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MAPPING OF SLOW VERTICAL GROUND MOVEMENT CAUSED BY SALT CAVERN CONVERGENCE WITH SENTINEL-1 TOPS DATA

MONITORING POWOLNYCH RUCHÓW POWIERZCHNI TERENU WYNIKAJĄCYCH Z KONWERGENCJI KOMÓR SOLNYCH PRZY WYKORZYSTANIU ZOBRAZOWAŃ RADAROWYCH Z MISJI SENTINEL 1

The geodetic measurements optimization problem has played a crucial role in the mining areas affected by continuous ground movement. Such movements are most frequently measured with the classical geodetic methods such as levelling, tachymetry or GNSS (*Global Navigation Satellite System*). The measuring techniques are selected with respect to the dynamics of the studied phenomena, surface hazard degree, as well as the financial potential of the mining company. Land surface changes caused by underground exploitation are observed with some delay because of the mining and geological conditions of the deposit surroundings. This delay may be considerable in the case of salt deposits extraction due to slow convergence process, which implies ground subsidence maximum up to a few centimeters per year. Measuring of such displacements requires high precision instruments and methods. In the case of intensely developed urban areas, a high density benchmark network has to be provided. Therefore, the best solution supporting the monitoring of vertical ground displacements in the areas located above the salt deposits seems to be the Sentinel 1-A radar imaging satellite system.

The main goal of the investigation was to verify if imaging radar from the Sentinel 1 mission could be applied to monitor of slow ground vertical movement above word heritage Wieliczka salt mine. The outcome of the analysis, which was based on DInSAR (*Differential SAR Interferometry*). technology, is the surface distribution of annual subsidence in the period of 2015-2016. The comparison of the results with levelling confirmed the high accuracy of satellite observations. What is significant, the studies allowed to identify areas with the greatest dynamics of vertical ground movements, also in the regions where classical surveying was not conducted. The investigation proved that with the use of Sentinel-1 images sub centimeters slow vertical movements could be obtained.

Keywords: SAR Interferometry, DInSAR, Sentinel 1, slow mining subsidence, salt mine

Problem optymalizacji pomiarów geodezyjnych na obszarach poddanych wpływom ciągłych deformacji powierzchni terenu wciąż stanowi wyzwanie. Pomiary ruchów powierzchni na terenach górniczych

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najczęściej wykonywane są przy wykorzystaniu klasycznych metod geodezyjnych takich jak niwelacja, tachimetria czy pomiary GNSS. Technika pomiarowa jest dobierana w odniesieniu do dynamiki zjawiska, stopnia zagrożenia powierzchni terenu i potencjału finansowego, którym dysponuje zleceniodawca. Przekształcenia powierzchni terenu obserwowane są z pewnym opóźnieniem w stosunku do czasu prowadzenia wydobycia. Opóźnienie to wynika m.in. z warunków górniczo-geologicznych otoczenia złoża i jest zdecydowanie największe w przypadku prowadzenia wydobycia soli. Powolna konwergencja podziemnych wyrobisk powoduje osiadania powierzchni terenu dochodzące maksymalnie do kilku centymetrów rocznie. Pomiar tego typu deformacji wymaga wysokiej precyzji, a w przypadku intensywnego zagospodarowania powierzchni terenu również znacznej gęstości sieci pomiarowej. Dlatego też, optymalnym rozwiązaniem wydaje się być wykorzystanie zobrazowań radarowych satelity Sentinel 1-A jako metody wspierającej monitoring przemieszczeń pionowych powierzchni terenu na terenach znajdujących się nad złożem solnym. Prezentowane badania dotyczyły analizy możliwości wykorzystania zobrazowania satelitarnego pochodzącego z misji Sentinel dla wsparcia monitoringu deformacji powierzchni terenu na obszarze miasta Wieliczka na bazie technologii DInSAR. Wynikiem przeprowadzonych analiz jest powierzchniowy rozkład rocznych przyrostów osiadań w okresie 2015-2016 nad konwergującymi wyrobiskami górniczymi. Otrzymane wyniki, poddane analizie dokładnościowej poprzez ich porównanie z pomiarami geodezyjnymi realizowanymi na liniach obserwacyjnych, potwierdziły bardzo wysoką dokładność pomiarów satelitarnych. Prowadzone badania pozwoliły na wyłonienie rejonów o największej dynamice ruchów pionowych, również w strefach, w których klasyczne pomiary geodezyjne nie są prowadzone.

Słowa kluczowe: InSAR, DInSAR, Sentinel 1, powolne osiadanie powierzchni terenu, kopalnia soli

1. Introduction

The measurement of ground movement performed at the Measurement and Geology Department of Wieliczka Salt Mine concentrates on a thorough analysis of impact of underground, historical salt workings, and is mainly conducted with the use of precise levelling method. The measurement network is dense in the center of town, while in other areas data coverage is sparse (Fig. 1). The levelling series are conducted along the main streets. The low density of geodetic land network in some zones does not allow for reliable estimation of current displacement rates

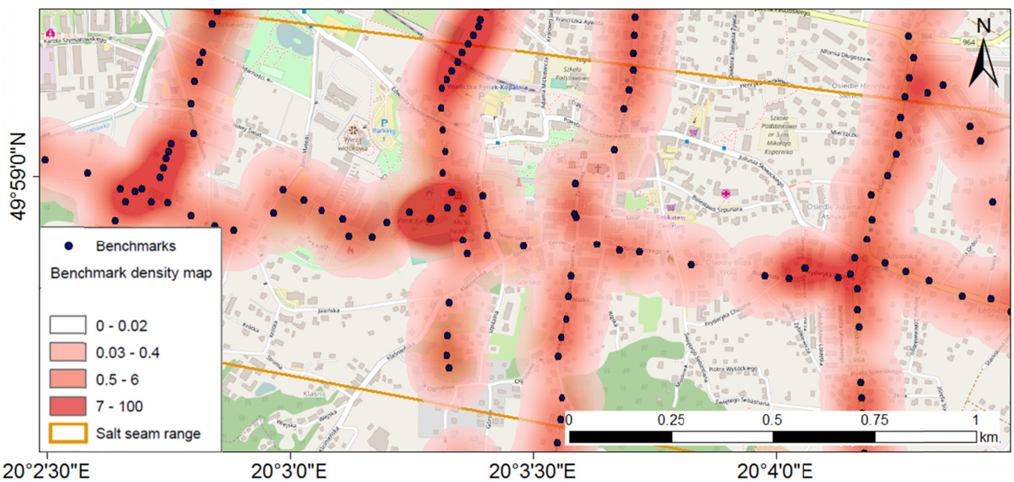

Fig. 1. Geodetic network near Wieliczka town and point density map which convey the intensity of an benchmark location (Ulmaniec & Stawarczyk, 2016)

and spatial distribution of land surface displacement. A map of intensity of benchmarks occurrence was provided to better representation of coverage of the surface with geodetic observations. Benchmark density map indicates a region where ground movement might be registered with high reliability (red color, Fig. 1). It has been assessed that ground displacements can be established for about 25% of the surface (Fig. 1). Whereas reliability of estimated displacement field in the remaining areas is lower.

The measured vertical ground displacement has been almost linear for years and equaled to ca. 0.03 m per year. Due to relative small increments of displacement the accurate measurements and information about factors influencing their uncertainty (instability and damaged benchmarks, natural movement of the ground surface, etc.) is a complex issue to address. This considerably increases the measurement time required for every time-series and also determine levelling technique. The Measurement and Geology Department undertakes efforts at optimizing measurements and simultaneously increasing the efficiency of monitoring to provide safety of the ground users. Hence loomed numerous concepts focusing on, among others, the implementation of new measurement technologies complementary to the classic measurements. The objective of this research is to assess applicability of Differential SAR Interferometry (DInSAR) to the analysis of slow ground movements caused by salt cavern convergence. The primary focus was to investigate whether the accuracy of the satellite mapping with Sentinel images could be applied to detect sub-centimeters ground displacement. Sentinel satellite data was analyzed for its suitability to complement classic measurements in a function of time, especially in areas with a scarce coverage of geodetic benchmarks.

In the framework of Copernicus program administered by the European Commission in cooperation with European Space Agency the Sentinel mission was developed (Sentinel-1 User Handbook, 2013; European Space Agency, 2017). Two satellites: Sentinel 1-A and Sentinel 1-B taking part in mission were designed for interferometric analyses. The first of them has had an operational status since October 2014, and the other one has provided imaging of the land surface since September 2016. The Sentinel satellites provide free-of-charge, generally available data, on the basis of which the natural environment can be monitored. Each satellite in Poland gives the coverage of the same fragment of surface in a 6-days interval, with a time shift of imaging of Sentinel 1-A and Sentinel 1-B, equal to 3 days (Yague-Martinez et al., 2016). The Synthetic Aperture Radar (SAR) systems mounted on the satellites operate in the C band of 5.405 GHz. The images are acquired by the Interferometric Wide Swath Mode, using the Terrain Observation with Progressive Scans SAR (TOPSAR). This method lies in interferometric imaging of a given surface in three sub-swaths, each 250 km long and situation resolution 5 m per 20 m, using a mobile antenna, which cyclically directs a radar beam to and from the azimuth of the satellite trajectory. In this solution a larger surface can be imaged during one passage and contemporaneously necessitates new algorithms for data processing. The TOPS scanning mode was already used experimentally in satellites *TerraSAR-X* and *RADARSAT-2* (Yague-Martinez et al., 2016).

2. Study area

The research was conducted in the area of Wieliczka town, over a historical salt mine. The analyses were focused on the entire area localized over salt caverns, i.e. ca. 18 km^2 (Fig. 2). Almost the whole densely built up center of Wieliczka town is located above former underground

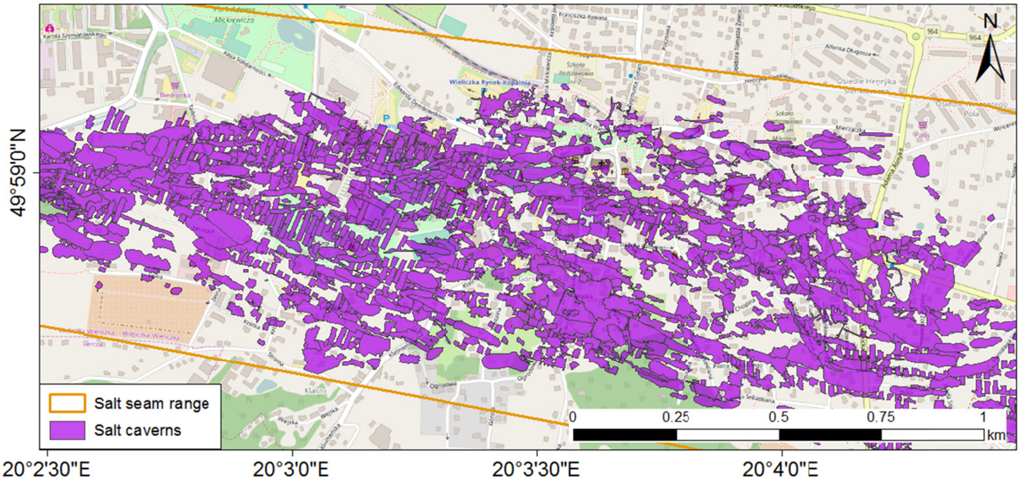

Fig. 2. Salt caverns located below the Wieliczka town (Ulmaniec i Stawarczyk, 2016)

mine workings. A discussion of geological, hydrogeological and mining settings is presented in order to set context and root cause of ground movements.

2.1. Geological and mining settings

The salt deposit under Wieliczka town extends in the form of a belt about 1.5 m wide and 10 km long. The depth of deposition ranges from about 30 or so meters b.s. to ca. 340 m b.s. Salt deposit can be divided into a shallower block formations and underlying bedded deposit (Hwałek, 1971; Kleczkowski, 1993; Garlicki i Szybist, 1995).

Block deposit mainly consist of waste rock (marly siltstones dominate) which are distributed by halite blocks ('zubry', Fig. 3). It is visibly laminated as a result of the presence of silt, which contaminates the intercrystalline space. The salt from that deposit has been extracted since the

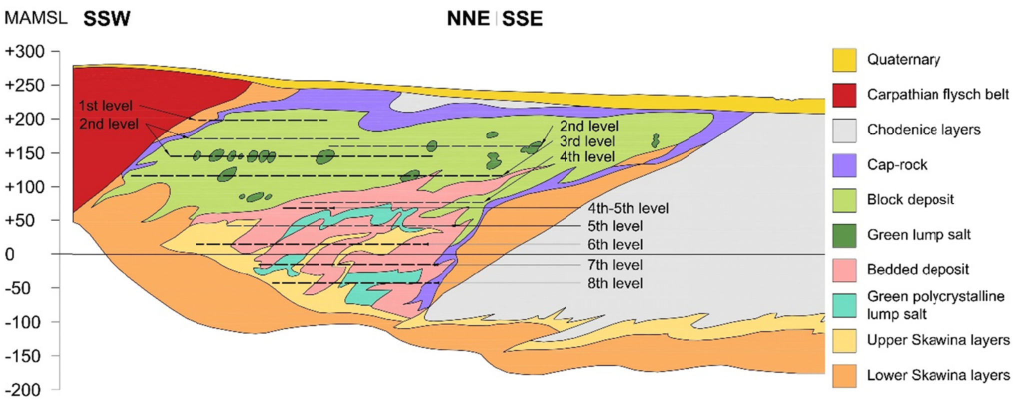

Fig. 3. Geological cross section for the salt seam near to Kościuszko shaft (Hwałek, 1971)

16th century with the dry and wet methods. The dry methods (cutting off the salt blocks) were conducted by the end of the 19th century. In the 20thcentury explosives were used for the salt production. In the second half of the 20thcentury the block deposit was extracted by leaching of salt with fresh water. Used excessively, this method resulted in caves collapse in some parts of the deposit. In some areas post-mining voids migrated between levels, in other water inflow was observed in the underground workings.

High complexity of geological setting determined chosen mining extraction systems. The chambers in the bedded deposit have varying forms depending on the shape of the deposit and tectonics (d'Obyrn & Wiewórka, 2012; Ulmaniec & Stawarczyk, 2016). Part of chambers were extracted with the room and pillar method have regular cuboids shape (width 2-3 m and length 20-30 m). The geometry of chambers extracted with leaching method is burdened with high uncertainty. The degree of contraction of mining workings is also conditioned by rock mass pressure, which generally increases with depth. The total number of extracted chambers is assessed to about 2400. Their original volume before backfilling was about 8.1 mln m^3. As a result of constantly performed protection works, the volume of backfilled chambers currently equals to 4.9 mln m^3 (Garlicki & Szybist, 1995). Depending on the type of salt and shape of caves the rate of volumetric convergence oscillated from –0.16 to 1.64 m^3/year.

Analysis of spatial distribution of height of empty void, lead to creation raster image representing left voids for each mining level. That raster images allowed for calculating the total void in vertical plane for all levels. The maximum sum height of the void was 23 meters (Fig. 4). The height of the void in most of the areas did not exceed 3 meters (76 % of voids). The surface of the area located directly above the voids equaled to about 1.1 km^2.

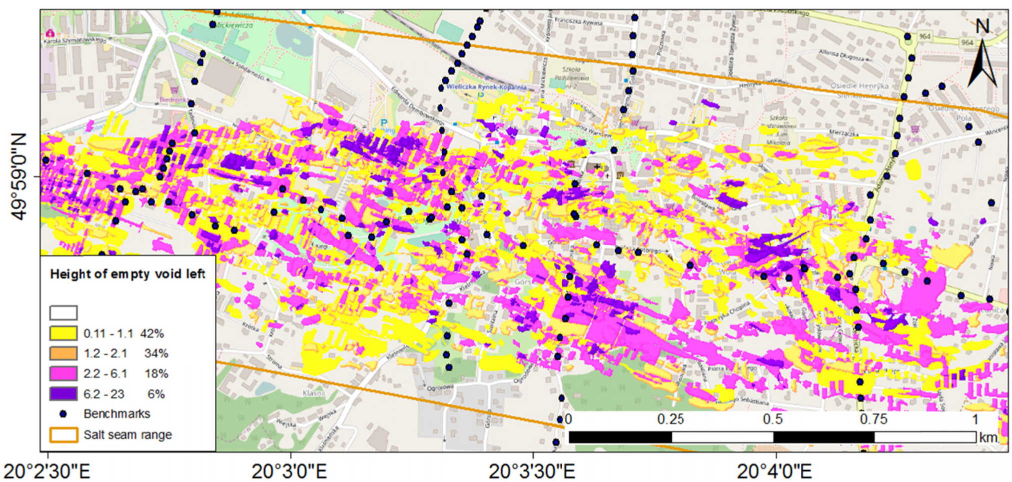

Fig. 4. Raster image of summarized height of post mining void for all mining levels (Ulmaniec & Stawarczyk, 2016)

To better visualize the distribution of non-backfilled voids under the town addition raster image was generated. The spatial distribution of voids left was presented in form of density map (Fig. 5). The bigger is empty void left below the surface the more dens color is marked on the map.

The density map of underground empty voids has obtained by kernel density interpolation function (Epanechnikov, 1969; Rosenblatt, 1956; Scott & Terrell 1987). That method allows one to non-parametrically determine the density of occurrence of a given random variable. The random variable was dimension of empty void for each pixel (Fig. 4). The kernel density estimator as a non-parametric solution enable to present distribution of voids in a continuous form (Fig. 5).

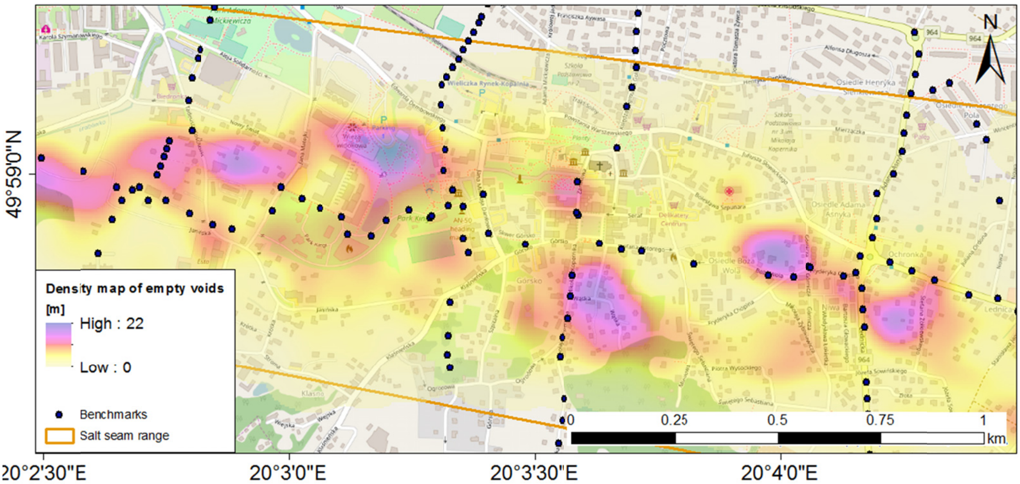

Fig. 5. Raster image of voids left underground prone to convergence

The intensity indicates that a zone of highest displacement rate potential exists in the north part of the town (Fig. 5). That void slowly converges, being one of the major causes of surface and rock mass deformations (d'Obyrn & Wiewórka, 2012).

2.2. Hydrogeological setting

Another factor influencing ground and rock masses deformation is water migration in the old mining workings. Four aquifer levels could be recognized in the neighborhood of the Wieliczka deposit (Kleczkowski, 1993). The Chodenice beds are considered to be the dominating water collector in the area of the Wieliczka deposit. These beds are built of fine sandstones and dusty sandstones about 20 m thick. The complex, and highly disturbed tectonic build creates advantageous conditions for hydraulic connections with shallower layers. The cracks and fractures prompt the water flow to the mine even from distant areas. Therefore this horizon creates the major water threat for the mine. A number of sinkholes caused by dissolution of salt chambers have been observed in the history of the mine (Fig. 6). The most serious water inflow causing treat to the surface happened in 1992. The terrain subsided 1.6 meters many infrastructure objects was damaged (Brudnika et al., 2010; Perski, et al., 2009). Water is considered as a major treat to mine that is why Salt Mine Wieliczka is systematically monitored for leaks in levels I to IV (Brudnika et al., 2010). Many years' observations prove that the biggest water flux hazard is associated with the northern area of the deposit border. The strongly watered Chodenice beds lying beyond the deposit at its northern border and the considerable density of workings in this part of the deposit may contribute to the increased migration of water in this area. A considerable number of leaks are also observed in the central part of the deposit, but these are drop leaks. The highest rates of water droplets are observed for leaks in the northern part of the deposit.

Density map of water leakages proved the thesis about distribution of former sinkholes and areas prone to water migration in mine. Fracturing of the watered areas may lead to additional ground movements due to water withdrawal from the Chodenice aquifer (Brudnika et al., 2010).

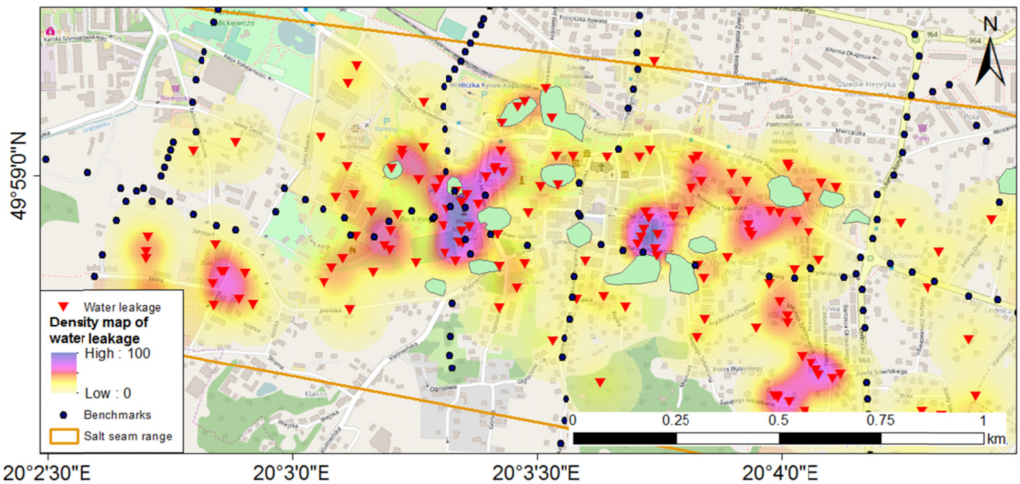

Fig. 6. Density map of underground water leakage (Ulmaniec & Stawarczyk, 2016)

As shown above, the diversified geological-mining and hydrogeological conditions are a cause of complex deformation processes taking place both in the area of mining workings and on the surface. The evaluation of dynamics of such movements should be based on multidimensional cause-and-effect analyses, linking mining, geological and hydrogeological conditions with deformations inside the rock mass and on the surface.

3. Material and methods

The main objective of the research was evaluation of applicability of radar imaging from Sentinel mission to assess the slow movements caused by convergence of mining workings in Wieliczka Salt Mine.

3.1. Differential interferometry

The SAR images in this study were processed with DInSAR (Differential Interferometry SAR), which allows for obtaining information about the movement of the ground surface by comparing differences of phases of two radar images performed over the same area in different periods of time. The use of this method in Wieliczka is justifiable because of the relatively dense development and strongly developed technical infrastructure – own properties of this type of objects produce a relatively strong reflection of radar wave and a high coherence interferogram is obtained. The choice of this method can be also proved by the examples of satellite imaging for detection of discontinuous or continuous ground movement deformations caused by different physical phenomenon. Investigation which has been carried out since early nineties proved high applicability of differential interferometry to observe of significant vertical ground movements caused by mining activity (Abdikan et al., 2014; Krawczyk & Perski, 2010; Lazecky et al., 2012; 2017; Milczarek et al., 2017; Szczerbowski & Piątkowska, 2015; Yerro et al., 2013). Not only vertical movement caused by mining activity or water extraction, which have linear character, can be observed with DInSAR (Hoffmann & Zebker, 2003; Galloway & Hoffmann, 2007; Sowter et al., 2016). More dynamic phenomenon like ground movement caused by seismic tremors (Majmudar, 2013) or eruption of volcanoes (Ozawa i Kozono) can be also observed with DInSAR technique. Observation of ground movement related to landslides are also supported by InSAR (Greif & Vlcko, 2012; Perski et al., 2010; Wasowski et al., 2009). Latest investigation revealed that satellite interferometry could support early warning monitoring system against sinkhole occurrence (Chang & Hanssen, 2014).

The differential interferogram was performed on the basis of two radar images obtained from the same orbit of Sentinel 1-A satellite in 2015 and 2016 (Tab. 1). Sentinel images were selected according to the dates of leveling measurements. Due to relatively small ratio of ground movements one sub timeframes was analyzed. The noise from subsequent differential images in shorter sub timeframes was bigger than observed ground movement.

TABLE 1

Images obtained from Sentinel 1-A satellite used in the investigation

Type of image	Date of SAR imaging	Number and type of satellite orbit	Angle of radar beam [deg]	Length of transverse base [m]	Time [days]
Master image	10/03/2015	175, ascending	23	29	371
Slave image	15/03/2016	175, ascending	23		

Data processing consisted of several steps (Fig. 7). At first the radarograms were coregistered, i.e. the respective pixels in the slave image were spatially adjusted to the pixels in the master image. This process was performed on the basis of information about precise orbits of Sentinel 1-A satellite and Numerical Model of Terrain (NMT) of field resolution equal to 3" (ca. 90 m per 90 m) and height accuracy ca. 16.7 m, from the Shuttle Radar Topography Mission. At the next stage, an interferogram was formed by multiple production of the amplitude of signals of two radarograms, and it contained an information about the difference of phases between two SAR images and the calculated coherence for each pixel. The phase difference of interferometric image should solely depend on the difference of distance between satellites performing radar imaging and a given point on the ground surface (m. in. Prats-Iraola et al. 2008, Rucci et al. 2012). The atmospheric delay was separated by filter application (Zebker et al., 1997; Zebker 2003; Hanssen, 2001). Using equation (1), one can calculate line-of-sight displacement from satellite (LOS).

$$\Delta\varphi_{disp} = \frac{4\pi\Delta R}{\lambda} \tag{1}$$

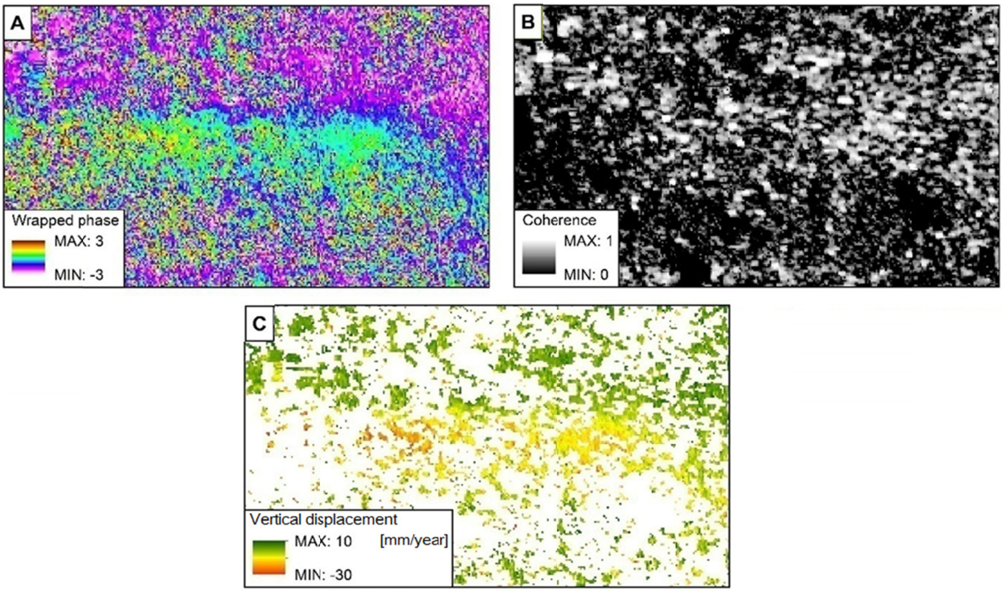

Fig. 7. Interferogram with wrapped phase information a), estimated coherence b), vertical displacement with high value of coherence >0.6 c)

where:

- ΔR — difference of distance between satellites performing radar imaging and a given point on the ground surface;
- λ — length of radar beam.

The observed value of phase difference is a sum of five components (2):

$$\Delta\varphi = \Delta\varphi_f + \Delta\varphi_{el} + \Delta\varphi_{disp} + \Delta\varphi_{atm} + \Delta\varphi_n \tag{2}$$

where:

- $\Delta\varphi_f$ — part of phase resulting from the curvature of the Earth;
- $\Delta\varphi_{el}$ — part of phase resulting from the topography of terrain;
- $\Delta\varphi_{disp}$ — part of phase responsible for displacements of the observed surface;
- $\Delta\varphi_{atm}$ — value resulting from the atmospheric impact (humidity, temperature, pressure);
- $\Delta\varphi_n$ — noise.

Vertical movement of ground surface was estimated based on equation:

$$d = \frac{\Delta\varphi_{disp}unw \cdot \lambda}{-4\pi\cos(\theta)} \tag{3}$$

where:

- d — vertical movement of ground surface;
- $\Delta\varphi_{disp}unw$ — unwrapped length of radar beam responsible for part of phase difference resulting from the movement of observed surface;
- θ — angle of radar beam propagation.

3.2. Results validation based on classical surveying measurements

For the sake of validating DInSAR displacement image the geodetic stable benchmarks has to be chosen. The stability of benchmarks was defined on the basis of precise levelling results conducted in 2015 and 2016. Benchmarks with the module of annual vertical displacements lower than 0.1 mm were considered to be constant (Fig. 8). Additionally, benchmarks in the landslide area and in places where the coherence of the interferogram were lower than 0.6 were rejected (Perski et al., 2009; Wasowski et al., 2009). Finally, 27 points were classified in the group of constant benchmarks (Fig. 8)

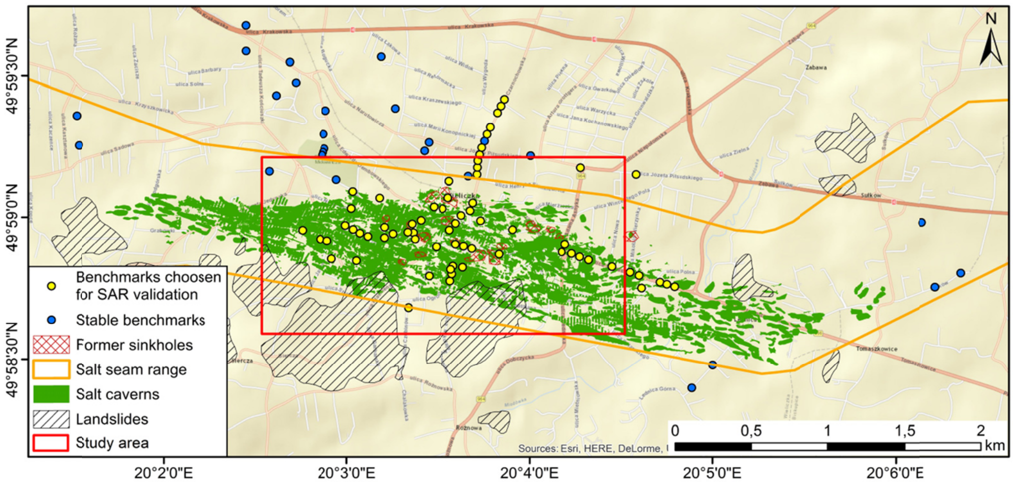

Fig. 8. Stable benchmarks chosen for SAR validation

In order to determine the 'reference constant' there was analyzed a zone around the constant benchmarks being a buffer of a 42 m radius (Fig. 9). On the assumption of a normal distribution of vertical displacement calculated with the DInSAR technique, the average value of the 'reference level' was established in areas considered as stable. From among 426 pixels of a difference interferogram benchmark inside definite buffer areas 283 statistically significant pixels were selected. The 'reference level' calculated on this basis equaled to -42.6 mm, and standard deviation ±1.8 mm.

Then the reference level was used to generate the real value of surface movement towards the radar beam propagation, in the years 2015-2016. The comparison of the results of precise levelling with the results of the interferometric survey was carried out based on 67 benchmarks. The height that points was defined with the precise levelling method in the years 2015-2016 (Fig. 9). The difference between the value of surface displacement calculated from the difference interferogram and precise levelling was determined on the basis of 714 pixels of interferometric image of statistically significant pixels from among 1221 pixels inside the buffer zones. It equaled to 1.3 mm, at a standard deviation of ±0.8 mm (Fig. 9).

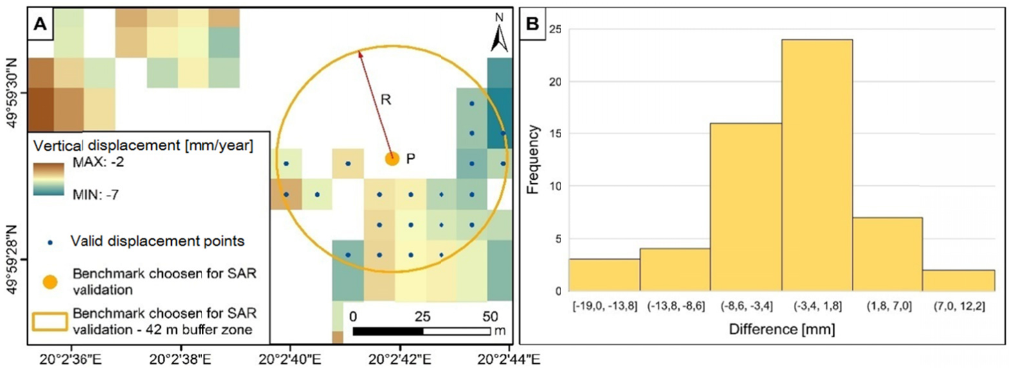

Fig. 9. Selecting valid points around an arbitrary benchmark P with a radius of R corresponding to vertical displacement pixels a), normal distribution of displacement calculated with the DinSAR technique b)

4. Results discussion

Areas undergoing surface movement are more and more frequently subjected to various remote sensing analyses, including InSAR surveys. In a number of cases the analysis of such movement in areas transformed anthropogenically and naturally does not account for the causes of the observed phenomena. The element needed for achieving a reliability of analyses based on radar imaging is information on the basis of which the obtained results can be validated, e.g. results of precise classic surveying. Authors attempted to present the nature of this problem on a scheme of InSAR data.

The results of the investigations reveal (Fig. 10), that areas localized south of the mine area undergo natural landslide movements. The entire center of the former mining area and its immediate neighborhood are the mining impact areas. For this reason these facts were accounted for in the analysis of stability of benchmarks and further calculations of ‘reference constant’.

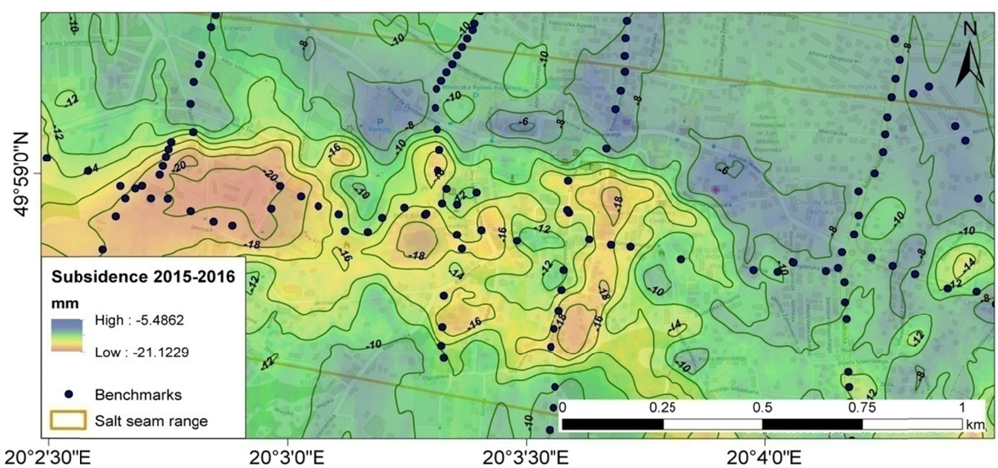

Fig. 10. Observed ground subsidence [mm] derived from Sentinel-1A images in the years 2015-2016

The obtained results prompt a conclusion that two zones of various vertical displacement can be detected in the post-mining-impact areas, i.e. zone of more and less dynamic movements. The annual subsidence of up to 21 mm are observed in the western and partly in central part of the former mining area. In the east the movements fade away or are close to zero (Fig. 10).

The comparison of the spatial vertical movement of surface with the results of mining-geological and hydrogeological analyses proves the dependence between the converging void and the high-dynamics zones (Fig. 11). Further investigation revealed that there was no spatial correlation between observed ground movements and areas affected by former sinkholes.

Moreover analysis of relation between measured ground movements and height of empty void was conducted (Fig. 12). That relation is almost linear. With the increase of volume of empty voids the ground subsidence was raising.

In the eastern part of the town the surface is observed to subside up to 20 mm per year. This is a result of convergence of underground voids. A similar spatial distribution of surface dynamics can be expected in the successive years.

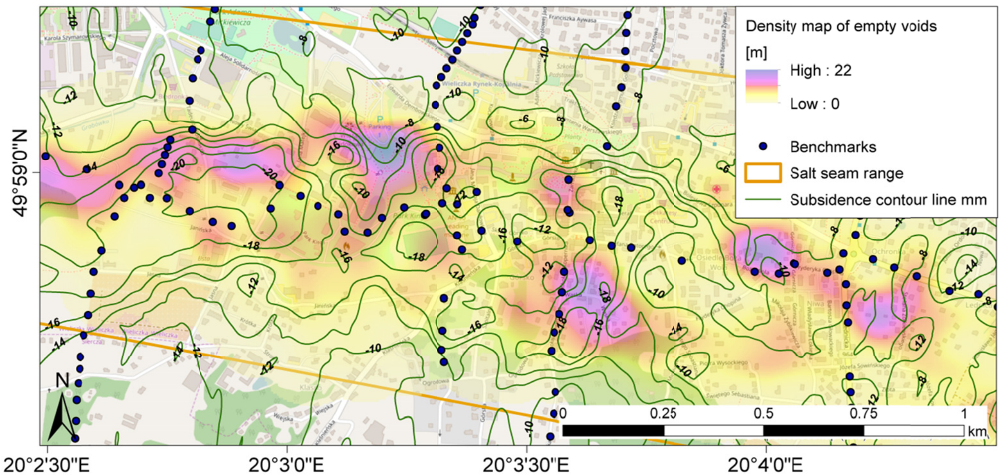

Fig. 11. Cause and effect analysis among spatial distribution of observed subsidence in 2015-2016 and height of left underground voids in mining workings

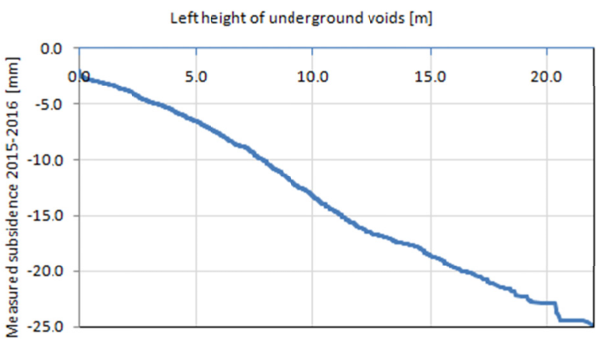

Fig. 12. Relation between ground subsidence and volume of underground void

5. Conclusions

The presented analytical results reveal that radar imaging from Sentinel mission may support surveying of slow movement of the ground surface due to the convergence of salt chambers. The imaging of the surface movements in the years 2015-2016 confirmed the high accuracy of observations with the use of DInSAR technology, even for the annual mean subsidence up to 21 mm. The satellite imaging results were validated on the basis of surveying in that area. Classic, precise surveying are needed to provide good reliability of satellite measurements. The differences between satellite and surveyed vertical movements of the ground surface was calculated from 714 pixels of interferometric image. The difference equated to 1.3 mm, at standard deviation ±0.8 mm. The satellite imaging proved the subsidence dynamics in the western part of the town up to 20 mm per year. Smaller subsidence was observed in the eastern part of the town. Observed surface displacements are congruent with many years' surveys in the area of the Wieliczka town. Cause and effect analysis between mining and geological condition and observed ground movement proved evidence about significant link between scale of movement and volume of converging underground void. The western part of study area is subsiding 21 mm per year, were the subsidence in the eastern part do not exceed 10 mm. Further investigation revealed that areas with observed significant movements (up to 20 mm) did not correlate with areas influenced by water infiltration or movements related to former sinkholes. That statement could support the thesis about lack of hazard caused by reactivation of former sinkholes.

The proposed methodic of quasi continuous monitoring of ground movement dynamics in the „Wieliczka" Salt Mine allows for a better control of stability of rock mass in the area of underground voids. In this approach, the zones and values of subsidence have also been defined in the areas where no direct surveying has been conducted. In the successive years the satellite imaging can be successfully implemented in „Wieliczka" Salt Mine as a method supporting classic surveying.

Acknowledgements

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