Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Application of integrated geodetic and UAV technologies for monitoring environmental changes due to the mining activities in Solotvyno salt mine, Ukraine

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Funding information:
HUSKROUA/1702/8.1/0065 - Cross-border cooperation program "Hungary-Slovakia-Romania-Ukraine" European Neighborhood Instrument 2014-2020
Grant Projects of the Ministry of Education of the Slovak Republic KEGA No. 003TUKE-4/2023 and VEGA No.1/0340/22

Acknowledgement:
The authors would like to thank the Cross-border cooperation program "Hungary-Slovakia-Romania-Ukraine" for providing financial support to project "Extension of the "SPACE EMERGENCY SYSTEM" for operational monitoring of dangerous natural and man-made geo-processes in the cross-border region HU-SK-RO-UA, Hungary, Slovakia, Romania and Ukraine" (HUSKROUA/1702/8.1/0065).

How to cite this article:
Kablak, N., Pukanska, K., Bartoš, K., Savchyn, I., Nychvyd, M., Kalynych, I., Fehér, J. and Prodanets, I. (2024). Application of integrated geodetic and UAV technologies for monitoring environmental changes due to the mining activities in Solotvyno salt mine, Ukraine. *Acta Monstanistica Slovaca*, Volume 29 (2), 267-275

DOI:
https://doi.org/10.46544/AMS.v29i2.03

Abstract
This paper covers the spatio-temporal evolution of land surface deformation in the Tisza River basin within the Transcarpathian region, analyzing geodetic observations obtained over the last decade. In the town of Solotvyno, in the western part of Ukraine, near the Romanian border, there is an abandoned salt deposit where salt was extracted in several mining operations. In 2010, the mine was closed, and mine chambers 7 and 8 were flooded with water, causing the collapse of this region. Since then, the extent of the damage has been increasing, with sinkholes steadily growing larger and larger, threatening not only the entire surface area around the quarry but especially the groundwater that connects the deposit to the Tisza River. Several research institutions have been involved in monitoring the shifts over time. We have monitored the karst by identifying the most dangerous areas of the earth's surface subject to vertical shifts - trench sinkholes by UAV survey and terrestrial measurements using precise levelling in 4 stages. The situation on the site is an emergency with a major ecological impact of salt contamination in the whole Upper Tisza Basin region and requires not only continuous geodetic, geological, and chemical monitoring but especially an urgent solution to reverse the state of damage to the region.

Keywords
Karst; deformation monitoring; hazard detection; geodetic observations; UAV, precise levelling.

Introduction

Subsurface subsidence caused by underground mining causes a series of geological and environmental problems, ultimately degrading the environment, destroying landscapes, encroaching on inhabited areas, and destroying watercourses, grasslands and forests (Sun, 2017; Nie, 2013). Multiple surface hazards cause houses to crack and collapse, groundwater levels to drop, fertile soil to be destroyed, and roads to be damaged, posing a huge threat to the safety of lives and property of local residents (Bell et al., 2000; Li et al., 2004). Therefore, it is essential to monitor the changes caused and predict the direction of their development. In doing so, numerical modelling, finite element and theoretical analysis methods are used (Zhang, 2019; Najjar, 1993; Alejano, 1999; Díaz-Fernández, 2010; Thongprapha, 2015; Sheorey, 2000).

A prerequisite to solving this problem is understanding the multihazard effect, which involves tracking surface hazards using GNSS systems, geodetic surveying, monitoring and hazard analysis. Traditional geodetic technologies provide discrete point information on subsidence characteristics, but differential interferometric synthetic aperture radar (D-InSAR) technologies are currently mainly used (Zhang 2019; Fan, 2023; Pukanska, 2023), and three distinct stages are identified: the initial stage, the rapid development stage, and the creep stage of the affected area (Ma, 2022).

According to the State Geological Service, more than 26.0 thousand surface and underground karst manifestations have been recorded within the territory of Ukraine. In the areas of mining operations and intense technogenic load, the development of technogenic karst continues, sometimes with catastrophic manifestations of the process (Information Yearbook, 2020). Due to gravity and the subsidence of the earth's surface, trench sinkholes are formed under the mine workings, which are constantly expanding. Abandoned mine workings around the world pose a serious risk of damage to the hydrogeological system of the region, causing considerable ecological and economic damage that must later be remediated by future generations (Hallman, 2010). Anthropogenic impacts on water quality in the Tisza River have also been investigated in the past, as excavations indicate several potential flow paths that could discharge the physiological solution of water originating from the salt dome contact towards the Tisza River. Although the risk of salt pollution in the Tisza River from the abandoned Solotvyno mines was considered low at the time, given the proximity of such a large quantity of saline groundwater to the river, there was a strong recommendation to design and implement a monitoring program (Stoeckl et al., 2020).

When investigating the deformation of the earth's surface due to mining activities, it is necessary to develop a deformation investigation project that takes into account the geological, hydrogeological, and built-up situation of the area and, at the same time, develops the technical, measurement, and processing aspects of the implementation of the deformation investigation (Bieda et al., 2021). Territories with observed deformations of the earth's surface (geotectonic movements, landslides) are found in relatively densely populated areas, in industrial, agricultural, and urban recreation areas, as well as in landscapes with different levels of nature protection (Kalynych et al., 2017). This process has received particular development in the areas of salt mineral extraction (Solotvynske, Kalushske, Novo-Karfagenske, etc.) within the Transcarpathian, Ivano-Frankivsk, Lviv and Donetsk regions (Diakiv, 2012; Diakiv and Pakshyn, 2018).

Fig.1 The schematic plan of the Solotvyno rock salt deposit [for the materials of SE"Solotvyno Salt Mine"] (After Yakovlev, 2016)

The Solotvyno rock salt deposit is geographically located in the southwest of Ukraine, not far from the border with Romania, within the inner Carpathian depression, between the mountain ranges of Solov in the northwest and Magura in the north and northeast. In the administrative position, the deposit is located in the southeastern part of the Tyachiv district of the Zakarpattia region.

According to archival data, the Solotvyno deposit has been exploited underground for more than 220 years. Industrial development of the Solotvyno deposit of rock salt began in 1778. At the deposit, 9 mines operated at different times (Fig. 1). All seven old mines were previously closed due to economic and technical (emergency) reasons, and until recently, their condition was determined as ecologically balanced since they were timely mothballed by backfilling or flooding (natural, artificial or combined).

The central part of the salt massif, which contains the flooded workings of mine No. 7, fell into the development of destructive processes. Mines No. 8 and No. 9 worked the longest (Fig. 1). Allergological hospitals operated in the mine workings of the salt mines, at mine No. 8 - the regional allergological hospital, and at mine No. 9 - the Ukrainian Allergological Hospital. With the activity of mines No. 8 and No. 9, the development of an environmentally dangerous situation is connected (Bosevska and Khrushchov, 2011).

Salt extraction by the State Enterprise "Solotvyno Salt Mine" was stopped at the beginning of 2007. In 2009, the company stopped pumping mine water into surface reservoirs. The working horizons of the salt mine and the underground departments of the regional and Ukrainian allergological hospitals were flooded. The territory of the mine workings of the Solotvyno Salt Mine was declared an emergency zone in 2010. At the same time, the Expert Commission defined the situation at the Solotvyno salt mine as a state-level emergency.

The lack of funding for emergency recovery works, as well as technical re-equipment, led to the destruction of a complete property complex and the activation of karst processes on the enterprise's territory and beyond.

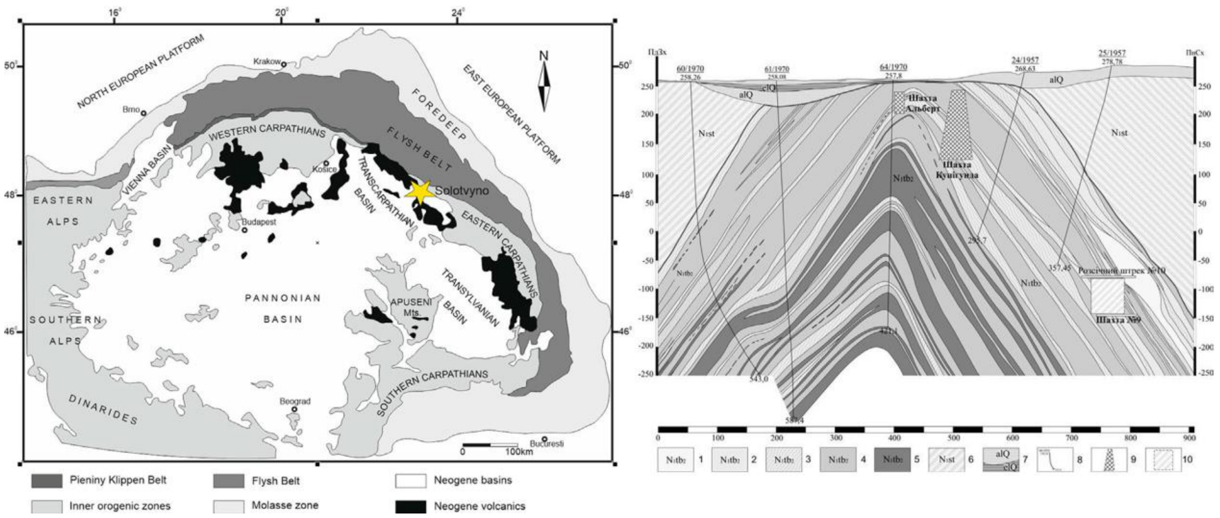

Fig. 2. Main geological unit distribution in Central Europe and geological sections of the Solotvyno rock salt deposit (Jacko et al., 2016; Yakovlev et al., 2016).

The prerequisite for creating large-scale karst was to ensure the movement of aggressive waters and the removal of saturated brines. This role was performed by the widespread drainage system, which was created at various levels in the salt massif itself to ensure the possibility of mining operations. Nevertheless, frequent falls were recorded in adits and pits, blocking the self-flow of tree waters. These fallouts were not eliminated in time due to the underfunding of the Solotvyno salt mine. Artificial dams were formed, which created a backwater of supra-salt waters and their accelerated infiltration into the salt massif along weakened zones, primarily in the Chornyy Mochar region. This led to the catastrophic consequences that are observed in the field today. Violation of the natural regime of supra-salt waters established in geological time led to the activation of salt dissolution. The presence of an extensive system of drainage workings at the base of the Quaternary deposits and in the upper part of the salt body created zones of underground discharge. It also expanded the zone of active water exchange to easily soluble rock salt and became the main reason for the intensive use of the territory. The flooding of mines No.7 (8 (Fig. 3a, 3b) and No. 8 (Fig. 4) resulted in the appearance of new karst channel formations, the waterproof cover (canopy) destruction and the formation of dips through which atmospheric water flows (Kalynych, I. et al., 2022).

Fig. 3. Left - pictures of some sinkholes in the Solotvyno salt mining area (credit: Ivan Prodanets); right - Flooded mine No. 7 (aerial photography materials as of 2020 carried out using a UAV – Tarot 680PRO Hexacopter)

The technogenically activated karst within the Solotvyno deposit caused radical relief changes in the earth's surface, an increase in the runoff coefficient, and changes in the places of groundwater recharge and discharge.

In order to characterize the long-term processes of surface deformation and identify their spatial and temporal trends and changes at the Solotvyno site in terms of geological, chemical and economic risks, several studies have been devoted (Shekhunova et al., 2019; Yakovlev et al.,2016; Onencan et al., 2018; Molenda et al., 2022a,b; Dobos et al., 2021; Szűcs et al., 2021; Pakshin et al., 2021; Pukanska et al., 2023). Quantitative analysis derived from multitemporal InSAR analyses indicated intense surface displacement and subsidence over the mining area (Gönczy et al., 2021). Using images from Sentinel 1A/B satellites as well as historical images from satellites such as ERS and Envisat by several authors, it is evident that the study area is steadily subsiding at a rate of -15 to -20 mm/year (Pukanska et al., 2023; Magyar et al., 2021, 2022a, 2022b; Dobos et al., 2022). The situation is serious and requires adequate geohazard management and strategic planning measures. Our research complements ongoing multidisciplinary research in this area.

Material and Methods

Precise levelling

After the detection of the most dangerous areas based on satellite interferometry, local geodetic monitoring was carried out at facilities within the urban settlement to prevent possible accidents. To study regional background geodynamic processes, quantify the deformation processes of the earth's surface in the zone of active technogenic manifestations, and create an epoch of observations, regional lines were created at the first stage of work, along with precise geometric levelling.

Fig.4a Observation plan of the first cycle of measurements in Solotvyno

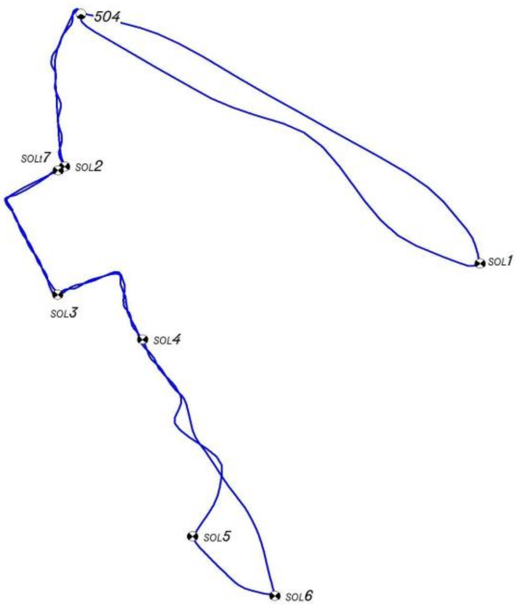

Fig.4b Levelling scheme of the first cycle of measurements

GNSS methods should be used to monitor surface deformation processes, but they do not allow control of internal deformation processes in the middle of the slope. It is generally accepted to use traditional mobile and/or fixed inclinometers to study internal deformation processes (Savchyn, 2021).

Levelling lines were based on the points of the state levelling network in the form of closed polygons. The centres of geodetic points were also included in the levelling network. The measurements were carried out with a Trimble DiNi 22 Digital Level (Trimble DiNi 22, 2024) with metrological verifications digital level Trimble DiNi 22 (standard deviations for 1 km of reciprocal levelling are 1.3 mm/km with a folding staff or 0.7 mm/km with a precise invar staff). Levelling was carried out four times, cyclically, once per quarter.

The seven benchmarks were laid on the terrain to determine the coordinates and elevations. The location of the levelling benchmarks is shown in Fig. 4a. Levelling moves were laid in the form of closed polygons based on the original benchmark No.504. Benchmark No.504 is the levelling mark, which is located in the wall of the railway booth, the height of which is determined from precise levelling and is noted in the Catalog of heights) (Catalogue of Heights, 1999). The total length of the moves was 5.5 km (Fig. 4b).

Aerial survey

To obtain information on the current state of the relief of the territory of the State Enterprise "Solotvyno Salt Mine" in November 2021, an aerial survey was conducted using the FLIRT Arrow aerial survey system (fig. 5) (https://abris.aero/flirt-arrow-4/). This system is equipped with a Sony QX1 camera (focal length 28 mm) for high-quality images.

Figure 5. Arrow aerial photography system

The aerial survey was performed in sunny weather with moderate surface winds up to 5 m/s. The input parameters for the aerial survey were a survey height of 250 meters, as well as forward and side overlap of 80% and 70%, respectively. The result of the aerial survey was 1154 aerial images.

The set parameters of the aerial survey, as well as the technical capabilities of the aerial survey system used, made it possible to obtain orthophoto, point cloud and DTM with a fairly high resolution (average GSD) of 4 cm/pixel. 12 control and 47 checkpoints were used for their georeferencing and evaluation. The coordinates of the control and checkpoints were determined by the dual-frequency GNSS receiver SOUTH Galaxy G1 in RTK mode. The coordinates were determined from the GNSS station SOLT (Solotvyno), which belongs to the GeoTerrace network of permanent GNSS stations (https://geoterrace.lpnu.ua/en). The coordinates were determined in the Ukrainian state coordinate system USK2000, with WGS84 (ellipsoidal) used as the height system. The coordinates' accuracy was better than 2 cm, and the accuracy of the height was better than 3 cm. As a result of the evaluation, it was found that the average square error of the georeferencing is 19 mm.

Results

Precise levelling

The work carried out on precise levelling (the first cycle) made it possible to obtain data on the value of the heights of the points of the geodynamic polygon, thereby creating an era of observations.

To determine the coordinates of the points, a GNSS survey was carried out using a dual-frequency GNSS receiver Trimble R8 in RTK mode from the ZAKPOS network of permanent GNSS stations (https://ua-pos.net). The coordinates of the points are determined in the Ukrainian State Geodetic Reference Coordinate System USK-2000. The coordinate accuracy is 2 cm, and the height accuracy is 3 cm.

During the measurements, we determined that the reference benchmark No. 504 (levelling mark, the height of which is taken from the precise levelling catalogue of 1997) was off by 14 cm. Therefore, in the second cycle, the length of the levelling moves was increased (Fig.6). Benchmarks established by the Lviv company HIRPROM were also used to clarify the results.

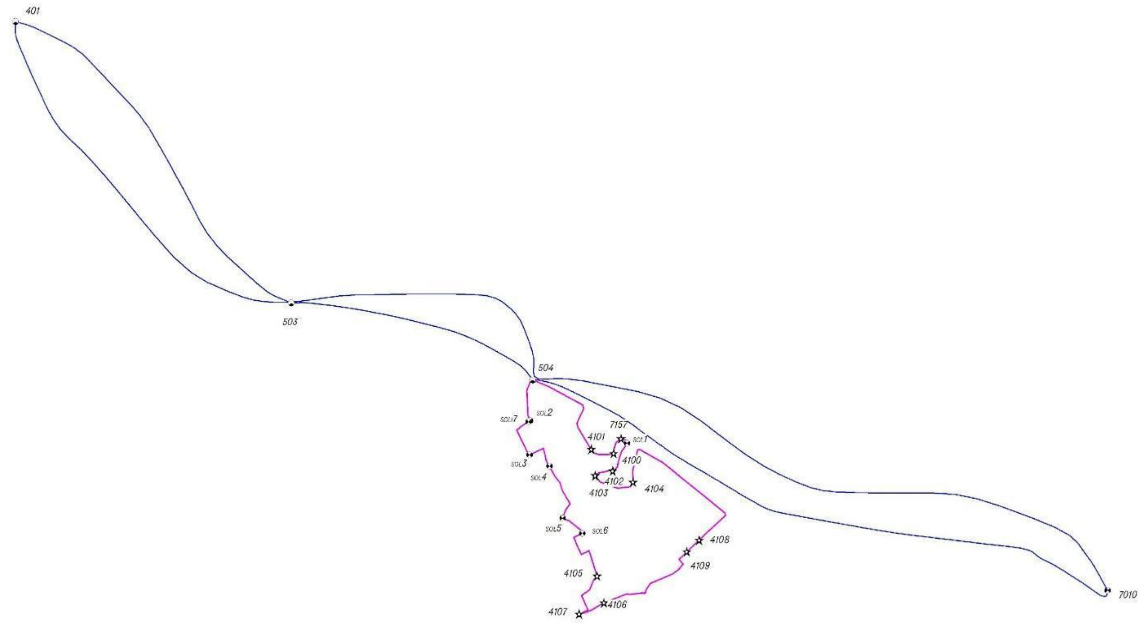

Fig. 6 Leveling scheme in the second cycle of measurements in Solotvyno

Thus, four cycles of levelling were carried out every six months between April 2020 and November 2021. According to the results of the 4 cycles, the benchmark SOL6 has the largest offset: in plan 68 mm/month, in height 60 mm/month. It is located near mine №7. This point is located on the edge of the largest trench depression and is confirmed by previous measurements (Pukanská, 2023). The minimum offset is defined on the benchmark SOL5: the displacement in the plan is 4 mm/month, in height - 1 mm/month.

Aerial survey

By combining the RGB composition of the orthophoto and DTM from the aerial survey, we were able to determine the extent of sinkholes in 2021 as well as identify newly emerging ones (Fig. 7). The red arrows illustrate the total dimensions of visible sinkholes, while given area numbers provide the water surface areas. Additionally, white dashed circles indicate newly forming craters, suggesting ongoing significant subsidence in the area. It is important to note that these craters may expand over time and contribute to further degradation by forming larger sinkholes.

Additionally, the created digital terrain model was used to generate three cross-sectional profiles of flooded sinkholes (see Figure 8) to analyze the spatial characteristics of the terrain. The point cloud was processed by filtering and noise elimination while also being classified into standard classes based on different criteria such as elevation and slope. To ensure accurately classified ground data, advanced vegetation filtering techniques were applied on a steep slope within the sinkholes, enhancing the overall quality of the analysis.

Fig. 7 a) the size and extent of monitored area in 2021, with the location of newly emerging sinkholes; b) DTM of the monitored area

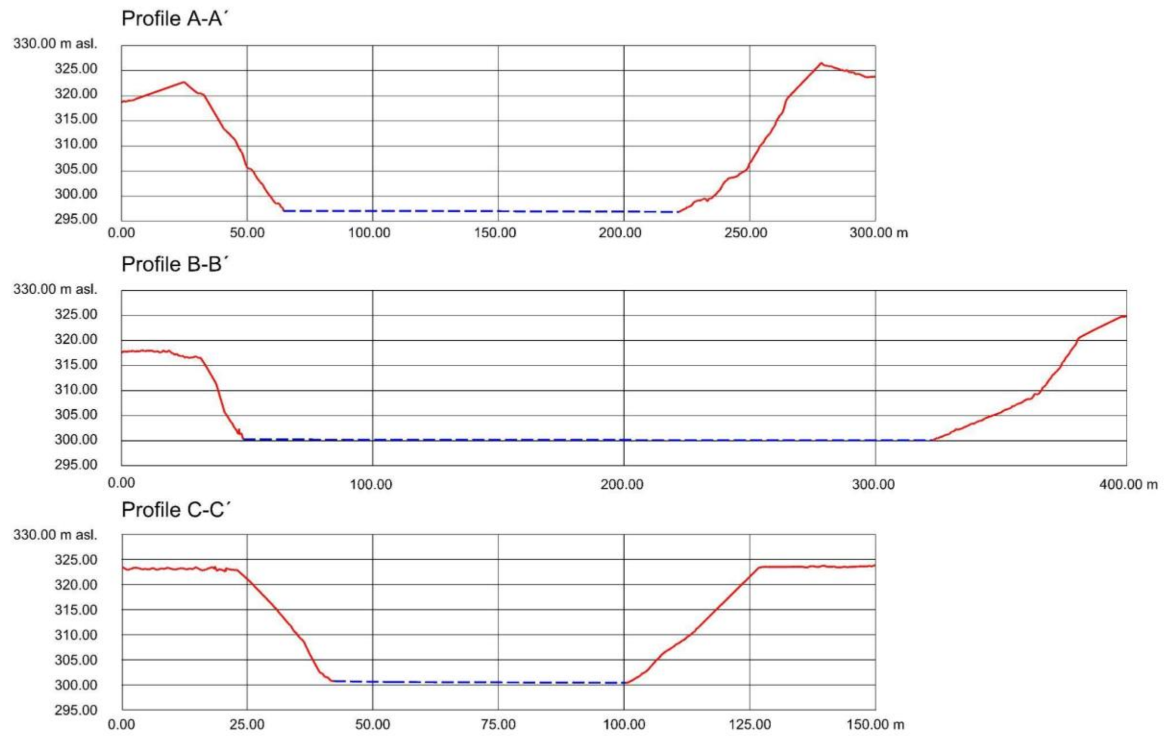

Fig. 8 Cross-section profiles through individual sinkhole areas (see Figure 7b for profile position)

From the UAV survey data, we were able to derive major spatial relations between the monitored sinkholes and many newly developing and extending sinkholes. Profiles derived from DTM also show a varying water level for the flooded sinkholes (297,130 m asl. - 300,700 m asl.). Based on this data, if data on the water level, river flow and water level changes of the Tisza River are available, it will be possible in the future to determine to what extent the water in the monitored sinkholes is connected to the water in the Tisza River.

Conclusions

For the first time, the cross-border research territory was comprehensively surveyed using modern technologies with the help of instrumental geodetic, aerial, and interferometric methods.

According to the results of four cycles at the Solotvyno site, the SOL6 rapper has the largest shift. The maximum rate of subsidence (SOL6, which is located near mine No.7) in the plan is 68 mm/month, and the height is 60 mm/month. The minimum (SOL5) in the plan is 4 mm/month, and the height is 1 mm/month. This is also confirmed by radar interferometry data (Pukanska et al., 2023; Dobos et al., 2022; Magyar et al., 2021).

Thanks to research, we believe that the most acceptable technology for monitoring karst and deformational movements is the combination of the radar interferometry method with precise levelling and GNSS surveying. From a practical point of view, this development can become a standard that can be adapted to other degraded lands.

The completed works once again testify to the existence of complex surface changes in Solotvyno, which is why it is necessary to continue the system of permanent geomonitoring of the Solotvyno salt mine. After all, according to National Program No. 3: Restoring a Clean and Safe Environment, activities are planned for the ecological restoration of Solotvyno salt mines in 2026-2032.

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