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Application of geodetic and mine surveying technologies in monitoring deformations of man-made structures

The development of industry, transport, mining and urban infrastructure leads to an increased risk of deformation processes in the ground and on engineering structures of anthropogenic origin. This necessitates the development and implementation of reliable monitoring systems for early detection of dangerous shifts, subsidence, or structural instabilities. Modern geodetic and mine surveying technologies provide a robust basis for the continuous and precise observation of such processes in real-time. This article explores the practical application of traditional geodetic techniques alongside advanced methods such as GNSS observations, terrestrial and mobile laser scanning, UAV photogrammetry, and satellite radar interferometry (InSAR). A comparative analysis of their accuracy, temporal resolution, cost-effectiveness, and implementation challenges is conducted. The integration of these technologies into digital geoinformation systems (GIS) and automated monitoring platforms significantly enhances the capability to model, forecast, and manage deformation processes at industrial sites, mining operations, dam structures, and urban territories. Examples of successful implementations in various sectors – including open-pit mining, subsurface gas storage facilities, tunnels, and high-rise construction – are analyzed to demonstrate the practical efficiency of a multidisciplinary approach. Particular attention is paid to the role of regular geodetic control in risk management and safety regulation compliance. The study also identifies key parameters for the classification of deformation risk levels and the selection of optimal monitoring strategies depending on the object's characteristics and environmental conditions. The research concludes with recommendations for future improvements, including the integration of artificial intelligence for anomaly detection, the use of digital twins for infrastructure behavior modeling, and cloud-based data processing for real-time decision support. The results affirm the necessity of a combined geodetic and mine surveying methodology for proactive geotechnical risk mitigation and sustainable development of technogenic territories.

Keywords: *geodetic monitoring; mine surveying; man-made structures; deformation control; GNSS; laser scanning; satellite interferometry; UAV photogrammetry; digital twin; geotechnical risk.*

Relevance of the topic. In recent decades, the rapid expansion of industrial activities, urban development, and mineral resource extraction has led to a significant increase in anthropogenic (technogenic) pressure on infrastructure and mining-related facilities. This intensification of human-induced stress on natural and engineered environments has made such structures more vulnerable to deformation processes including subsidence, landslides, and other forms of structural instability.

The growing complexity of modern infrastructure and the risks associated with its deformation underscore the urgent need for reliable and high-precision deformation monitoring systems. These systems are critical not only for ensuring the structural integrity and operational safety of facilities but also for preventing accidents that could result in human casualties, environmental degradation, and economic losses. Accurate and timely monitoring enables early detection of critical changes, allowing for proactive risk mitigation and management.

At the same time, regulatory frameworks governing infrastructure safety, environmental protection, and mining operations are becoming increasingly stringent [1, 2]. Updated national and international safety standards now demand continuous and verifiable monitoring of potentially hazardous facilities, particularly in areas exposed to dynamic geological and human-made impacts [3, 4]. Compliance with these evolving legal requirements necessitates the adoption of advanced geospatial technologies capable of providing real-time, high-resolution data.

In this context, the integration of modern geodetic and mine surveying technologies into monitoring practices has become especially relevant. Technologies such as satellite-based GNSS positioning, terrestrial and mobile laser scanning, UAV photogrammetry, and InSAR (Interferometric Synthetic Aperture Radar) offer enhanced capabilities for precise deformation tracking. Their application allows for the development of automated, scalable, and cost-effective monitoring solutions suited for a wide range of technogenic environments.

Thus, the relevance of this research lies in addressing the increasing need for innovative, interdisciplinary approaches to geotechnical monitoring, which combine technological advancement with evolving safety standards and the growing demand for sustainable infrastructure management.

Analysis of recent studies and publications referenced by the authors. The study of deformation processes in technogenic environments has been an active area of research over the past two decades, particularly in relation to the application of geodetic and mine surveying technologies. Numerous scientific works emphasize the importance of integrated monitoring systems for ensuring the safety of mining operations, dams, tailings storage facilities, pipelines, tunnels, and high-rise structures.

Recent studies have demonstrated the effectiveness of high-precision GNSS (Global Navigation Satellite Systems) in detecting slow ground movements and structural displacements (e.g., Q.Tao et al., 2025 [5]; F.Carnemolla et al., 2023 [6]). These systems are often used in continuous monitoring configurations to ensure real-time data collection and immediate anomaly detection.

The use of terrestrial laser scanning (TLS) and mobile mapping systems has gained traction for capturing detailed 3D models of infrastructure and terrain surfaces, allowing for periodic comparison and deformation analysis (S.Selvarajan et al., 2022 [7]; M.Storch et al., 2025 [8]). TLS is especially valued for its millimeter-level accuracy in short- and medium-range applications.

UAV (unmanned aerial vehicle) photogrammetry has emerged as a valuable tool for high-resolution surface modeling, particularly in inaccessible or hazardous areas. Authors such as E.Puniach et al. (2025) [9], and G.Costantino (2024) [10] have laid the groundwork for combining drone data with photogrammetric techniques to monitor open-pit mines, slopes, and landfill deformations.

Another breakthrough has been the application of spaceborne InSAR technology for detecting wide-area surface deformation with centimeter- to millimeter-level precision. Research by Y.Jiang et al. (2025) [11] and R.Ma et al. (2025) [12] shows that this technique is especially effective for monitoring slow, large-scale ground movement, particularly in urbanized and mining-affected areas.

Several Ukrainian researchers have also contributed to this field, especially in adapting geodetic instruments and methodologies for mining regions with unique geological and infrastructural challenges (e.g., N.Kablak et al., 2024 [13]; S.Shekhunova et al., 2019 [14], R.Greku et al., 2005 [15]).

These publications collectively support the author's approach of integrating geodetic and mine surveying methods into deformation monitoring, confirming both the scientific relevance and practical viability of such technologies for risk mitigation and infrastructure resilience.

The purpose of this article is to substantiate the effectiveness of applying modern geodetic and mine surveying technologies for accurate and continuous monitoring of deformations in technogenic structures. The research aims to demonstrate how the integration of advanced spatial data acquisition methods – such as GNSS measurements, laser scanning, UAV photogrammetry, and InSAR techniques – can significantly improve the reliability, efficiency, and safety of monitoring systems used to detect and evaluate structural and ground deformations. This justification is especially relevant in the context of increasing technogenic pressures, evolving safety regulations, and the growing need for proactive risk management in industrial and mining environments.

Presentation of the main material. Technogenic structures, based on their operational environment, construction type, and exposure to anthropogenic and natural impacts, are categorized by deformation risk into low-, medium-, and high-risk categories. High-risk sites often include tailings dams, mine shafts, oil and gas wellheads, and urban underground infrastructure affected by nearby extraction activities.

Classical geodetic methods have been used for centuries to measure and monitor deformations in the Earth's surface. These techniques rely on angular and linear measurements. Two of the most common methods are theodolite traverses and leveling. Theodolite traverses measure angles and distances between points to calculate their relative positions. While precise, this method depends heavily on equipment quality and the surveyor's expertise. Leveling determines height differences between points and is useful for monitoring vertical deformations like land subsidence [16]. The formula for calculating total height error in leveling is:

$$N_{total} = \sqrt{N \cdot \sigma^2}\ , \tag{1}$$

where N – number of measurements;

σ – standard error for each measurement.

Increasing measurements may accumulate error, so minimizing measurement error is essential for high precision. Classical methods achieve sub-millimeter precision but are limited by spatial coverage and temporal resolution. They require dense measurement networks and are labor-intensive, often unsuitable for large-scale, real-time monitoring.

Modern GNSS technologies, such as Real-Time Kinematic (RTK) and Precise Point Positioning (PPP), provide high-precision measurements for slow deformations, achieving centimeter- and sub-decimeter accuracy, respectively. RTK GNSS uses a base station to correct the rover's position in real time, ideal for infrastructure monitoring. PPP GNSS offers global coverage without a nearby base station, useful for wide-area geotechnical applications.

To model GNSS time series and detect slow displacements, Kalman filtering is employed. The Kalman filter refines estimates over time by updating the system's state using incoming measurements, accounting for errors and uncertainties [5]. The filter's recursive process uses the following equations:

$$\begin{aligned} x_k &= Fx_{k-1} + Bu_k + w_k, \\ z_k &= Hx_k + v_k, \end{aligned} \tag{2}$$

where x_k – state vector (position and velocity);

z_k – observation vector (measured position);

w_k, v_k – process and measurement noise.

The Kalman filter optimizes the state estimation, which is crucial for detecting subtle or long-term deformations.

Terrestrial Laser Scanning (TLS) and Mobile Laser Scanning (MLS) capture detailed 3D representations of structures. TLS uses stationary scanners mounted on tripods, while MLS involves mobile platforms like vehicles or drones. Both methods use LiDAR technology to generate dense point clouds with sub-centimeter accuracy. These point clouds are compared over time using cloud-to-cloud (C2C) or cloud-to-mesh (C2M) comparisons, employing algorithms like Iterative Closest Point (ICP) to detect deformations in structures.

UAV-based photogrammetry uses structure-from-motion (SfM) algorithms to generate 3D models from overlapping images taken by drones. The resolution of the resulting models depends on the number of Ground Control Points (GCPs) and flight parameters like altitude and camera angle. This method is especially useful for monitoring large areas and detecting subtle deformations like foundation settling or road subsidence [17].

InSAR, particularly Persistent Scatterer InSAR (PS-InSAR), uses radar signals to measure surface deformation with millimeter precision. PS-InSAR tracks stable reflective points on the Earth's surface, such as buildings or roads, to detect small deformations over time. The deformation velocity v is calculated from the phase difference $\Delta\phi$ between radar acquisitions using the formula:

$$v = \frac{\lambda \cdot \Delta\phi}{4\pi \cdot \Delta t}, \tag{3}$$

where λ – radar wavelength;

$\Delta\phi$ – phase difference;

Δt – time difference between acquisitions.

PS-InSAR can detect deformations like subsidence or structural shifts with remarkable precision, offering advantages like all-weather capability, wide-area coverage, and long-term monitoring.

Each of these technologies offers unique advantages and can be applied to different contexts (table 1). For example, continuous GNSS and InSAR are used to monitor subsidence in mining areas, while TLS and GNSS are often used to track the movement of wellheads in the oil and gas industry. UAV photogrammetry supports settlement monitoring in construction, particularly in high-rise foundations.

The combination of these technologies can provide more comprehensive and robust monitoring systems. For example, InSAR, GNSS, and TLS can be combined for monitoring tailings dams and other large infrastructures, enabling both 3D and temporal analysis. For urban mining zones, combining InSAR with UAV photogrammetry and geodetic control can provide a more detailed and accurate monitoring solution. For well pads, a combination of GNSS and TLS can enable real-time monitoring of movements.

Table 1

Comparative analysis of monitoring systems

Technology	**Accuracy**	**Frequency**	**Coverage Area**	**Automation Level**
Geodetic Methods	< 1 mm	Low (manual)	Point-based	Low
GNSS RTK/PPP	1–2 cm	High (real-time)	Point-based	High
TLS/MLS	< 1 cm	Medium	Local-scale	Medium-High
UAV Photogrammetry	2–5 cm	Medium	Local/regional	Medium
InSAR (PS/DInSAR)	< 5 mm	High (weekly)	Wide-area	High

To implement the various geospatial monitoring technologies in the context of real-time and long-term deformation tracking, a strategic combination of these tools, each suited for specific types of infrastructure and environments, is essential (fig. 1). Below is a detailed implementation outline for key sectors such as mining, oil and gas, and construction, illustrating how these technologies can be applied in practice.

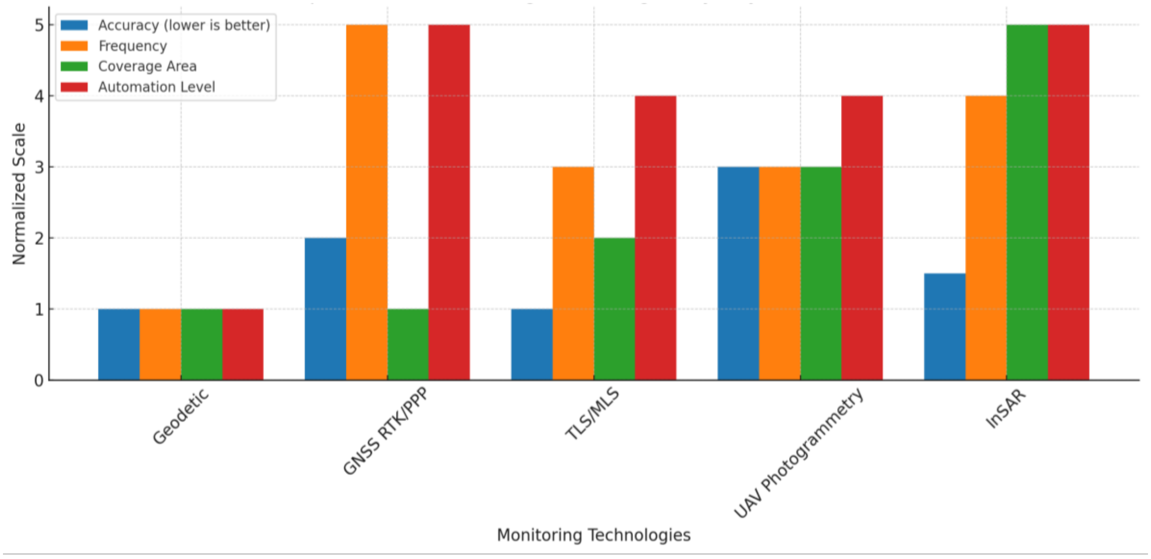

Fig. 1. Comparison of monitoring technologies by key characteristics

1. Mining Sector: Monitoring Subsidence and Surface Deformations

In mining operations, surface subsidence is a common issue, particularly in areas where longwall mining methods are used. The deformation of the land due to underground excavation can lead to severe safety hazards and environmental impacts. Therefore, continuous monitoring is necessary.

Technologies for Implementation:

- GNSS RTK/PPP (Used for real-time, precise monitoring of surface displacements in areas where infrastructure like buildings or roads may be at risk due to subsidence. GNSS stations installed on stable ground near mining operations can provide centimeter-level accuracy for ongoing monitoring);
- InSAR (Can be used for wide-area monitoring of mining regions, especially when GNSS cannot cover the entire area. PS-InSAR techniques help detect small deformations by measuring radar phase shifts over time. This allows operators to detect changes even in areas that are difficult to reach);
- TLS (For local-scale, high-accuracy monitoring of specific subsidence zones. TLS can provide detailed 3D scans of surface deformations, allowing for precise tracking of vertical and horizontal shifts in the ground surface).

Implementation Example:

- Continuous GNSS Stations (Install a network of GNSS stations around the mining site to monitor slow or rapid surface shifts. The GNSS data can be processed in real-time to trigger alerts if any deformation surpasses predetermined thresholds;
- InSAR for Subsidence Mapping (Use satellite-based InSAR technology to periodically monitor the mining region for any large-scale deformations or shifts across vast areas. PS-InSAR provides the ability to detect millimeter-scale deformations over wide regions);
- TLS Scanning of Critical Infrastructure (Deploy TLS to scan the surface of the mining area and surrounding critical infrastructure, such as dams or roads, to precisely detect local deformations that GNSS or InSAR might miss.

A combination of these methods ensures that both local and large-scale deformations are detected and monitored. The GNSS network offers real-time updates, InSAR enables wide-area coverage, and TLS provides highly detailed point cloud data for specific locations at risk.

2. Oil & Gas Sector: Monitoring Wellhead Movements

In the oil and gas industry, it is crucial to track movements at wellhead sites, especially when pressure changes or fluid injections affect the surrounding structures. Wellhead displacement can be a signal of pressure buildup or geological instability that may lead to dangerous outcomes such as blowouts or well failures.

Technologies for Implementation:

- GNSS RTK (GNSS technology is ideal for monitoring wellhead movements with real-time precision. It provides centimeter-level accuracy, allowing operators to detect small, yet critical, displacements. RTK GNSS receivers are placed at the wellheads to track any movements that could signal pressure buildup);
- TLS (Provides high-precision 3D scanning of wellheads and surrounding structures. TLS is particularly useful for capturing high-resolution surface data and detecting small deformations in the wellhead area. Combined with GNSS, it ensures a full spatial analysis of the structure);
- InSAR – optional for larger areas (InSAR can be used to monitor large oil fields or areas around the wellhead for ground movements. While GNSS and TLS handle local measurements, InSAR can monitor wider expanses, potentially detecting subsidence or large-scale geological shifts).

Implementation Example:

- Wellhead Monitoring with GNSS RTK (Install GNSS RTK receivers on the wellhead to monitor real-time displacement. If any wellhead movement is detected beyond a specific threshold, an alarm is triggered for further investigation and action);
- TLS Scanning of Wellhead and Structure (Regular TLS scanning captures highly detailed 3D models of the wellhead and nearby infrastructure, ensuring precise monitoring of local-scale deformations);
- InSAR for Large-Scale Monitoring (Use satellite-based InSAR to detect larger regional displacements in oil fields, which may indicate potential issues that need addressing, such as gas reservoir movements or sinkholes).

The integration of GNSS RTK and TLS provides real-time monitoring with high precision for wellhead displacement. InSAR offers valuable insight into regional movements, and all systems together ensure that any irregularities are detected early, improving safety and operational efficiency.

3. Construction Sector: Monitoring Settlements in High-Rise Foundations

In construction, particularly for high-rise buildings, settlement monitoring is crucial to prevent structural damage due to differential subsidence. Accurate deformation monitoring is vital in ensuring that buildings settle evenly and remain structurally sound.

Technologies for Implementation:

- UAV Photogrammetry (UAV-based photogrammetry is ideal for large-area monitoring, especially in urban construction sites. UAVs capture overlapping images of the construction site, and structure-from-motion (SfM) algorithms generate 3D models of the area. UAV photogrammetry can provide high-resolution data, enabling precise detection of settlement and movement in the foundation area);
- GNSS RTK (GNSS technology can be used to monitor the movement of individual foundation points with high accuracy. The system can provide real-time feedback on any shifts in the ground or foundation);
- TLS (TLS can scan the construction site and create detailed point clouds of the foundation and surrounding structures. The TLS data can be compared with earlier scans to detect subtle shifts that might not be visible to the naked eye).

Implementation Example:

- UAV Photogrammetry for Site Surveys (Regular UAV flights over the construction site can provide updated 3D models of the building foundation. These models can be compared with previous scans to detect settlement or uneven subsidence);
- GNSS for Foundation Points (Install GNSS receivers at key points of the foundation to monitor displacement in real-time. This allows for precise tracking of any movement in the foundation that could affect the stability of the building);
- TLS for Detailed 3D Scanning (Deploy TLS scanners periodically to capture the overall condition of the construction site. By analyzing the 3D point clouds, engineers can detect any minor deformations or irregularities in the foundation).

The combination of UAV photogrammetry, GNSS RTK, and TLS offers an effective monitoring solution for high-rise foundations. UAVs provide large-area coverage and high-level detail, GNSS tracks local displacements in real time, and TLS offers the precision necessary to detect small changes in the site's structure.

Recommended Technology Combinations for Deformation Monitoring:

- Tailings and Dams (InSAR + GNSS + TLS for 3D and temporal analysis);
- Urban Mining Zones (InSAR + UAV photogrammetry + geodetic control for detailed and wide-area monitoring);
- Well Pads – Oil & Gas (GNSS + TLS for real-time monitoring with high accuracy);
- High-Rise Construction (UAV photogrammetry + GNSS + TLS for comprehensive monitoring of settlement and structural shifts).

By strategically implementing these technologies in the mining, oil and gas, and construction sectors, companies can achieve accurate, real-time, and wide-area monitoring of surface and structural deformations. This combination of advanced methods ensures early detection of potential issues, helping to prevent costly repairs and avoid catastrophic failures.

Conclusions and prospects for further research. The conducted analysis confirms that the integration of modern geodetic and mine surveying technologies significantly enhances the accuracy, efficiency, and temporal resolution of deformation monitoring systems in technogenic environments. Classical geodetic methods, despite their high precision, are limited by low automation and spatial coverage, making them suitable primarily for control measurements and calibration tasks. In contrast, GNSS technologies, especially RTK and PPP, provide real-time positioning data with centimeter-level accuracy, enabling continuous monitoring of point displacements such as wellhead movements and slope instabilities. Terrestrial and mobile laser scanning systems (TLS/MLS) offer sub-centimeter accuracy and dense spatial data, allowing for detailed modeling of surface structures and the detection of small-scale deformations over time. UAV-based photogrammetry presents a flexible and cost-effective solution for monitoring large construction zones or inaccessible areas, particularly when frequent data acquisition is required. Meanwhile, InSAR techniques, including Persistent Scatterer (PS) and Differential InSAR (DInSAR), provide millimeter-scale precision across wide territories, with the added advantages of all-weather operability and long-term deformation tracking. The synergistic use of these methods enables a comprehensive, multi-scale approach to deformation monitoring. For example, combining InSAR and GNSS allows for precise calibration and validation of satellite data, while the integration of UAV photogrammetry and TLS facilitates 3D reconstruction and temporal change detection in built environments. This layered strategy supports both wide-area surveillance and local-level structural assessment, thereby improving the reliability and responsiveness of geotechnical and geospatial monitoring systems. Future research directions should prioritize the development of hybrid monitoring platforms that seamlessly combine GNSS, InSAR, laser scanning, and photogrammetry data streams using unified software environments and AI-driven data fusion algorithms. Enhanced real-time analytics for deformation prediction – leveraging machine learning and Kalman filtering techniques applied to multi-sensor datasets – will be critical. Equally important is the investigation of deformation precursors in high-risk zones (e.g., tailings dams, sinkhole-prone areas, and active fault lines) through continuous GNSS and InSAR time series analysis. To maximize efficiency, standardization and automation of processing pipelines for UAV and TLS/MLS data must advance to reduce human error and improve operational scalability. Field validation of integrated systems via pilot projects in mining, oil and gas extraction, and urban infrastructure zones will be essential to develop practical guidelines for industrial deployment. In summary, modern geodetic and surveying technologies, when used in an integrated framework, offer robust, scalable, and high-resolution tools for proactive deformation monitoring. Their adoption is critical for ensuring safety, sustainability, and regulatory compliance in industries affected by ground movements and structural instabilities.

References:

1. An, Z., Wang, Y., Ma, W. et al. (2024), «Safety Monitoring Technology for Tunnel Construction Based on Lidar», *Tunnel Construction*, Vol. 44, Issue 12, pp. 2393–2402, doi: 10.3973/j.issn.2096-4498.2024.12.009.
2. Pashchenko, O., Khomenko, V., Ishkov, V. et al. (2024), «Protection of drilling equipment against vibrations during drilling», *IOP Conference Series: Earth and Environmental Science*, Vol. 1348, Issue 1, doi: 10.1088/1755-1315/1348/1/012004.
3. Lin, N., Tan, L., Zhang, D. et al. (2024), «Spatiotemporal Analysis and Prediction of Landslide Deformation Combining Time-Series InSAR and LSTM», *Journal of Geo-Information Science*, Vol. 26, Issue 12, pp. 2772–2787, doi: 10.12082/dqxxkx.2024.240409.
4. Pashchenko, O.A., Khomenko, V.L., Ratov, B.T. et al. (2024), «Comprehensive approach to calculating operational parameters in hydraulic fracturing», *IOP Conference Series: Earth and Environmental Science*, Vol. 1415, Issue 1, doi: 10.1088/1755-1315/1415/1/012080.
5. Tao, Q., Liu, R., Li, X. et al. (2025), «A method for monitoring three dimensional surface deformation in mining areas combining SBAS-InSAR, GNSS and probability integral method», *Scientific Reports*, Vol. 15, Issue 1, doi: 10.1038/s41598-025-87087-4.
6. Carnemolla, F., De Guidi, G., Bonforte, A. et al. (2023), «The ground deformation of the south-eastern flank of Mount Etna monitored by GNSS and SAR interferometry from 2016 to 2019», *Geophysical Journal International*, Vol. 234, Issue 1, pp. 664–682, doi: 10.1093/gji/ggad088.
7. Selvarajan, S., Mohamed, A. and Barnes, G. (2022), «Modeling 3D Deformation Using Terrestrial LiDAR», *Advanced Structured Materials*, Springer, Vol. 179, pp. 31–45, doi: 10.1007/978-3-031-15676-2_3.
8. Storch, M., Kisliuk, B., Jarmer, T. et al. (2025), «Comparative analysis of UAV-based LiDAR and photogrammetric systems for the detection of terrain anomalies in a historical conflict landscape», *Science of Remote Sensing*, Vol. 11, doi: 10.1016/j.srs.2024.100191.
9. Puniach, E., Matwij, W., Gruszczyński, W. and Ćwiąkała, P. (2025), «Determining ground surface deformation indices in urbanized mining areas based on UAV-photogrammetry products», *Measurement*, doi: 10.1016/j.measurement.2025.117431.
10. Costantino, G., Giffard-Roisin, S., Dalla Mura, M. and Socquet, A. (2024), «Denoising of Geodetic Time Series Using Spatiotemporal Graph Neural Networks: Application to Slow Slip Event Extraction», *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 17, pp. 17567–17579, doi: 10.1109/JSTARS.2024.3465270.
11. Jiang, Y. and Yu, X. (2025), «Space-based long term condition monitoring of cold region pavement with PS-InSAR», *Journal of Infrastructure Preservation and Resilience*, Vol. 6 (1), doi: 10.1186/s43065-024-00110-2.
12. Ma, R., Yu, H., Liu, X. et al. (2025), «InSAR-YOLOv8 for wide-area landslide detection in InSAR measurements», *Scientific Reports*, Vol. 15 (1), doi: 10.1038/s41598-024-84626-3.
13. Kablak, N., Pukanska, K., Bartoš, K. et al. (2024), «Application of integrated geodetic and UAV technologies for monitoring environmental changes due to the mining activities in Solotvyno salt mine, Ukraine», *Acta Montanistica Slovaca*, Vol. 29 (2), pp. 267–275, doi: 10.46544/AMS.v29i2.03.
14. Shekhunova, S.B., Aleksieienkova, M.V., Meijer, S.D. et al. (2019), «Monitoring of hazardous geological processes as a tool for risks minimization on post-mining areas in Solotvyno (Transcarpathian region, Ukraine)», *Proceedings of the 13th International Scientific Conference on Monitoring of Geological Processes and Ecological Condition of the Environment (Monitoring 2019)*, Kyiv, Ukraine.
15. Greku, R.Kh. and Greku, T.R. (2005), «Determination of hazardous subsidence in the mining region of Ukraine with the ERS SAR interferometry», *Proceedings of the 31st International Symposium on Remote Sensing of Environment (ISRSE 2005): Global Monitoring for Sustainability and Security*.
16. Malinowska, A., Hejmanowski, R., Witkowski, W.T. and Guzy, A. (2018), «Mapping of slow vertical ground movement caused by salt cavern convergence with Sentinel-1 TOPS data», *Archives of Mining Sciences*, Vol. 63, Issue 2, pp. 383–396, doi: 10.24425/122453.

17. Lau, Y.M., Wang, K.L., Wang, Y.H. et al. (2023), «Monitoring of rainfall-induced landslides at Songmao and Lushan, Taiwan, using IoT and big data-based monitoring system», *Landslides*, Vol. 20, Issue 2, pp. 271–296, doi: 10.1007/s10346-022-01964-x.

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Застосування геодезичних і маркшейдерських технологій у моніторингу деформацій техногенних об’єктів

Розвиток промисловості, транспорту, гірничої справи та міської інфраструктури супроводжується зростанням ризику деформаційних процесів у ґрунтах і на інженерних спорудах антропогенного походження. Це зумовлює необхідність створення й впровадження надійних систем моніторингу для своєчасного виявлення небезпечних зсувів, осідань або структурної нестійкості. Сучасні геодезичні та маркшейдерські технології забезпечують ефективну основу для безперервного і високоточного спостереження за такими процесами в режимі реального часу. Розглядається практичне застосування як традиційних геодезичних методів, так і сучасних засобів – супутникових GNSS-спостережень, наземного та мобільного лазерного сканування, фотограмметрії з безпілотних літальних апаратів (БПЛА), а також супутникової радарної інтерферометрії (InSAR). Проведено порівняльний аналіз точності, часової роздільності, економічної доцільності та особливостей впровадження цих методів. Інтеграція зазначених технологій у цифрові геоінформаційні системи (ГІС) і автоматизовані платформи моніторингу значно підвищує можливості моделювання, прогнозування та управління деформаційними процесами на промислових об’єктах, у гірничодобувних районах, на гідротехнічних спорудах і в умовах щільної міської забудови. Проаналізовано приклади успішного застосування таких систем у відкритих кар’єрах, підземних сховищах газу, тунелях і при будівництві висотних споруд, що підтверджує ефективність комплексного міждисциплінарного підходу. Особливу увагу приділено ролі регулярного геодезичного контролю у системі управління ризиками та забезпеченні відповідності нормативним вимогам безпеки. Також визначено основні параметри для класифікації рівнів деформаційної небезпеки та вибору оптимальних стратегій моніторингу залежно від характеристик об’єкта та зовнішніх умов. У підсумку сформульовано рекомендації щодо подальшого вдосконалення, враховуючи впровадження штучного інтелекту для виявлення аномалій, використання цифрових двійників для моделювання поведінки інфраструктури та хмарних технологій для обробки даних у реальному часі. Результати дослідження підтверджують необхідність поєднаного геодезичного та маркшейдерського підходу для проактивного управління геотехнічними ризиками та сталого розвитку техногенних територій.

Ключові слова: геодезичний моніторинг; маркшейдерія; техногенні об’єкти; контроль деформацій; GNSS; лазерне сканування; супутникова інтерферометрія; фотограмметрія БПЛА; цифровий двійник; геотехнічний ризик.

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