wide used InSAR method (Perski 1999; Smith 2002; Mirek 2006). The PSInSAR exploits set of few dozen of radar images in order to measure small, long-period ground deformations in PS points. PS (Permanent Scatterers) points are stable radar targets that have stable in time amplitude and phase in each exploited radar image (Ferretti et al. 2001). PS points correspond with objects on the ground like buildings, bridges, viaduct, outcrops and etc. PSInSAR method gives information only about small deformations not larger than several centimeters per year. This limitation is connected with the length of waves used by the SAR system. The accuracy of this technique is very good. It allows measuring ground displacements of the order of 0.1 mm/yr. The PSInSAR method can be used to monitor urban areas where a density of PS points can be higher than 100 PS/km^2. This technique exploits archival radar images hence it gives us a possibility to study values and dynamics of previous ground deformations.

In this work the exploited PSInSAR data were obtained as a result of radar images processing and the images were taken by ESA's satellites (ERS-1, ERS-2 and ENVISAT).

For the study area the values of ground displacements were measured for 24,725 PS points. Their spacing is very irregular (Fig. 2.1). PSInSAR data derive information about small, long-period terrain deformations that occurred in the study region between years 1992 and 2003. Basic statistical indicators for average annual motion rate measured by the PSInSAR technique are presented in Figure 2.1.

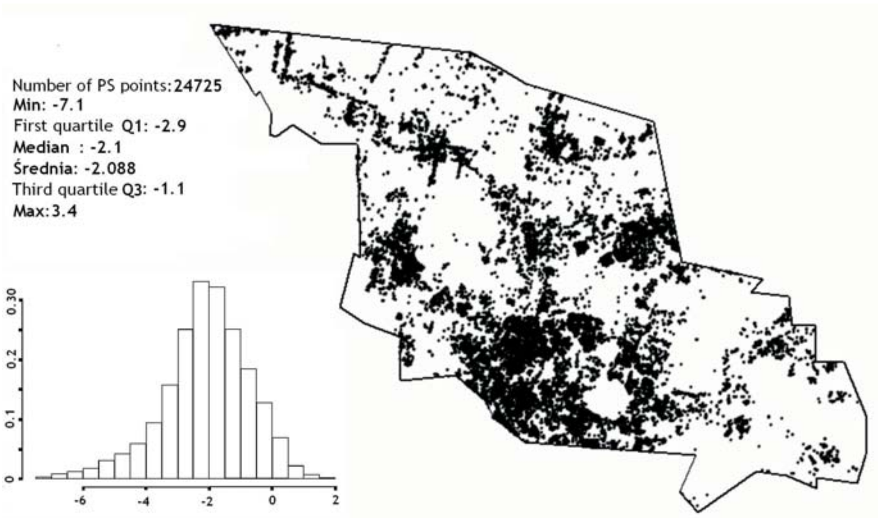

Fig. 2.1. PS points locations in the mining areas of Dabrowskie Coal Basin and basic statistical indicators for values of average annual motion rate [mm/yr]

Rys. 2.1. Rozmieszczenie punktów PS na terenach górniczych kopalń Zagłębia Dąbrowskiego oraz podstawowe wskaźniki statystyczne dla średnich szybkości deformacji terenu [mm/rok]

3. Analysis of PSInSAR data

The aim of PSInSAR data analysis performed in this work was to study how values of ground deformations measured in PS points depend on their locations referred to position of selected faults. This work is an important part of the spatial-temporal analysis of PSInSAR data and it is a continuation of researches connected with ground displacements monitoring using the PSInSAR technique (Leśniak et al. 2007; Leśniak et al. 2008).

In the first part of the analysis the values of ground deformations were interpolated in points that were not stable radar targets. In order to perform this task, the inverse distance weighted (IDW) interpolation was used. Results of interpolation were presented in Fig. 3.1.

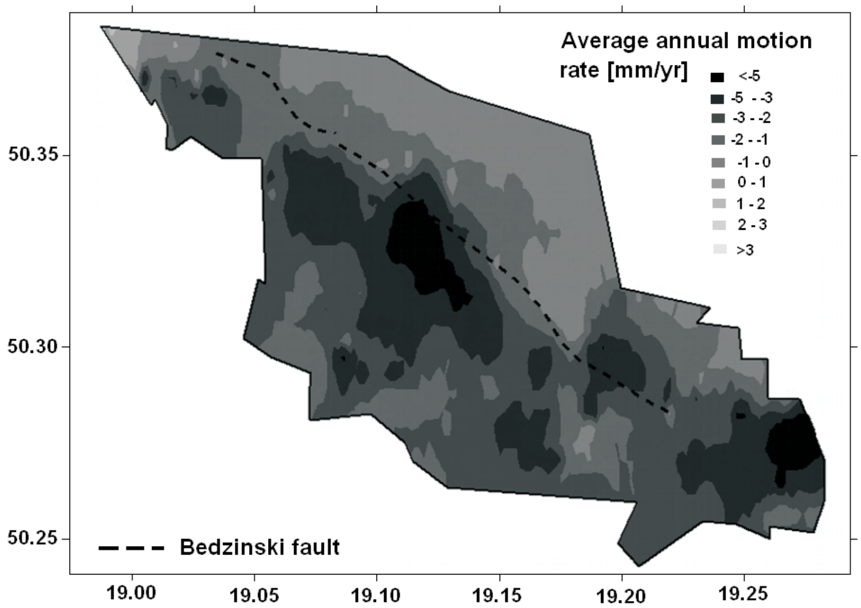

Fig. 3.1. Values of average annual motion rates estimated using inverse distance interpolation method

Rys. 3.1. Wartości średnich szybkości deformacji terenu wyznaczone za pomocą metody odwrotnych odległości

The line of the Bedzinski fault was marked in the map. The difference between average annual subsidence rates for the NE and SW parts of study region can be seen in Fig. 3.1. A hypothesis that the values of ground deformations are connected with the Bedzinski fault was verified. In order to study the impact of the tectonics on ground deformations it was necessary to perform a more detailed analysis.

Based on the map of interpolated values of ground deformations, the values of subsidence were checked along five lines in SW-NE direction (Fig. 3.2A). The changes between values of terrain deformations for upthrown and downthrown parts of the Bedzinski fault can be clearly seen in the profiles performed for lines with numbers 3, 2 and 4 (Fig. 3.2).

In the next part of the work, the trend analysis was preformed. It was done for several different directions. The trend in the values of ground deformations was observed (Fig. 3.3.) only for SW-NE direction (perpendicular to the line of the Bedzinski fault). The values of subsidence measured in PS points decrease from SW to NE. It can be seen in Fig. 3.3 that there is no trend in data in direction from NW to SE (parallel to the line of the Bedzinski fault).

In the following part of the described work the one-way analysis of variance was performed. This analysis was done in order to study if the average values of ground deformations in the downthrown and upthrown blocks of selected faults are different. The analysis of variation was performed separately for the Bedzinski fault and for faults with meridional strikes.

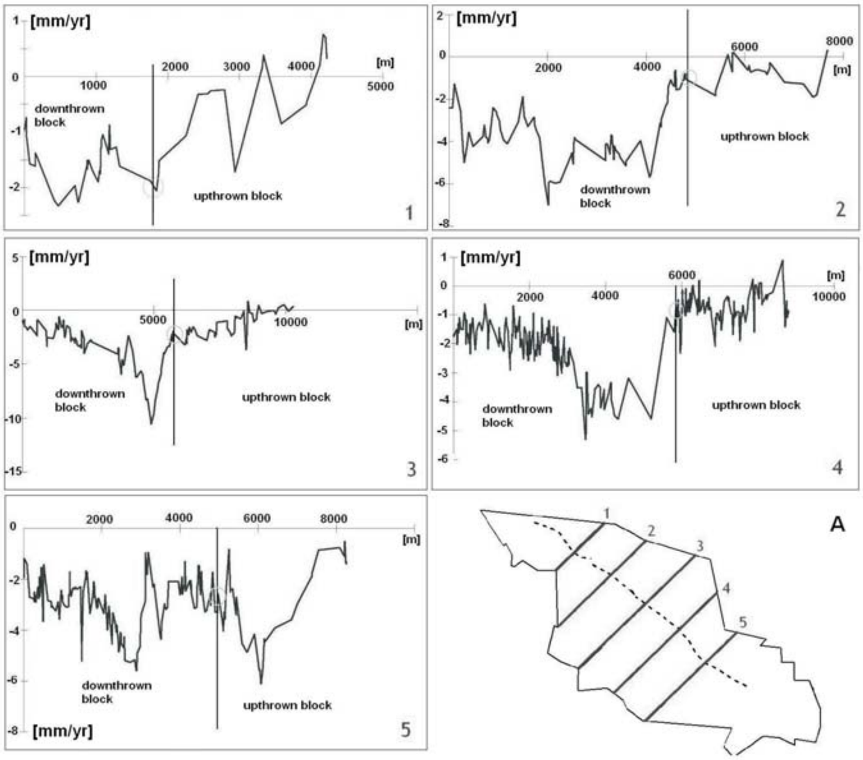

Fig. 3.2. Values of average annual motion rate along selected lines

Rys. 3.2. Wartości średnich szybkości deformacji terenu wzdłuż wybranych linii

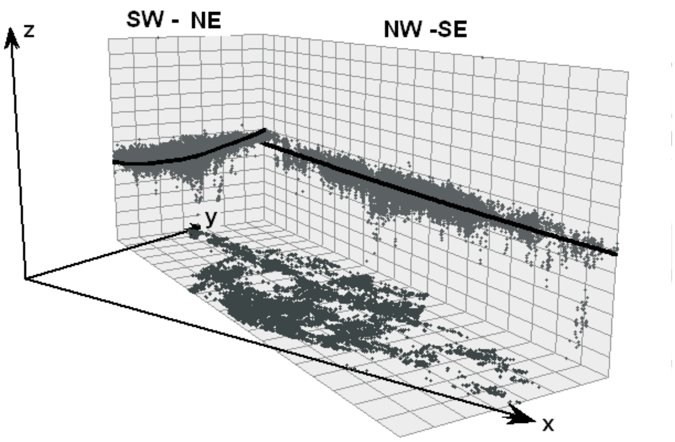

Fig. 3.3. Trend analysis for directions SW-NE and NW-SE

Rys. 3.3. Analiza trenu w kierunkach SW oraz NE oraz NW na SE

In case of the Bedzinski fault, PS points located in the selected mining areas of the Dabrowskie Coal mine were taken to analysis. The outliers were removed form the data set. The sample of $n = 7289$ PS points was randomly selected from the PS points located in the downthrown block of the Bedzinski fault whereas the sample size for the upthrown block was equal to $n = 2323$. The selection with the probability proportional to the size was used. The probability distributions of populations taken into analysis are normal. In Fig. 3.4 the histograms of average annual motion rates for downthrown and upthrown blocks of the Bedzinski fault are presented. It can be seen that there is a difference between values of ground displacements for downthrown and upthrown block. In order to study if this difference is statistically significant, it is necessary to check the variances of parameter among particular groups.

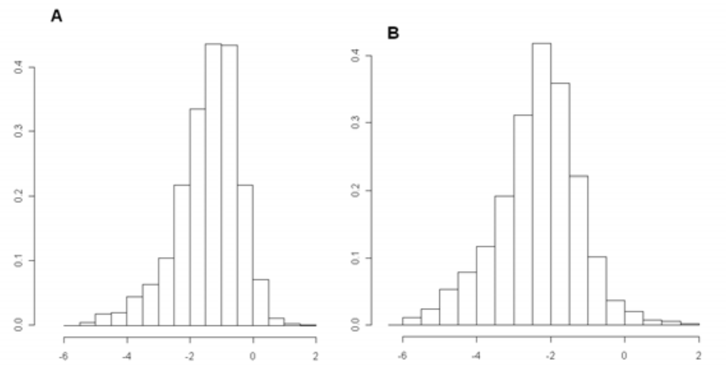

Fig. 3.4. Histograms of average annual motion rate for Bedzinski fault
A – upthrown block, B – downthrown block

Rys. 3.4. Histogramy częstości dla wartości średnich szybkości deformacji terenu w obrębie uskoku będzińskiego
A – skrzydło wiszące, B – skrzydło zrzucone

The value of p, less than 0.001 was determined from conducted variance analysis based on test F. According to expectations, it legitimizes the refuse of zero hypothesis (H_0: $\mu_1 = \mu_2$, where μ_1 – mean value of ground deformations in the upthrown block of fault, μ_2 – mean value of ground deformations in downthrown block of fault) in favor of alternative hypothesis (H_1: $\mu_1 \neq \mu_2$). With significance level $\alpha = 0.001$ it can be considered that average values of ground deformations in the upthrown and dwonthrown blocks of the Bedzinski fault are statistically different.

The one-way analysis of variance was performed also for faults with meridional strikes. In this case, PS points located within a distance smaller than 500 m form the line of faults were taken into analysis. The histograms (for upthrown and downthrown blocks) were performed (Fig. 3.5) for randomly selected PS points. The probability distributions of populations are normal. Based on F test the value of $p = 0.85$ was determined. There are no prerequisites to reject the H_0 hypothesis. Despite the fact, that faults with meridional strikes

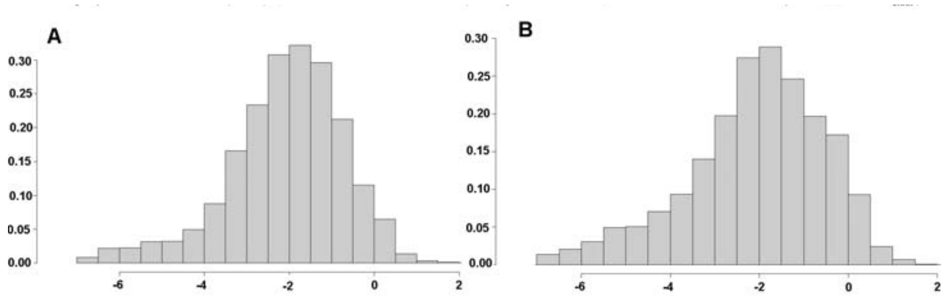

Fig. 3.5. Histograms of average annual motion rate for faults with meridional strikes
A – upthrown blocks, B – downthrown blocks

Rys. 3.5. Histogramy częstości dla wartości średnich szybkości deformacji terenu dla uskoków N-S
A – skrzydła wiszące, B – skrzydła zrzucone

have similar values of throws as the Bedzinski fault, they do not divide the study region into parts with statistically different average values of ground deformations.

In the presented work the correlation between values of ground deformations in PS points and their distances to lines of faults was studied. In order to perform this task the minimal distances form PS points to the line of faults were calculated. The study of correlation was performed separately for the upthrown and downthrown blocks of the Bedzinski fault and for upthrown and downthrown blocks of meridional faults. The scatter XY plots were drawn but they do not give unequivocal information about the studied relations. The calculated Pearson's coefficients (Table 3.1) attest about a weak linear correlation between parameters.

TABLE 3.1

Pearson's correlation coefficients

TABELA 3.1

Współczynniki korelacji Pearson'a

	Pearson's coefficient
Bedzinski fault – downthrown block	0.3045245
Bedzinski fault – upthrown block	0.1266517
Meridional faults – upthrown block	0.2357616
Meridional faults – downthrown block	0.2193632

In the next part of the analysis the spatial variability of the values of ground deformations was studied. In order to perform this task the directional semivariograms were calculated. They were determined separately for downthrown (Fig. 3.6A) and upthrown (Fig. 3.6B) blocks of the Bedzinski fault.

A semivariogram is the basic tool in geostatistical analysis of data. It plots the semivariance between data as a function of distance (Bivand et al. 2008). It can be used to determine the spatial autocorrelation between data.

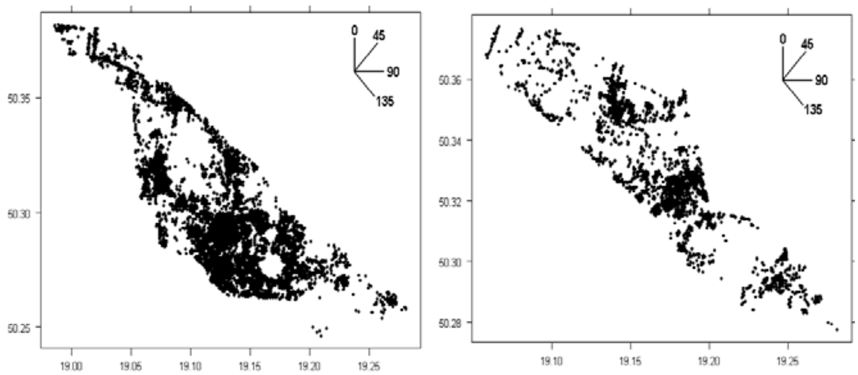

Fig. 3.6. PS points for downthrown block (A) and upthrown block (B) of Bedzinski fault and directions in which the semivariograms were calculated

Rys. 3.6. Punkty PS dla skrzydła zrzuconego (A) i wiszącego (B) uskoku będzińskiego oraz kierunki, dla których obliczono semiwariogramy

In both cases the experimental semivariograms were calculated for four directions: N, NE, E and SE. It was done in order to study the data autocorrelation parallel and perpendicular to the line of fault. Calculated experimental semivariograms were fitted by theoretical models. The visual analysis of semivariograms gives a possibility to check the spatial variation of studied parameter.

The analysis of directional semivariograms for the downthrown block revealed that values of ground deformations are autocorrelated. The range of autocorrelation depends on directions in which the data are studied. This dependency proves the occurrence of anisotropy of ground medium deformation velocity alternation. It can be seen in Fig. 3.7 that the range of autocorrelation in SE direction (parallel to line of Bedzinski fault) is equal to about 2.5 km and it is larger than the range of the autocorrelation in NE direction (perpendicular to line of Bedzinski fault) that is equal to about 1.8 km. In both cases, the experimental models were fitted by spherical theoretical models. The range of autocorrelation in N direction is smaller than for E direction. For experimental semivariograms for 0° and 45° azimuths the increase of semivariogram values for points within the distance larger than 2.8 km (N direction) and 3.8 km (NE direction) can be seen. Such kind of increase does not occur in cases of semivariogram for azimuths equal to 90° and 135°.

Figure 3.8 presents the experimental directional semivariograms for the upthrown block of the Bedzinski fault. In three cases (azimuth: 0°, 45° and 135°) the experimental semivariograms were fitted by spherical theoretical models. The ranges of autocorrelation were determined and are equal to 1.5 km (azimuth 0°), 2.1 km (azimuth 45°) and 1.9 km (azimuth 135°). In case of the azimuth equal to 90°, the experimental semivariogram was fitted by the power model. It is important to pay an attention to values of experimental semivariograms for N and NE directions. For points within the distance larger than the determined range of autocorrelation the values of semivariogram periodically increase and decrease. It can attest to occurrence of areas with larger and smaller values of ground deformations.

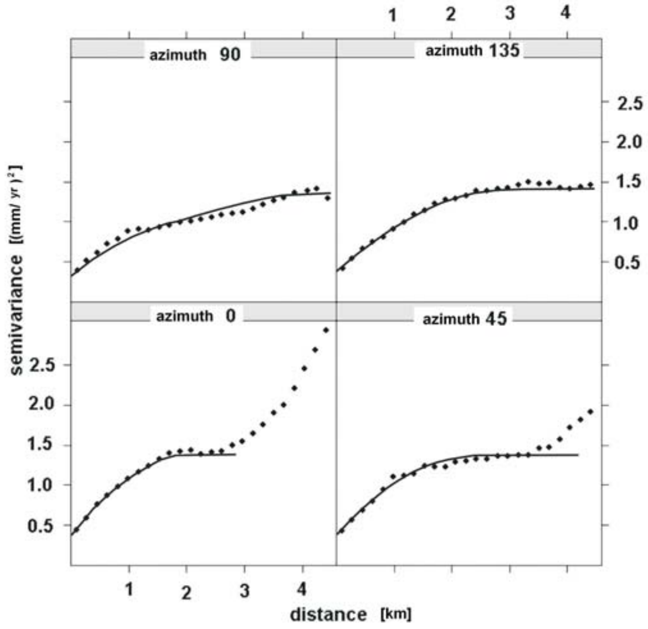

Fig. 3.7. Directional semivariograms for downthrown block of the Bedzinski fault

Rys. 3.7. Semiwariogramy kierunkowe dla skrzydła zrzuconego uskoku będzińskiego

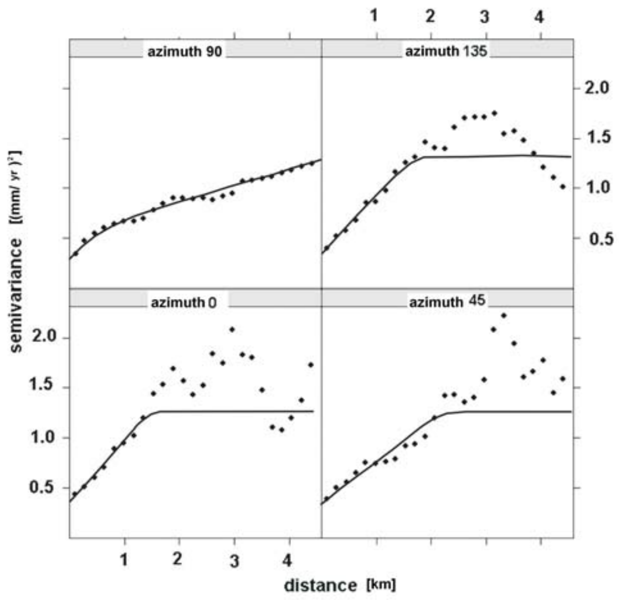

Fig. 3.8. Directional semivariograms for upthrown block of Bedzinski fault

Rys. 3.8. Semiwariogramy kierunkowe dla skrzydła wiszącego uskoku będzińskiego

Conclusions

The performed analysis revealed that there is a trend in values of ground deformations in the SW-NE direction. Moreover, this analysis showed that the Bedzinski fault divides the study region into two parts that have different average values of the subsidence rate. The areas that correspond with the upthrown block of the fault are rather stable while the areas that correspond with the downthrown block suffer from the subsidence. In case of meridional faults the average annual motion rates in downthrown and upthrown blocks are similar. It must be emphasized that the Bedzinski fault and meridional faults have similar values of throws. The analysis of directional semivariograms performed separately for downthrown and upthrown blocks of the Bedzinski fault revealed that there was autocorrelation of values of ground deformations. In the downthrown block, the range of autocorrelation in direction along the strike of the Bedzinski fault is higher than it is perpendicular to its strike. In the upthrown block the range of autocorrelation is smaller than in the downthrown block of the Bedzinski fault. In this work the small correlation between values of ground deformations and their distance to strike of the Bedzinski fault was revealed. The presented analysis is an important part of the work that aimed at finding the origin and mechanism of ground deformations in mining and postmining areas.

This work was supported by project no. 11.11.140.561 AGH University of Science and Technology (Faculty of Geology, Geophysics and Environmental Protection)

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IMPACT OF TECTONICS ON GROUND DEFORMATIONS CAUSED BY MINING ACTIVITY IN THE NORTH-EASTERN PART OF THE UPPER SILESIAN COAL BASIN

Key words

PSInSAR, Dabrowskie Coal Basin, ground deformations, faults

Abstract

The aim of the presented research was to analyze the dependencies between slow surface deformations and faults distribution. The area of the research included seven mines of the Dabrowskie Coal Basin. Coal exploitation has been conducted in this region for over 200 years. The region faces a problem of vertical ground deformations. The PSInSAR technique was used in this area to measure small, long-period ground displacements. The PSInSAR method exploits a set of a few dozen satellite radar images of the same area performed at different times. The velocities of deformations are measured only in points called “persistent scatterers - PS”. The PS points are good radar wave reflectors located on the Earth’s surface, e.g. buildings, bridges, rock outcrops.

The important feature of the Dabrowskie Coal Basin is a dense fault system with throws, which range from several meters to over three hundred meters. The main dislocation in the discussed region is the Bedzinski fault with NW-SE direction. It is crossed by smaller faults with S-N orientation. Only large faults with throws over fifty meters were used in described analysis.

In the first part of this work, the analysis of ground deformations values was made. It was performed separately for downthrown and upthrown blocks. The one-way analysis of variance was made to examine the statistical significance of the difference between average velocities of subsidence in those two blocks. The analysis was performed separately for the Bedzinski fault and for faults with S-N directions.

In the second part of the work, an analysis of spatial dependence between fault location and velocities of deformations was performed. The directional semivariograms were calculated in downthrown and upthrown blocks of the Bedzinski fault. The semivariograms in N, NE, E and SE directions were analyzed.

Results of analysis show that despite the fact that all faults have similar values of vertical displacements, only the Bedzinski fault divides the study area into two regions with significant difference of average values of ground deformations. It has been found that the downthrown and upthrown blocks of the Bedzinski fault have different variations of ground deformations in space. The performed analysis shows also that there is no linear correlation between values of ground displacements measured in PS points and their distances to lines of faults.

WPŁYW TEKTONIKI NA DEFORMACJE TERENU WYWOŁANE DZIAŁALNOŚCIĄ GÓRNICZĄ W PÓŁNOCNO-WSCHODNIEJ CZĘŚCI GÓRNOŚLĄSKIEGO ZAGŁĘBIA WĘGLOWEGO

Słowa kluczowe

PSInSAR, Zagłębie Dąbrowskie, deformacje terenu, uskoki

Streszczenie

Celem pracy była zbadanie wpływu tektoniki na deformacje terenu wywołane działalnością górniczą. Obszar badań opisany w artykule obejmuje tereny górnicze wybranych kopalń Zagłębia Dąbrowskiego. Ze względu na prowadzoną w tym rejonie od lat eksploatację węgla kamiennego oraz skomplikowaną budowę tektoniczną rejon ten zagrożony jest występowaniem pionowych przemieszczeń terenu. Na obszarze badań pomierzone zostały niewielkie, długookresowe deformacje terenu, dzięki wykorzystaniu techniki PSInSAR. Technika ta polega na przetwarzaniu zestawu satelitarnych obrazów radarowych i dostarcza informacje o przemieszczeniach terenu w punktach PS. Punkty PS to stabilne reflektory odbijające promieniowanie mikrofalowe, odpowiadające takim obiektom terenu jak budynki, mosty, wiadukty, wychodnie skał itp. Szczegółowo zbadane zostały wartości przemieszczeń terenu w punktach PS w zależności od ich położenia względem głównych jednostek tektonicznych.

Zagłębie Dąbrowskie charakteryzuje się występowaniem gęstej sieci uskoków. Główną dyslokacją tego terenu jest uskok będziński o rozciągłości NW-SE. Uskok ten przecięty jest licznymi uskokami o rozciągłości południkowej. Do analizy wybrane zostały jedynie największe uskoki, których wartości zrzutów przekraczają 50 m.

Analiza danych PSInSAR obejmowała trzy etapy. Pierwszy z nich polegał na interpolacji średnich szybkości terenu w punktach nie objętych techniką PSInSAR. Zadanie to zostało wykonane z zastosowaniem metody odwrotnych odległości. Zbadane zostały wartości deformacji terenu w kierunku prostopadłym do linii uskoku będzińskiego Następnie wykonana została analiza trendu, dla wszystkich wykorzystanych w pracy, danych PSInSAR.

W drugim etapie badań wykonana została jednoczynnikowa analiza wariancji mająca na celu sprawdzenie, czy różnica pomiędzy średnią wartością deformacji terenu dla skrzydła zrzuconego i wiszącego jest statystycznie istotna. Analiza wariancji została wykonana osobno dla uskoku będzińskiego i uskoków o przebiegu południkowym.

W trzecim etapie analizy zbadana została struktura zmienności średnich szybkości deformacji terenu względem uskoku będzińskiego. Zadanie zrealizowano poprzez obliczenie i analizę semiwariogramów kierunkowych. Badanie struktury zmienności parametru zostało przeprowadzone dla uskoku będzińskiego osobno dla skrzydła zrzuconego i wiszącego. Empiryczne semiwariogramy w obu przypadkach zostały obliczone, dla kierunków: N, NE, E, SE, tak aby zbadać wzajemną korelację deformacji terenu osobno w kierunku prostopadłym i równoległym do linii uskoku.

Wykonana w pracy mapa deformacji terenu pozwoliła na wstępną ocenę wartości przemieszczeń terenu względem głównych uskoków rejonu badań. Analiza deformacji terenu w kierunku prostopadłym do linii uskoku będzińskiego wykazała różnicę w wartościach przemieszczeń terenu w skrzydle wiszącym i zrzuconym tego uskoku. Stwierdzono występowanie trendu średnich szybkości deformacji terenu w kierunku SW-NE. W wyniku przeprowadzonej analizy wykazano, iż pomimo faktu, że wszystkie uskoki uwzględnione w pracy charakteryzują się podobnymi wartościami zrzutów to jedynie dla uskoku będzińskiego stwierdzona została statystycznie istotna różnica między średnimi deformacjami terenu w skrzydle wiszącym i zrzuconym. W odniesieniu do tego uskoku stwierdzono również różnicę w strukturze zmienności analizowanego parametru dla obu jego skrzydeł. Ponadto wykazano brak korelacji pomiędzy wartościami deformacji terenu a odległością punktów pomiarowych od linii uskoku.