Mon-21-075

The satellite radar monitoring of post-mining area (Solotvyno, Ukraine)

S. B. Shekhunova *(Institute of Geological Sciences NAS of Ukraine, Kyiv, Ukraine)*, ***M. Yu. Pakshin*** *(Center of the Special Information Receiving and Processing and the Navigating Field Control, Zaliski, Ukraine)*, ****S. M. Stadnichenko*** *(Institute of Geological Sciences NAS of Ukraine, Kyiv, Ukraine)*, ***I. I. Liaska*** *(Center of the Special Information Receiving and Processing and the Navigating Field Control, Zaliski, Ukraine)*, ***M. V. Aleksieienkova*** *(Institute of Geological Sciences NAS of Ukraine, Kyiv, Ukraine)*

SUMMARY

Radar research is an area of remote sensing of the Earth, which has been successfully used recently, including monitoring the earth's surface in mining and post-mining areas. The territory of Solotvyno, the emergence and development of which is associated with salt extraction, differs in the development of natural and man-made hazardous geological processes, which in recent decades have become uncontrolled. Analysis of satellite images interpretation results was carried out in order to establish the basic patterns of surface deformations (earth's surface vertical displacements frequency and scale), assess the intensity of hazardous geological processes manifestations and their impact on critical infrastructure objects, areas of enhanced vulnerability and/or uncertainty of risks. Using the results of satellite radar monitoring, the assessment of natural-technogenic hazardous geological processes of Solotvyno area in 2016-2020 was done. The assessment of the control objects vertical displacements was performed using interferometric processing of satellite radar monitoring data with the ENVI software SARScape module by applying multi-pass radar interferometry technologies (SBAS and PS approaches). As the result of monitoring, the new data were obtained on the parameters of hazardous natural-technogenic processes manifestations in Solotvyno, their impact on critical infrastructure objects was assessed, zonation and risk scheme were improved.

Introduction. Radar research is an area of remote sensing of the Earth, which has been successfully used recently, including monitoring the earth's surface in mining and post-mining areas. The active use of radar data for the last six years has become possible only due to the advent of the European Space Agency's (ESA) Copernicus program and Sentinel-1 data, which are in the public domain. Taking advantage of the radar imagery availability from the satellites Sentinel-1A and 1B, it has become possible for most researchers to quantify the Earth's deformations in both vertical and east-west directions by combining radar scanning data obtained during satellite flights from south to north and from north to south. The territory of Solotvyno (Transcarpathian region, Ukraine), the emergence and development of which is associated with salt extraction, differs in the development of natural and man-made hazardous geological processes, which in recent decades have become uncontrolled. The development of salt karst, subsidence and landslides, flooding, surface and groundwater pollution, limit the use of natural resources, economic development of the territory, pose the threat of transboundary pollution of the Tysa River etc. The current research is carried out within the framework of the REVITAL 1 project (HURSKOVA/1702/6.1/0072 under the ENI CBS Programme), the main goal of which is the development of a permanent complex monitoring system for the Solotvyno post-mining area and adjacent territories. The authors' previous studies have focused on hazards identification and characterization, hazards mapping, analysis and ranking. As a result, the territory of Solotvyno was conditionally divided into 16 zones that are characterized by the probability of natural and technogenic hazardous geological processes manifestations: from first zone of catastrophic (100 % probability) to the last 16 zone without visually established hazardous processes manifestations (Shekhunova et al., 2019). In this regard, satellite radar monitoring was carried out to establish the basic patterns of earth's surface deformations (rate and scale of vertical displacements) in order to improve developed zonation scheme, assess the intensity of hazardous geological processes manifestations and their impact on critical infrastructure objects, areas of enhanced vulnerability and / or uncertainty of risks.

Materials and methods. The assessment of vertical displacements of objects and land surface was carried out using interferometric processing of satellite radar monitoring data obtained by means of new satellite constellations including Sentinel-1A and 1B (2016-2020, Centre of the Special Information Receiving and Processing and the Navigating Field Control (CSIRP NFC), Ukraine). Due to the use of long time series of images obtained by Synthetic aperture radar (SAR), the errors of orbital data and the influence of atmospheric phenomena were effectively suppressed. Radar data processing was performed using the ENVI software package SARScape module with multi-pass radar interferometry technologies: areal interferometric analysis (Small Baseline Subset – SBAS approach) and point analysis of permanent reflectors (Persistent Scatterers – PS approach) (Liaska et al., 2017; Pakshin et al., 2021; Parker et al., 2021). The research area was 33 sq. km. The results of processing are digital maps with the accuracy of estimating of objects average vertical displacements rate – 2-4 mm/year using the "PS" technique, 6-15 mm/year using "SBAS".

It's worth noting that, developed Solotvyno zonation scheme was established on the basis of expert assessment of the former hazardous events frequency and scale, changes of topography and geomorphology, geodetic survey, remote sensing data, satellite imagery, Differential Interferometric Analysis data (DinSAR), provided by Copernicus for the European Union Civil Protection Team advisory mission to Ukraine (EUCPT Risk Assessment Report, 2016) and Copernicus reports EMSN-030, EMSN-064; authors' systematic field observations 2008-2020, coupled with summarized previous research results etc. (Stoeckl et al., 2020; Yakovlev et al., 2016).

Results and Discussion. The final information products were created, which made it possible to analyse changes in spatial and temporal dimensions. The values and rates of surface deformations have been determined. The control objects (critical infrastructure objects, areas of enhanced vulnerability and / or uncertainty of risks) were selected according to the Solotvyno zonation scheme, taking into account geomorphological zoning, geological structure, hydrological and hydrogeological conditions (directions of surface and groundwater flows), Solotvyno territory field observations (2008-2020), modern anthropogenic interventions and placement of critical infrastructure facilities etc. (Figure 1).

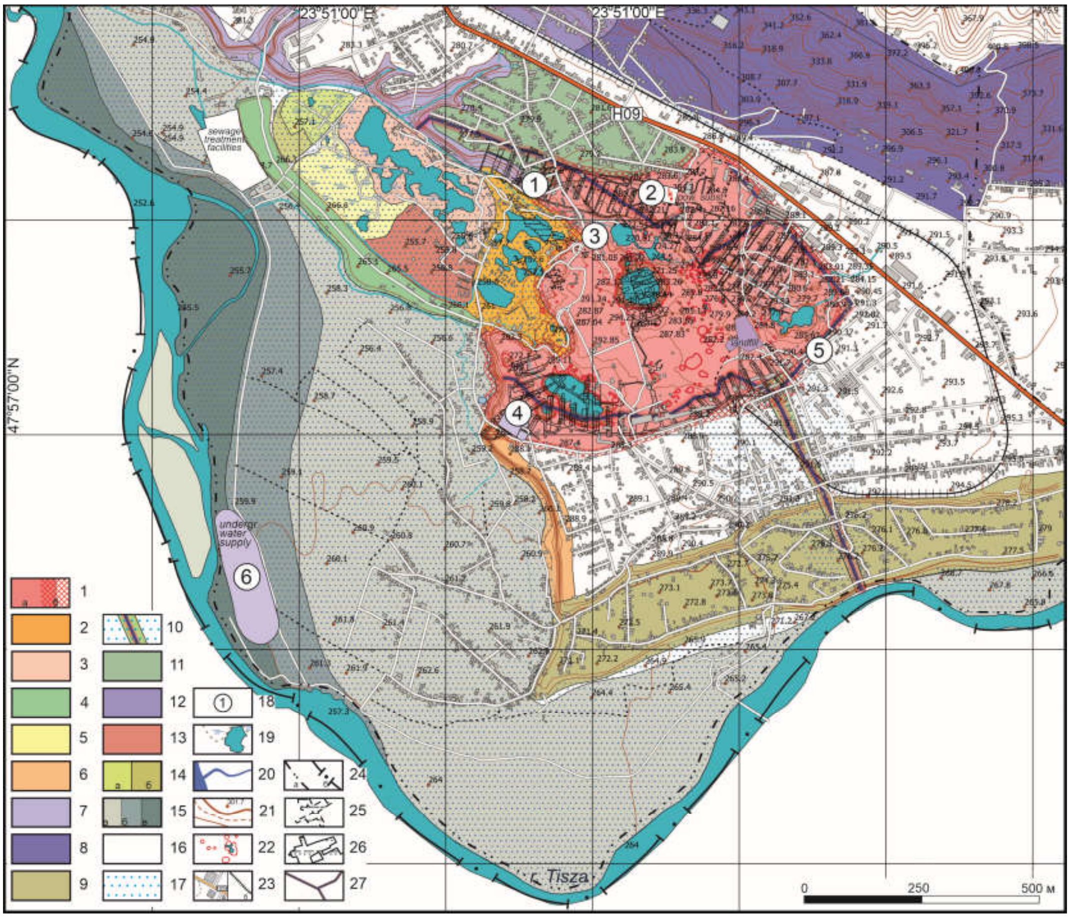

Figure 1 *Zones of hazardous processes manifestations (1-16): 1 – catastrophic, (a) and undefined degree (b), (100%): karst-suffosion sinkholes, subsidence, collapses, landslide formation, erosion etc. (the area of mine fields of shafts No. 7, 8, 9 and Black Mochar); 2 – potentially dangerous (50%): subsidence, karst-suffusion sinkholes, surface displacement, micro-landslides, erosion etc. (technogenically disturbed territory of historical mining activity); 3 – moderate (40%): rock salt dissolution, formation of lakes of different salinity and surface deformation; 4 – moderate (30%): slope erosion and suffosion, enhanced by anthropogenic activity on the dam main body; 5 – moderate (25%): flooding, waterlogging, leaching (Zaton area); 6 – moderate (20%): slope erosion, technogenic flooding etc. (southwestern slope of the 1-st Tisza River floodplain terrace); 7 – moderate (20%): slope erosion, ravine formation due to inherited tectonic disturbances, technogenic flooding etc. (western part of the Tysa River 1-st and 2-nd floodplain terraces slopes); 8 – insignificant (15%): slope erosion, paleolandslides, etc. (Mahura mount slope); 9 – insignificant (15%): slope erosion, paleolandslides, flooding etc. (1-st and 2-nd Tysa River floodplain terrace southeastern slope); 10 – moderate (15): potential technogenic flooding after Tysa drainage gallery collapse; 11 – insignificant (10%): suffusion in tectonic disturbances influence area, technogenic flooding etc. (mine No. 9 western flank); 12 – insignificant (10%): slope erosion, periodical technogenic flooding (Mahura mount); 13 – insignificant (10%): flooding; 14 – insignificant (1%): hydrocarbon contamination (southern (a) and northern (b) part of the abandoned underground infrastructure facility); 15 – potentially dangerous, moderate: floods and flooding with various probability (3%, 50%, 75%) respectively; 16 – without visually established hazardous processes; 17 – potentially dangerous, moderate: flooding of different genesis; 18 –* ***Control objects****: 1 – power transmission tower; 2 – electrical substation, 3 – balneological resort facility, 4 – water pumping station, 5 – five-storey building; 6 – underground water supply facility; 19 – lakes and waterlogged lands of different genesis (natural and technogenic); 20 – rivers and streams; 21 – horizontals (though 5 m) and hypsometric data; 22 – sinkholes and collapses outlines; 23 – streets with buildings, roads, highway H09 (a), railway (b); 24 – Solotvyno contour (a) and the state border zone (b); 25, 26 – contours of mines; 27 – main drainage galleries.*

Based on the satellite radar monitoring data analysis (for the period 30.04.2016 – 30.06.2020) graphs of accumulated earth's surface deformations were plotted for control objects, the assessment of

geodynamic subsidence state of these objects with the vertical displacements rates was carried out (Table 1).
According to the available satellite radar data of the control object – **Balneological / resort facility**, it was possible to assess surface deformations only for the period 2018-2020. Significant values of vertical displacement of -139.98 mm with an average subsidence rate of -67.54 mm/year were established. The data obtained characterize the object as *unstable*, that is related to its position in the first zone with a 100% probability of hazardous geological processes manifestations and close proximity to the field of sinkholes. As for **Underground water supply** facility, the object area is *relatively unstable* with average vertical displacement rate of -28.17 mm/year. At the same time, the slight increase of displacement rate up to -31.59 mm/year in the period 2018-2020, compared to -24.75 mm/year in 2016-2018 were detected, with the total displacement value ranged from -60.32 mm to -69.38 mm.

***Table 1** Satellite radar monitoring data interpretation results on the earth's surface deformation for the control objects*

№ of control object	Control object / Critical infrastructure	Technique (number of measured points per control object)	Vertical displacement, mm	Average displacement rate, mm/year	Time period	Zone	Probability, %
1	Power transmission tower	PS (1); SBAS (5)	-15.44	-3.81	2016-2018	7	20
		PS (2); SBAS (10)	-17.46	-2.79	2018-2020		
2	Electrical substation	PS (35); SBAS (4)	-25.46	-7.98	2016-2018	1	100
		PS (59); SBAS (45)	-27.52	-11.93	2018-2020		
3	Balneological resort facility	PS (1); SBAS (4)	-139.98	-67.54	2018-2020	1	100
4	Water supply pumping station	PS (2) SBAS (5)	-24.25 … -94.93	-11.72 … -34.08	2016-2018 2016-2018	1	100
		PS (8) SBAS (17)	-77.85 -43.56 …	-22.29 -31.66 -20.18 …	2018-2020 2018-2020	1	100
5	Five-storey building	PS (5); SBAS (2) PS (4); SBAS (10)	-13.21; -12.78 …	-1.70 -0.27 …	2016-2018 2018-2020	1(?) 2	50
6	Underground water supply facility	PS (2); SBAS (9) PS (2); SBAS (28)	-60.32 … -69.38	-24.75 … -31.59	2016-2018 2018-2020	15	50-75

The Electrical substation is geomorphologically located on the Tysa River second floodplain terrace, in the immediate vicinity of the steep slope edge. It is situated in the zone of open fracturing and increased water conductivity of the Solotvyno suite deposits. Based on the results of interferometric processing of satellite radar data, the territory is *relatively stable* with an average subsidence rate - 9.96 mm/year. However, there was a slight increase of vertical displacements rate from - 11.93 mm/year in the period 2018-2020, compared to -7.98 mm/year in 2016-2018. The total estimated values of subsidence were from -25.46 to -27.52 mm. According to field monitoring surveys 2018-2020 the uneven subsidence of the territory was confirmed with the formation of areas with difficult water exchange that is expressed in the development of areas with marsh vegetation. The **Water supply pumping station** area can be defined as *conditionally unstable*. The values of vertical displacement up to -94.93 mm for the period 2016-2018 and up to -77.85 mm for the period 2018-2020 with an average subsidence rate from -11.72 to -34.08 mm/year were established. The variability in the data obtained for this object indicates the need to continue monitoring to clarify the character of the earth's surface deformations. It has been established that the **Power transmission tower** is geomorphologically located on the Tysa River second floodplain terrace, in the immediate vicinity of the steep slope edge. The stability of the terrace is due to the lithological composition, the terrigenous rocks (interbedded mudstones, siltstones and sandstones without fracture zones and brecciations). Based on the satellite radar monitoring data analysis in 2016 – 2020 the area near the power transmission tower is characterized by relatively stable conditions – *insignificant subsidence* with an average rate of

- 3.3 mm/year (-3.81 and -2.79 mm/year relatively) and vertical displacements values -15.44 – - 17.46 mm. **The five-story building,** regarding to which there were serious concerns due to its close location to the mine field, the analysis of the obtained results of satellite images interpretation made it possible to reduce the probability of hazardous geological processes, and, accordingly, to reduce the risks. The vertical displacements values differ from -12.78 to -13.21 mm with an average rate of vertical displacements of -0.27 – -1.7 mm/year (PS technique).

Therefore, using the results of satellite radar monitoring data analysis, the earth's surface vertical displacements frequency and scale assessment were carried out. Based on results obtained zonation scheme was improved, the zones boundaries were specified and dynamic state of control objects (critical infrastructure facilities) was estimated. It has been established that the highest values of surface deformation from -94.93 to -139.98 mm with vertical displacement rates from -34.08 to - 67.54 mm/year, were estimated for control objects located within the first zone, which is characterized by the most intensive development of karst-suffosion processes with associated formation of sinkholes, collapses, landslides and subsidence.

Conclusions. Reconstruction of land surface vertical displacements in time was carried out through performed studies. As the result of satellite radar monitoring for the period 2016-2020, new data were obtained on the parameters of hazardous natural-technogenic processes manifestations in Solotvyno, their impact on critical infrastructure objects was assessed, zonation and risk scheme were improved. In order to ensure life safety in Solotvyno, the results might be used for territory development and permanent monitoring system establishment.

Acknowledgements. The research was carried out under the financial support of the EU – projects REVITAL 1 (HURSKOVA/1702/6.1/0072) and ImProDiReT (No. 783232) and co-financing under the state budget program CPCEL 6541030.

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