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QUALITATIVE RELATIONSHIP OF SEISMIC ACTIVITY WITH VERTICAL DISPLACEMENTS OF TERRAIN AFTER MINE CLOSURE WITH THE USE OF DInSAR TECHNOLOGY

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Abstract

The liquidation process of mines is very complex and long. It relates to various hazards, including post-mining seismicity and deformations of ground surface. The above issues are the subject of the research project under which the monitoring of ground surface movements is carried out in the area of the closed coal mine "Kazimierz-Juliusz", which is currently being flooded. The monitoring is carried out using the GNSS technique and satellite radar interferometry (InSAR). The project makes use of radar data from the Copernicus project, which is being implemented by the European Commission in cooperation with the European Space Agency (ESA). InSAR monitoring started in December 2020. Additionally, we analyzed the impact on ground surface of 5 rock tremors of the energy not exceeding 6.5E + 05 J (tremor magnitude Mw = 2.1), which were reported in the investigated area in 2018–2020. The article presents the results of qualitative analysis involving the relationship between seismic activity and vertical movements of ground surface. To investigate potential changes in altitude, DInSAR technology was applied. On the basis of interferometric images generated from radarograms in the periods before and after the tremor, in January 2019, it was found that vertical movements of ground surface were possible to occur. Altitude changes can be characterized with the values in the range of single millimeters, which are only slightly beyond the accuracy range of the InSAR method. The analysis of interferograms, comprising wider time databases, indicated that the impact of the tremor on the deformations of ground surface is incidental.

Keywords: satellite radar interferometry, seismicity, rockmass tremors, post-mining areas, monitoring of ground surface movements, mining

ZWIĄZKI JAKOŚCIOWE AKTYWNOŚCI SEJSMICZNEJ Z PRZEMIESZCZENIAMI PIONOWYMI TERENU PO ZAMKNIĘCIU KOPALNI Z WYKORZYSTANIEM TECHNOLOGII DInSAR

Abstrakt

Proces likwidacji kopalń jest bardzo złożony i długotrwały. Towarzyszą mu różne zagrożenia, wśród których można wymienić sejsmiczność pogórniczą oraz deformacje powierzchni terenu. Problematyka ta jest przedmiotem projektu badawczego, w ramach którego wykonywany jest monitoring ruchów powierzchni na terenie nieczynnej już kopalni „Kazimierz-Juliusz", która jest obecnie zatapiania. Monitoring realizowany jest z wykorzystaniem techniki GNSS oraz satelitarnej interferometrii radarowej (InSAR). W projekcie wykorzystywane są dane radarowe z projektu Copernicus, który realizowany jest przez Komisję Europejską we współpracy z Europejską Agencją Kosmiczną (ESA – European Space Agence). Monitoring techniką InSAR rozpoczęto w grudniu 2020 roku. Dodatkowo przeanalizowano powierzchniowe skutki pięciu wstrząsów górotworu o energii nieprzekraczającej wartości 6,5E+05 J (magnituda wstrząsu Mw = 2,1), które zarejestrowano w rejonie badań w latach 2018–2020. W artykule przedstawiono wyniki analizy jakościowej związków aktywności sejsmicznej z ruchami pionowymi powierzchni terenu. W celu zbadania potencjalnych zmian wysokościowych wykorzystano technologię DInSAR. Na podstawie obrazów interferometrycznych wygenerowanych z radarogramów w okresach przed i po wstrząsie, w styczniu 2019 roku, stwierdzono możliwość wystąpienia pionowych ruchów powierzchni terenu. Zmiany wysokościowe scharakteryzować można wartościami w zakresie pojedynczych milimetrów, wykraczających tylko nieznacznie poza zakres dokładności metody InSAR. Analiza interferogramów, obejmujących szersze bazy czasowe, wskazała na incydentalny wpływ wstrząsu na deformacje powierzchni terenu.

Słowa kluczowe: satelitarna interferometria radarowa, sejsmiczność, wstrząsy górotworu, tereny pogórnicze, monitoring ruchów powierzchni, górnictwo

1. INTRODUCTION

The process of mine closures is associated with hazards to the natural environment, in particular to ground surface. The liquidation works pose a threat to working miners, both on the surface and underground. And as to the hazards occurring in post-mining areas, which have a significant impact on the state of public safety, we can mention water, flood or gas hazards, post-mining seismic activity and deformation of ground surface. The research studies involving the movement of rock mass and its surface layer in post-mining areas subjected to seismic impact is the subject of the research project coined with the acronym PostMinQuake. The Silesian University of Technology is a partner in the project. As part of the research, the University performs tasks involving the monitoring of surface ground movement in the already closed coal mine "Kazimierz-Juliusz" (currently being flooded), located in the eastern part of the Upper Silesian Coal Basin. The monitoring is carried out with the application of the GNSS technique and satellite radar interferometry which makes use of SAR technology (Synthetic Aperture Radar). The method with the use of InSAR technique allows, depending on the conditions of terrain and the consistency of radarograms, to obtain results with sub-centimeter accuracy. Currently, radar systems are widely used for terrain surface imaging due to a significant development in the field of radar imaging from satellite orbits and the accessibility of operational satellite systems, designed for long-term operation of programs supporting successive satellites. What is more, new imaging systems with higher resolving power are being launched. The breakthrough was triggered by the European systems TerraSAR-X and COSMO-SkyMed / TanDEM-X. In 2014, the European Space Agency launched a new radar satellite – Sentinel-1 – which is a continuation of the ERS and ENVISAT missions. Sentinel-1 is the first of five missions that ESA is developing under the Copernicus project [1]. The data of the Sentinel-1 satellite is made available free of charge, which gives unique opportunities for the development of this technique and the expansion of its application scope.

Currently, radar images and their developments are used in many sectors, including monitoring of areas hit by natural disasters, spatial planning, forestry, agriculture, geology, cartography, mining. Particularly interesting in view of the project being implemented is the use of InSAR for the monitoring of ground surface movements related to mining operations and induced by seismicity. Examples of the use of satellite radar interferometry to monitor ground surface deformation in effect of coal extraction in mining areas are described, among others, by the papers written in the Czech Republic, Germany [2], China [3], India [4], Canada [6] and Poland [5, 7].

The analyses of ground surface deformation in regions where mining induced seismicity has been observed, are becoming particularly important due to hazards posed to objects built on the surface and the safety of residents. The results of research which makes use of radar interferometry for quasi-continuous observations and the analyses of the phenomenon of deformation development over time, which can be attributed to the phenomena of mining seismicity, are presented, inter alia, in works [8–10].

Yet, in the studies conducted so far there are few comprehensive works that would analyze post-mining seismicity in terms of the observed ground surface movements during mine closures. This type of seismicity is mainly observed in post-mining regions, which in the past were characterized by high level of induced seismicity and high level of rock burst hazards. The observations to date show that after the termination of extraction, a rapid decrease of both number and energy of tremors is observed. But the drop in energy gradient varies over time, and the occurrence of post-mining seismicity may last up to several years from the termination of extraction, depending on the depth of the deposits, properties of rockmass and the phase of mine flooding. Water can affect the redistribution of stresses, the development of sliding processes that can lead to the development of seismic phenomena. In the process of underground mine liquidation, a change of factors that affect the likelihood of tremor occurrence is observed. In this case, seismic hazards involve the works carried out during the liquidation, such as disassembly of machines or equipment, construction of backfill plugs or insulation-retaining plugs, backfilling of shafts. Water may be an additional factor, which during the flooding process can have a significant effect on changing the geodynamic stability of the layers of rock massif. The magnitude of these phenomena is generally lower than that of seismic phenomena, the causes of which are directly attributed to the conducted mining operations. Nevertheless, it is important to define and research the mechanisms and causes of seismicity or ground surface deformation, and then to find the relationship between seismic events or ground surface deformations and mine flooding processes. Subsequently, it is important to determine methods and plans for long-term monitoring of post-mining areas in order to reduce seismic hazards during and after mine closure. The above issues are the main goals of the PostMinQuake project.

2. MATERIALS AND METHODS

2.1. Research area

The area of the mining area of the mine "Kazimierz-Juliusz" is 23.5 km^2 and administratively it covers the cities of Sosnowiec, Dąbrowa Górnicza and Jaworzno (Fig. 1). The beginning of mining in the research area is dated back to the opening of the opencast mine "Feliks". In 1814 the Warsaw Society of Mines and Metallurgical Works put into operation a new, larger mine called "Kazimierz", and then in 1914 the mine "Juliusz" was opened. In 1938, one mine was established under the name "Kazimierz-Juliusz". In 2015, coal extraction was completed, and the mining plant was fully closed by the end of 2018.

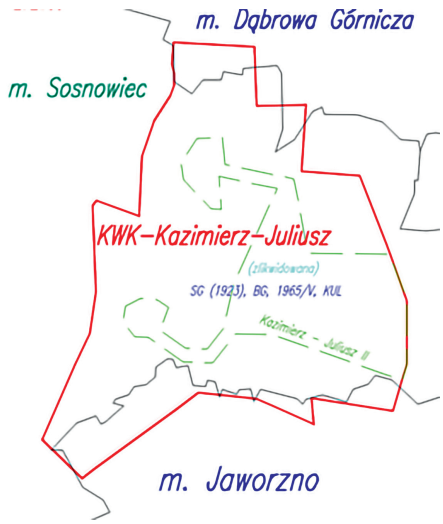


Fig. 1. Administrative location of KWK "Kazimierz-Juliusz"
Ryc. 1. Położenie admistracyjne KWK „Kazimierz-Juliusz"

The deposit in the area of the mine "Kazimierz-Juliusz" is located within the Bytom-Kazimierz trough and the Maczek dome, which is an extension of the main saddle towards the east. The Kazimierz basin is the central part of the deposit. Towards the west, the Kazimierz basin changes into the asymmetrical structure of Bytom trough, characterized by a variable inclination of the wings and layers. In the east, this basin turns into the asymmetrical Maczek dome. In the east the above-mentioned structures are cut by a dense network of faults with latitudinal and meridional directions or close to them (Fig. 2).

In the mining area of the mine "Kazimierz-Juliusz" there are documented formations of overburden (Quaternary and Triassic formations) and productive Carboniferous. Quaternary formations occur almost on the entire surface of the mining area, reaching the greatest thickness (about 50 m) in the area of the shaft "Maczki". Triassic formations occur in the southern and western parts of the mining area. The total thickness of the Triassic formations ranges from 35 m to 170 m. The productive Carboniferous formations are represented by the layers of Orzesze, Ruda, Siodło, as well as Poręba, Jakłowiec and Gruszów. The Orzesze layers, occurring in the southern and central part of the mining area, formed in clay-sand facies and comprising the seams 337–358, constitute a complex of the total thickness of approximately 470 m. The Ruda layers make up a complex 100 ÷ 150 m thick. The thickness of the sandstone series above the seam 510 ranges from 30 m to 50 m. The saddle layers are formed as thick-bed sandstones and claystones, in which the seam 510 is deposited. The total thickness of these layers ranges from several to 45 m. These layers occur on the entire of mining area except for the northern part. The layers of Poręba, Jakłowiec and Gruszów, with a total thickness of about 450 m, are characterized by a predominance of claystone sediments and mudstone sediments located over sandstones.

The deposit of the mine was exploited in seams 816, 819, 823, 829, 833, 409/2, 418, 420 and 510. The exploitation of seams 816, 819, 823, 829 and 833 was carried out at an average depth of 30 m to 420 m with a pillar and breast/ chamber system with caving to a height from about 0.5 m to about 2.1 m. The seam 409/2 was exploited at an average depth from about 150 m to about 600 m using a longwall system with fall of roof to the height from about 1.4 m to about 3.1 m. In the case of seams 418 and 420, the exploitation was carried out at an average depth from 370 m to 670 m using a pillar and breast or longwall system with caving or hydraulic backfilling, at a height approximately from 1.4 m to 2.7 m.

The most intensive exploitation was carried out in seam 510, which was exploited from the end of the 19th century to the beginning of the third decade of the 20th century at a depth from the outcrop of the seam to 470 m. The estimated thickness of the deposit exploited by pillar and breast /chamber system or by pillar and breast system was in the range from 3 m to 10 m. Since 1950s, mining was carried out using a longwall system with caving and hydraulic backfilling. The average depth of exploitation, depending on the area, ranged from 100 m to 700 m. The total thickness of the exploited deposit was also variable, reaching the maximum value of 15 m. Mining was carried out in layers, up to a maximum of 5 layers. In the last period of mining, the extraction was carried out using longwall top coal caving, with an average depth of exploitation in the range from 170 m to 330 m. Figure 2 presents the contours of completed mining. As we can observe, it was a multi-bed exploitation. The degree of rockmass disturbance caused by mining is very high.

Relatively high induced seismicity was reported in the mine "Kazimierz-Juliusz" during the mining operations. The vast majority of high energy events was induced near the Będzin fault and the Nożycowy fault. After the closure of the mine, in 2018–2020, the registration of events was carried out by the seismic stations of the Upper Silesian Regional Seismological Network. The configuration of the network did not allow registration of weaker seismic phenomena, due to the fact that the nearest stations were located approximately 10 km from the examined area. As part of the analyses being the subject of the article, the study involved the movements of ground surface in the periods related to 5 phenomena registered from 2018 to the end of August 2020. In the period from the commencement of the project, i.e., from September 2020 to October 20, 2021, 12 seismic phenomena with energies ranging from 103 J to 105 J were registered in the examined area. Registration of phenomena with lower energies is now possible owing to the installation of additional seismometric stations.

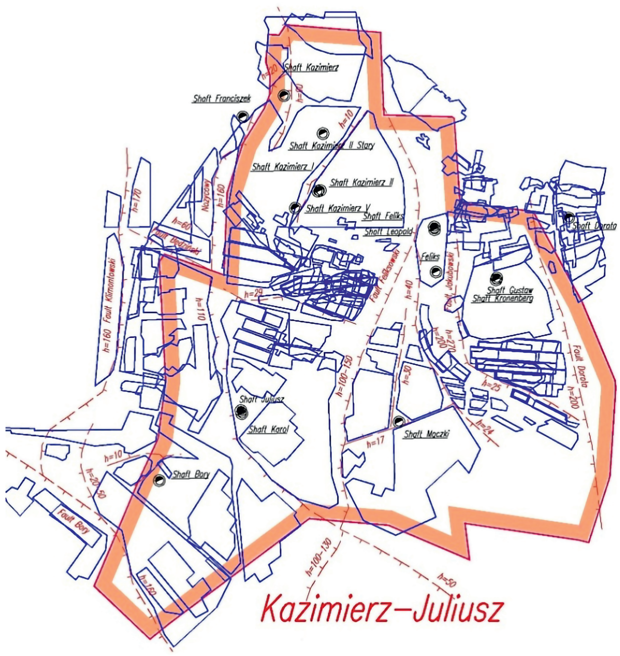


Fig. 2. Contours of completed exploration in the area of KWK "Kazimierz-Juliusz" – the course of major faults

Ryc. 2. Kontury eksplotacji dokonanej w rejonie KWK „Kazimierz-Juliusz" – przebieg głównych uskoków

2.2. Research methodology – development of radar data

The use of Copernicus project, implemented by the European Commission in cooperation with the European Space Agency (ESA), for a given research area enables the acquisition of large amounts of radar data. Radarograms are made from satellite boards of the Sentinel-1 mission (satellites A and B). These satellites follow polar orbits 51 and 102. The acquisition period for each orbit is 6 days. The periods are shifted by 3 days with respect to each other. It is the minimum time interval allowing to conclude about possible changes in the altitude of ground surface. The project assumed standard processing of interferograms (from both orbits) in 6-day periods. Processing in longer periods, being a multiple of the interval of 6 days, is provided for in two cases. The first case involves the detection of changes in altitude, or the premises of such changes on the 6-day interferograms. The second case applies when a tremor related to the post-mining area is reported in the research area. In both situations, even for small movements of ground surface, lengthening the period between the generated radar images increases the probability of detecting and analyzing these changes. It is connected with the dynamics of the phenomenon of surface ground subsidence effected e.g. by low-energy tremors of rockmass, where the altitude changes of ground surface in a short time interval may be within the range of the so-called radar signal noise. In such cases, we cannot exclude the use of the remaining available radar scenes of the research area from the passages of satellites moving in other orbits. The above-mentioned procedures will also be launched in the event of finding changes in altitude from the monitoring techniques simultaneously implemented in the research area. They are both satellite techniques (GNSS) and classical techniques (precision leveling). These techniques provide point information at the installation places of permanent GNSS stations, which operate in static mode (quasi-continuous measurement) and at places with stabilized leveling network points (observation line). The main advantage of these data is their precision and reliability within the range of single millimeters. This is a very important element of the entire post-mining area monitoring system, enabling, inter alia, verification of the interpreted results of the DInSAR method. This is especially important for detecting small ground surface movements with values close to the limit of radar signal noise.

The processing of the acquired satellite data in the form of radarograms is carried out in the dedicated SNAP software. In the first step, the radarograms are mutually registered (coregistration). Both processed images (master and slave) are taken down to the same pixel system geometry. This process enables further calculation steps based on the information contained in the corresponding terrain pixels. The processing of the images to obtain an interferogram starts with spectra filtering improving the signal-to-noise ratio which results from non-overlapping parts of the spectrum. The next step involves the estimation of coherence, i.e., spectral differences between two signals for the same terrain pixel. The coherence map (shown in grayscale) over the entire range of the raster image shows areas more or less useful for detecting altitude changes using the InSAR method. In the extreme case, in areas with very low or even no coherence, the possibility of interpreting the processing results of a given pair of radarograms practically does not exist. High quality of the interferogram is obtained in areas of high coherence. Then, in the development process of interferogram, a correct calculation of the phase shift for two signals of each terrain pixel takes place. However, the calculated phase shift has several components related to deformation, topography, atmosphere, orbits and noise of the radar signal. The deformation phase component is responsible for altitude changes of surface ground. Other components should be eliminated from the calculation results if it is possible. Not all of them can be removed or even minimized. The software enables to minimize phase components related to the orbits or topography of ground surface (based on accurate data about orbits and on the reference numerical model of the terrain DEM). The removal of the components related to the atmosphere or to the noise of radar signal is very difficult. The minimization of these components is generally done through an appropriate selection of a pair of processed radarograms, which should be made under relatively similar atmospheric conditions. This is related, inter alia, with the length of acquisition period, where the theoretically shorter time database should result in better quality of the interferogram.

The interferogram generated in this way in individual pixels contains information about the phase difference of two signals coming from the master and slave radar

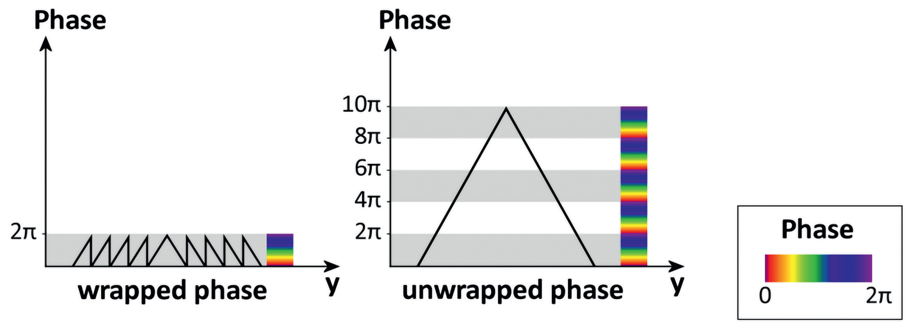


Fig. 3. Diagram of the unwrapping of radar signal phase
Ryc. 3. Schemat rozwinięcia fazy sygnału radarowego

images. The presented phase difference (in each pixel) ranges from 0 to 2π. The angular value is converted to distance based on the knowledge of the wavelength of the used radar signal. Thus, the repeated, ordered sequence of angular values in a series of pixels requires phase unwrapping. This operation is preceded by the filtering of signal phase. For this purpose, the filter Goldstein Phase Filtering which increases the signal-to-noise ratio can be used. The phase unwrapping operation (Fig. 3) can be performed in the SNAPHU program, where the finished interferograms are exported.

Therefore, by unwrapping the phase of radar signal we can determine vertical displacements related to

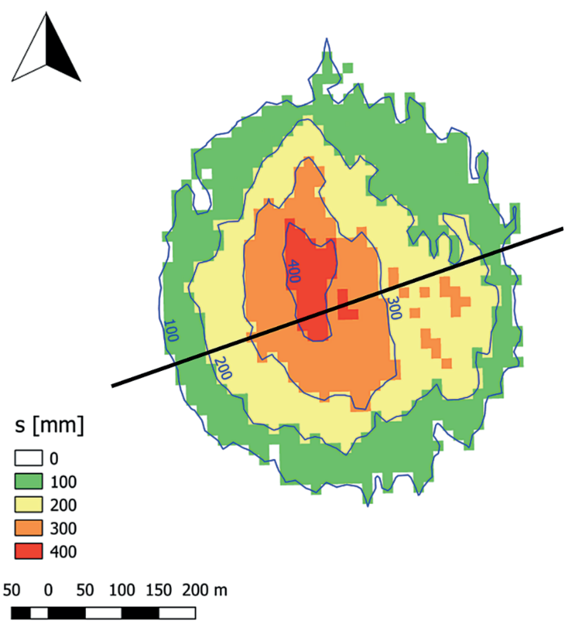


Fig. 4. Isolines of total subsidence based on raster image
Ryc. 4. Izolinie obniżeń całkowitych na podstawie obrazu rastrowego

the deformation of ground surface. Further processing of the interferograms is made possible by the QGIS computer program. Based on the subsidence visualized in the raster form, isolines are generated. Due to the above-mentioned undesirable phase components (including radar signal noise), these isolines are usually characterized by low regularity (Fig. 4). For this reason, the obtained image should be subjected to modeling. For this purpose, the modeling method developed by the authors' team [11], based on terrain profiles, can be used.

The modeling requires that several terrain profiles should be made, intersecting at the point where the highest values of subsidence of ground surface were found. The number of profiles (ranging from 2–3 to a maximum of a dozen) depends on the shape of the deformation. A more irregular shape requires more profiles. An example of a field profile (highlighted in Figure 4) is shown in Figure 5.

The irregular course of subsidence in each profile is interpolated with the use of 8th degree orthogonal polynomials (Fig. 6).

Simultaneously with the development of profiles, corrections should be made to the course of individual isolines in the raster image (Fig. 7). This operation can be performed manually.

The performed interpolation of terrain profiles enables to suitably allocate the value of subsidence to the corrected isolines. In this way, a spatial image of deformation (3D model) is obtained, largely close to reality (Fig. 8). The correctness of the obtained model can be additionally verified by comparing the profiles from the interpolation of raster data (polynomial) and the corresponding profile of the model. As demonstrated in previous studies [11], the differences in the course of both

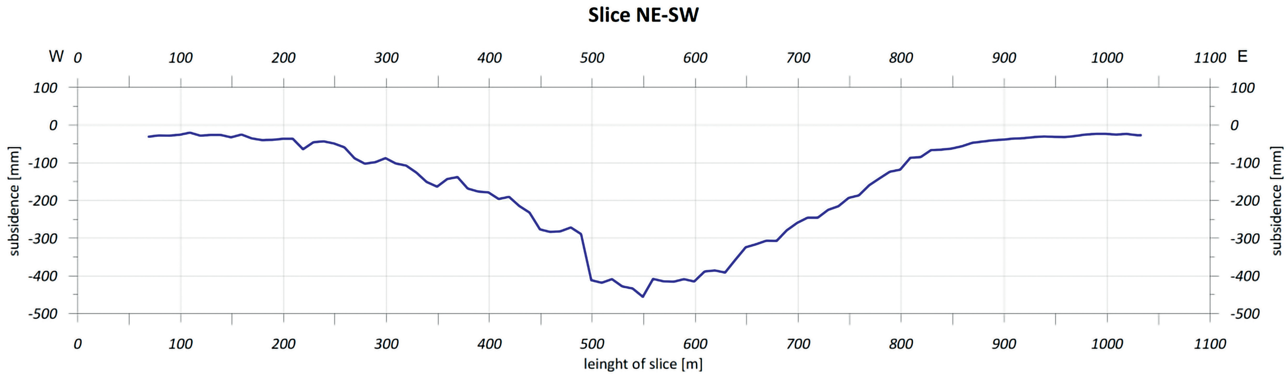


Fig. 5. Subsidence of ground surface in the exemplary vertical profile
Ryc. 5. Obniżenia powierzchni terenu w przykładowym profilu pionowym

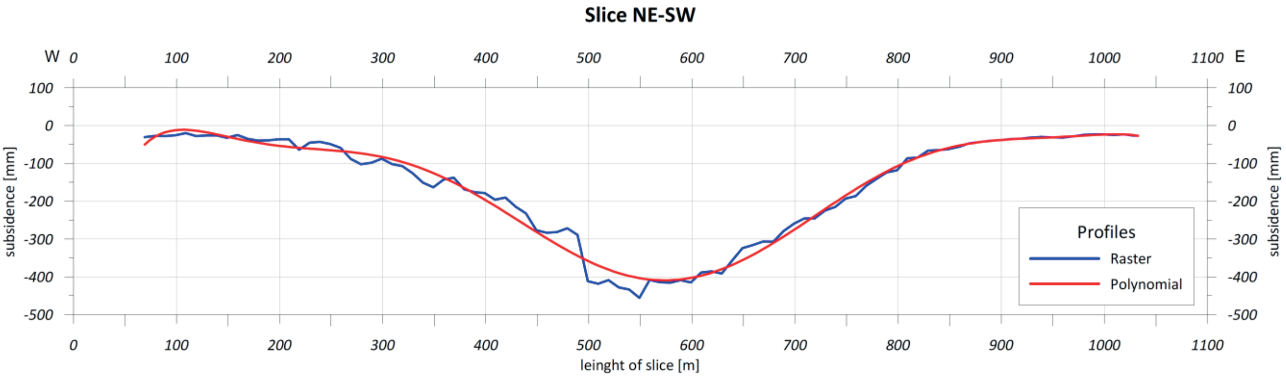
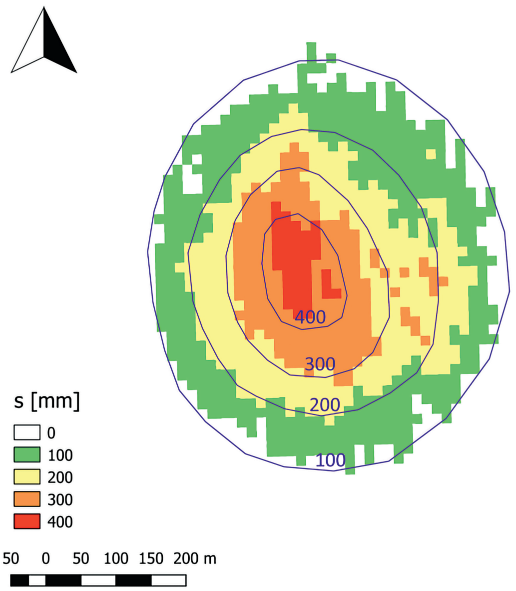


Fig. 6. Polynomial interpolation of the terrain profile
Ryc. 6. Interpolacja wielomianowa profilu terenowego



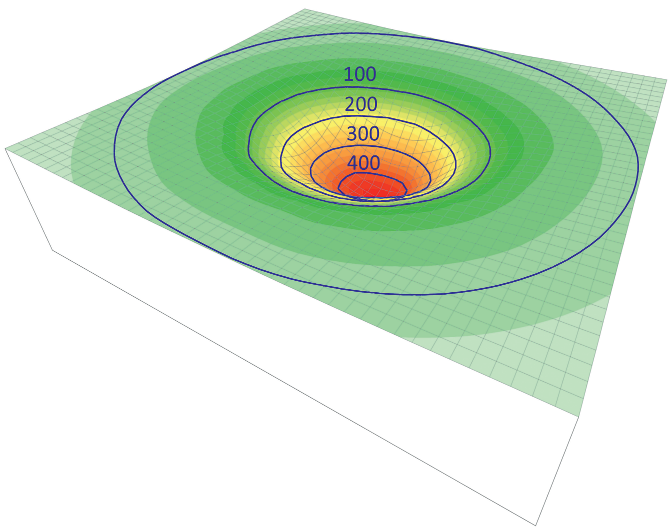


Fig. 7. Corrected isolines of total subsidences
Ryc. 7. Skorygowane izolinie obniżeń całkowitych

Fig. 8. Model of ground surface deformation
Ryc. 8. Model deformacji powierzchni terenu

profiles turned out to be small, which bespoke of high reliability of the modeled results. The adequate profile matching was evidenced by the high correlation coefficient, which reached values ranging from 95% to 99%. This correlation coefficient depended on the degree of irregularity of the field profile.

3. RESULTS AND DISCUSSION

3.1. Results – radarograms, interferograms

With respect to the main assumptions of the PostMinQuake research project, the monitoring of the ground surface using the InSAR method has been carried out on a quasi-continuous basis since December 2020. This means that an uninterrupted series of radarograms was acquired from two paths over a period of 6 days (Chapter 2.2). The acquisition of radarograms made from the board of the satellite moving in the orbit No. 51 began on November 30, 2020. In the case of the satellite moving in the orbit No. 102, the first acquired radarogram was made on December 3, 2020. Within the period of each month, a total of about 10 radarograms from both selected paths are obtained. As a standard, the interferograms are processed on an ongoing basis from each matching pair of radarograms. In the adopted standard, they cover a 6-day time database. Exemplary interferograms covering this period from both paths

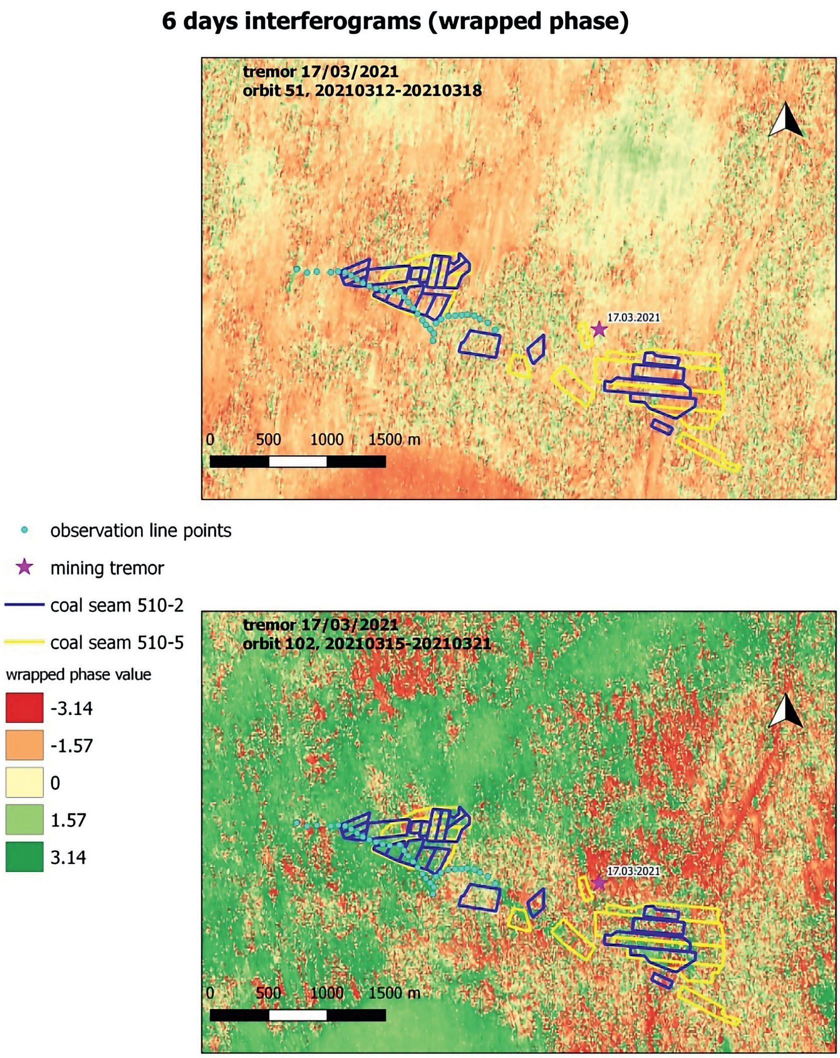


Fig. 9. Standard interferograms covering a period of 6 days (for paths 51 and 102)
Ryc. 9. Standardowe interferogramy obejmujące okres 6 dni (dla ścieżki 51 i 102)

Table 1. List of rockmass tremors in the area of "Kazimierz-Juliusz" mining area in the period 2018–2020
Tabela 1. Zestawienie wstrząsów górotworu w rejonie obszaru górniczego „Kazimierz-Juliusz" w okresie 2018–2020

No.	Tremor date	UTC time	Mw	Energy J	latitude N	longitude E
1	2018-06-11	12:08	2.0	4.20E+05	50° 16' 08"	19° 12' 07"
2	2018-10-20	16:22	1.9	3.20E+05	50° 16' 34"	19° 14' 10"
3	2018-11-03	19:40	2.1	6.50E+05	50° 19' 20"	19° 13' 44"
4	2019-01-21	23:36	No data	No data	50° 16' 02"	19° 15' 24"
5	2020-01-03	No data	No data	No data	50° 17' 06"	19° 16' 45"

(orbits 51 and 102) are shown in Figure 9. In the event of a rock tremor or detected signs of altitude changes of ground surface, the time databases are multiplied depending on spectral capabilities and later also on interpretation capabilities of satellite images. Currently, work is underway on the interpretation of the information contained in the interferograms made in the last weeks, when the rise in seismic activity in the area of the study was noted.

In addition, as part of the project, the impact of several small tremors that occurred in the period 2018–2020 (until the end of August) was investigated. In the area of the "Kazimierz-Juliusz" mining area, several rock tremors with the energy not exceeding 6.5E + 05 J (tremor magnitude Mw = 2.1) were recorded at that time. The summary of basic information about the analyzed rockmass tremors, concerning e.g. the time of their occurrence, energy or geographic coordinates of the foci is presented in Table 1. Figure 10 shows the layout of tremor epicenters.

In the period immediately preceding the tremors and in the period after the occurrence of individual tremors, historical data in the form of radarograms available in the ESA database (Copernicus program) was obtained. Radarograms made from satellites moving in polar orbits numbered 51, 102, 124 and 175 were used. A total of 82 radarograms were obtained. They enabled the processing of interferograms in the periods from 6 days to 18 days. In most cases, the study was performed on interferograms covering a period of 12 days. The total number of performed interferograms was 33. The interferograms generated from radarograms obtained from different paths (different orbits) were used to study in detail the potential ground surface movements effected by rock tremors. In this way, it improved the reliability of the analyses of the interpreted data involving the altitude changes of ground surface in the period from a few days to a dozen or so days after the rock tremor. The analysis of results obtained from the information contained in the generated interferograms (from the period 2018–2020) is presented in the next chapter (chapter 3.2).

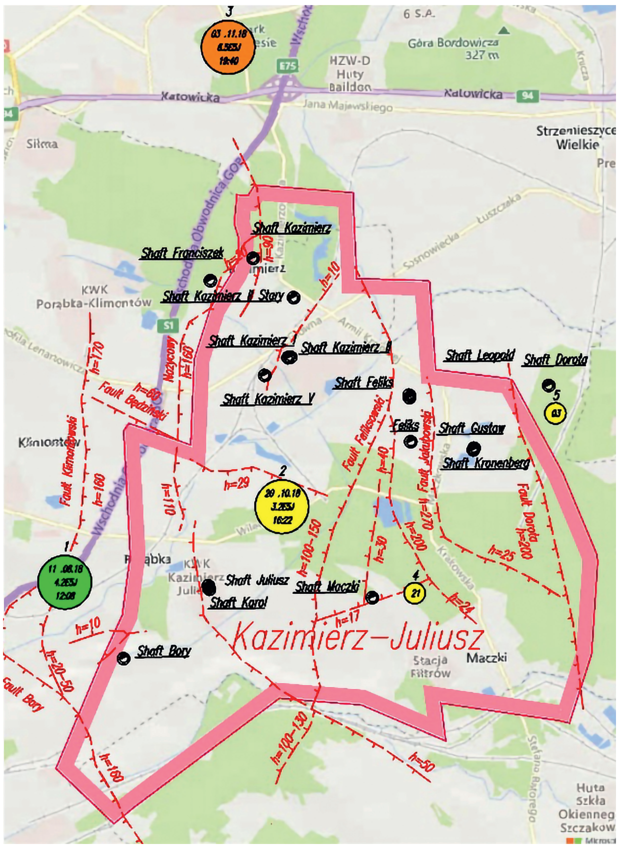


Fig. 10. Layout of epicenters of the analyzed tremors in 2018–2020

Ryc. 10. Rozkład epicentrów analizowanych wstrząsów w latach 2018–2020

3.2. Analysis of results – analysis of the area with the observation of potential qualitative relationships

The analyses presented in this chapter concern the results obtained in the period 2018–2020 (until the end of August). They were developed on the basis of historical satellite data. They are not supported by other results that can be obtained by classical or remote methods. This is a great limitation in terms of the potential to interpret the results obtained then from the InSAR method.

Based on interferometric images covering the period from January 12 to January 27, 2019, it was reported that there could be vertical movements of ground surface in the "Kazimierz-Juliusz" mining area. The interferograms generated from radarograms generated from satellites moving in orbits 102 and 175 include the rock tremor dated on January 21, 2019. Due to low energy of the tremor (with undetermined magnitude), only slight changes in the morphology of ground surface in the vicinity of the village of Maczki can be confirmed (Fig. 11). The village is located to the southeast of the recorded tremor focus. Altitude changes can be characterized by values in the range of single millimeters, which are only slightly beyond the accuracy range of the DInSAR method. Most likely, they did not exceed the value of 1 centimeter. The analysis of successive interferograms, covering wider time databases, indicates that the impact of the tremor on ground surface was incidental. The subsidence occurred most probably in a fairly short time, within a maximum of a few days. This conclusion was based on the identified lack of propagation of subsidence on the successive examined interferograms. We also cannot rule out the hypothesis of an immediate change in the course of ground surface, which could have occurred even during the tremor (possibly shortly after its occurrence). The characteristics, including the dynamics of changes in ground surface in effect of post-mining tremors, are the subject of research of the carried out project.

The analysis presented above is practically of qualitative character and it is burdened with a considerable uncertainty. The reason for this is that there is no additional (supporting) and more precise altitude information from the area of the research. For example, there is no precise information about changes in the altitude of permanent terrain points. This type of data could be obtained, for example, by geodetic methods (precise geometric leveling). For this reason, it is also impossible to precisely define the boundaries of the zone of changes in the morphology of ground surface. At the border of the zone there are "image blurrings" attributed to the small value of subsidence, falling within the range of the so-called measurement noise. For this reason, the zone of slight subsidence can be much larger.

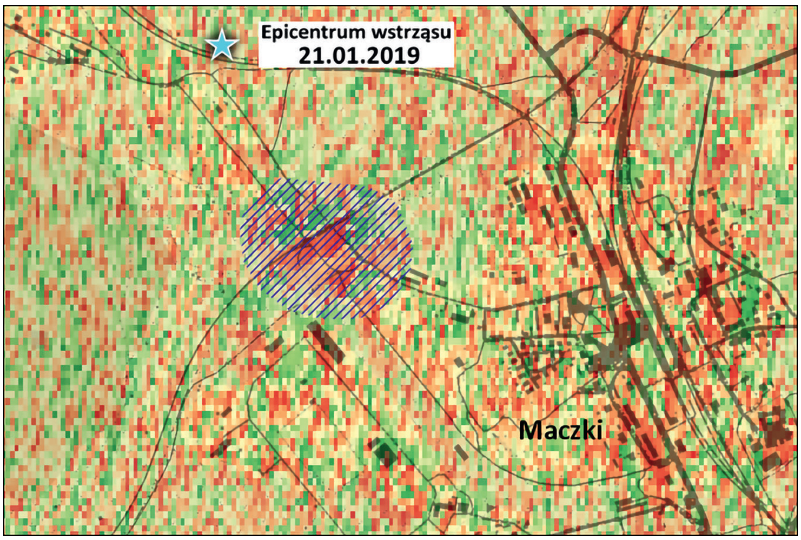


Fig. 11. Estimated zone of altitude changes of ground surface in the mining area Kazimierz Juliusz in January 2019

Ryc. 11. Szacowana strefa zmian wysokościowych powierzchni terenu w obszarze górniczym Kazimierz Juliusz w styczniu 2019 roku

4. CONCLUSIONS

Differential interferometric images obtained from repeatable satellite radar systems (SAR) provide a possibility to map the deformations of ground surface and to monitor their spatial-temporal changes. In particular, they can be successfully used to analyze the dynamics of ground surface changes effected by post-mining tremors.

The interferometric monitoring carried out in the period of 2018–2020 (until the end of August) in the mining area of the Kazimierz-Juliusz mine confirmed that there were altitude changes after one of post-mining tremors. The epicenter of the tremor was located near the area where these changes were found. The analysis of the developed series of interferograms pointed to the incidental impact of the tremor on the deformation of ground surface. The analyses presented in the article are of a qualitative nature and are burdened with high uncertainty. The main reason underlying this fact is the lack of reference measurement data with sufficiently high precision. As part of the research involving the presented project, a monitoring system was implemented in the research area to ensure the provision of such data. It includes both data obtained with the use of satellite methods (GNSS) as well as data from classical measurements (precise leveling).

An additional important aspect of research leading to the explanation of the mechanisms and causes of seismicity and deformation of ground surface, as assumed in the project, is aimed at establishing the relationship between seismic events or ground surface deformations and the process of mine flooding. This requires a series of multidirectional analyses which take into account both the structure and shape of rockmass, the existing subsidence trough and the completed mining of the deposit.

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