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GNSS MONITORING OF DEFORMATIONS IN TECHNOGENICALLY DISTURBED TERRITORIES FOR CONSTRUCTION APPLICATIONS

Y. Berezan, *PhD Student, Faculty of Civil Engineering*

E-mail: berezanevg@gmail.com

ORCID ID: 0009-0000-0647-4811

Kyryvyi Rih National University

Y. Hlypovka, *senior Lecturer, Department of Geodesy*

E-mail: hevgeng@knu.edu.ua

ORCID ID: 0009-0009-0855-8475

Kyryvyi Rih National University

Abstract. *This paper addresses the relevant scientific and practical problem of improving geodetic support for construction on technogenically disturbed territories through the implementation of modern Global Navigation Satellite System (GNSS) technologies. A considerable proportion of areas affected by mining activities are characterized by the development of slow deformation processes that may adversely affect the stability of building foundations, engineering structures, utility networks, and infrastructure facilities. Consequently, there is a growing need for a high-precision monitoring system capable of providing timely detection of ground surface displacements and forecasting the development of hazardous geodynamic processes.*

The objective of this study is to provide a scientific basis for and develop a comprehensive methodology for GNSS-based deformation monitoring of technogenically disturbed territories intended for engineering surveys, design, construction, and operation of civil and industrial facilities. The proposed methodology is based on the application of autonomous GNSS reference stations, high-precision static GNSS observations, advanced GNSS data processing software, and statistical methods for coordinate time-series analysis.

The study proposes the design of an autonomous GNSS reference station integrating a multi-frequency, multi-constellation GNSS receiver, a solar-powered autonomous energy supply system, a control unit, a wireless communication module, and a local data storage unit. The proposed technical solution enables long-term continuous operation of the monitoring network with minimal maintenance requirements. The originality of the developed design is supported by a patent application, demonstrating the practical significance of the proposed monitoring system.

Optimal parameters for organizing static GNSS observations are substantiated, including observation session duration, satellite signal sampling interval, observation frequency, satellite constellation geometry requirements, and quality assessment criteria. In addition, a GNSS data processing workflow based on Bernese GNSS Software, GAMIT/GLOBK, Trimble Business Center, and Leica Infinity has been developed, providing automated coordinate determination for monitoring benchmarks, generation of deformation time series, and statistical assessment of the reliability of the obtained results.

Keywords: *GNSS monitoring, deformation of engineering structures, geodetic monitoring, satellite measurements, geodetic control, measurement accuracy, automated data processing, economic efficiency of monitoring.*

Problem Statement. The development of technogenically disturbed territories for construction purposes is a complex scientific and engineering challenge, the relevance of

which is increasing due to the expansion of urban development and the shortage of available land resources. Such territories include areas undermined by underground mining operations, zones affected by open-pit mining, reclaimed waste dumps and disposal sites, areas of abandoned mines, underground cavities, and other technogenic facilities. This problem is particularly significant in the mining and industrial regions of Ukraine, especially within the Kryvyi Rih Basin, the Dnipro region, and Donbas, where a substantial proportion of prospective construction sites are characterized by disturbed geological conditions, heterogeneous soil foundations, and the long-term manifestation of technogenic geodynamic processes [1].

Construction and subsequent operation of structures in such areas are associated with an increased risk of differential settlement, horizontal displacement, local subsidence, landslide processes, and ground-surface deformation. These phenomena may cause changes in the design position of foundations, cracking of load-bearing structures, malfunction of utility networks, and a reduction in the operational reliability of buildings. Therefore, the timely detection of spatial displacements of the ground surface and structural elements is a prerequisite for ensuring construction safety and predicting the further development of deformation processes [5].

Traditional geodetic control methods, including high-precision geometric levelling, total station measurements, and linear-angular surveying, provide high accuracy in deformation determination; however, they are predominantly discrete in nature. Results can only be obtained at specific times during field observations, while repeated measurements require considerable labour and time, the continuous presence of personnel, and stable intervisibility between monitoring points. In inaccessible, unstable, or potentially hazardous areas, these limitations may hinder the prompt acquisition of information and reduce the overall efficiency of monitoring.

The application of Global Navigation Satellite Systems creates the prerequisites for the transition from periodic geodetic control to automated continuous monitoring. GNSS technologies enable the determination of three-dimensional coordinates of control

points, the accumulation of observation time series, remote data transmission, and the rapid detection of spatial displacements. When geodetic-grade multi-frequency receivers, stable monitoring points, long observation sessions, and precise post-processing are used, millimetre-level accuracy may be achieved for horizontal displacement determination and several-millimetre accuracy for vertical deformation assessment. In RTK mode, accuracy is generally at the centimetre level and depends on baseline length, satellite constellation geometry, atmospheric conditions, signal multipath, and the quality of connection to the reference network [6].

Thus, an important scientific task is to substantiate the structure of a GNSS monitoring system for technogenically disturbed territories, determine the optimal configuration of the control network, establish the frequency and duration of observations, assess the accuracy of spatial displacement determination, and develop criteria for identifying hazardous deformations. The results of such monitoring can be used to assess the suitability of territories for development, monitor the condition of construction sites, forecast deformation processes, and support timely engineering decisions aimed at ensuring the reliability and safety of buildings and structures [7].

Analysis of recent research and publications. The issues of geodetic monitoring of ground surface and engineering structure deformations using Global Navigation Satellite Systems (GNSS) have been extensively investigated over the past decades. Particular attention has been devoted to the development of high-precision monitoring systems for predicting hazardous deformations, assessing the stability of technogenically disturbed territories, and ensuring the safe operation of engineering and construction facilities.

Blewitt G. was among the first researchers to demonstrate the feasibility of applying GPS technologies for high-precision positioning in geodynamic monitoring. His studies showed that carrier-phase GNSS observations enable the determination of control point displacements with millimetre-level accuracy, making GNSS an effective tool for monitoring slow ground deformation processes. According to Blewitt, this

approach is based on the establishment of continuously operating observation networks, the accumulation of coordinate time series, and their statistical analysis to identify long-term trends in spatial displacement [8].

The methodology of GNSS-based deformation monitoring was further advanced by Teferle F. N., who demonstrated that continuous GNSS observations allow the detection of both long-term geodynamic movements and local deformations of engineering structures. The author emphasized that integrating permanent GNSS networks with advanced mathematical modelling techniques significantly improves the reliability of deformation prediction and spatial displacement assessment [9].

Studies conducted by Vernant P. confirmed the effectiveness of continuously operating GNSS stations for determining present-day horizontal and vertical crustal movements. The proposed methodology is based on comprehensive analysis of coordinate time series, enabling the separation of natural geodynamic processes from local anthropogenic deformations and improving the reliability of spatial displacement estimation [10].

Among Ukrainian researchers, Trevoho I. S. and Shevchenko T. H. have made significant contributions to the development of satellite geodetic technologies. Their studies demonstrated the effectiveness of GNSS technologies for engineering surveying, deformation monitoring of buildings and structures, and the establishment of high-precision geodetic networks. The proposed approach combines satellite observations, conventional geodetic methods, and modern processing software to improve the accuracy of spatial coordinate determination for monitoring stations [4].

The problem of geodetic monitoring of technogenically disturbed territories in mining regions of Ukraine has been extensively investigated by Khomenko P. A. The author emphasized that mining-affected territories are characterized by complex spatial and temporal deformation processes requiring systematic geodetic observations. His research highlights the advantages of modern GNSS technologies for the early detection of hazardous ground deformations and for predicting their future development [5].

However, an analysis of contemporary scientific publications indicates that most studies focus primarily on crustal deformation monitoring, the deformation analysis of individual engineering structures, or the development of permanent GNSS reference networks. Considerably less attention has been devoted to the comprehensive monitoring of technogenically disturbed territories for construction purposes, where it is necessary to simultaneously assess foundation stability, monitor spatial deformation processes, and evaluate the suitability of sites for future development.

Therefore, the literature review confirms the significant potential of GNSS technologies for geodetic deformation monitoring. Nevertheless, there is still no comprehensive methodology integrating continuous GNSS observations, advanced time-series analysis, spatial displacement assessment, and engineering evaluation of the suitability of technogenically disturbed territories for construction. The development of such an integrated approach constitutes the scientific novelty and practical significance of the present study.

Research Objective. The objective of this study is to provide a scientific basis for and develop a comprehensive methodology for GNSS-based deformation monitoring of technogenically disturbed territories using autonomous GNSS reference stations. The proposed methodology is aimed at improving the accuracy of spatial displacement determination, assessing the stability of soil foundations, and providing reliable geodetic support for construction projects in areas subjected to significant anthropogenic impacts.

Materials and methods of research.

The achievement of the research objective is ensured through the implementation of an integrated approach that combines modern satellite geodetic technologies, mathematical methods for spatial data processing, and geoinformation analysis tools for assessing deformations in technogenically disturbed territories. The proposed methodology is based on the principles of continuous geodetic monitoring, enabling high-precision determination of the coordinates of monitoring points, analysis of

coordinate time series, and timely detection of hazardous changes in the spatial position of the ground surface.

The experimental basis of the study consists of a network of autonomous GNSS reference stations equipped with multi-frequency, multi-constellation GNSS receivers capable of simultaneously tracking signals from the GPS, Galileo, and BeiDou satellite navigation systems. Depending on the required positioning accuracy, geodetic-grade receivers such as Leica GS18 T, Trimble R10-2, Topcon HiPer HR, or high-precision u-blox ZED-F9P modules may be employed.

To ensure long-term autonomous operation, each monitoring station is equipped with solar panels, rechargeable battery power systems, a charge controller, a wireless communication module for remote data transmission, and local data storage devices. This configuration enables continuous long-term monitoring without the permanent presence of field personnel, significantly reduces maintenance requirements, and minimizes the influence of human factors on measurement quality and reliability (Fig. 1).

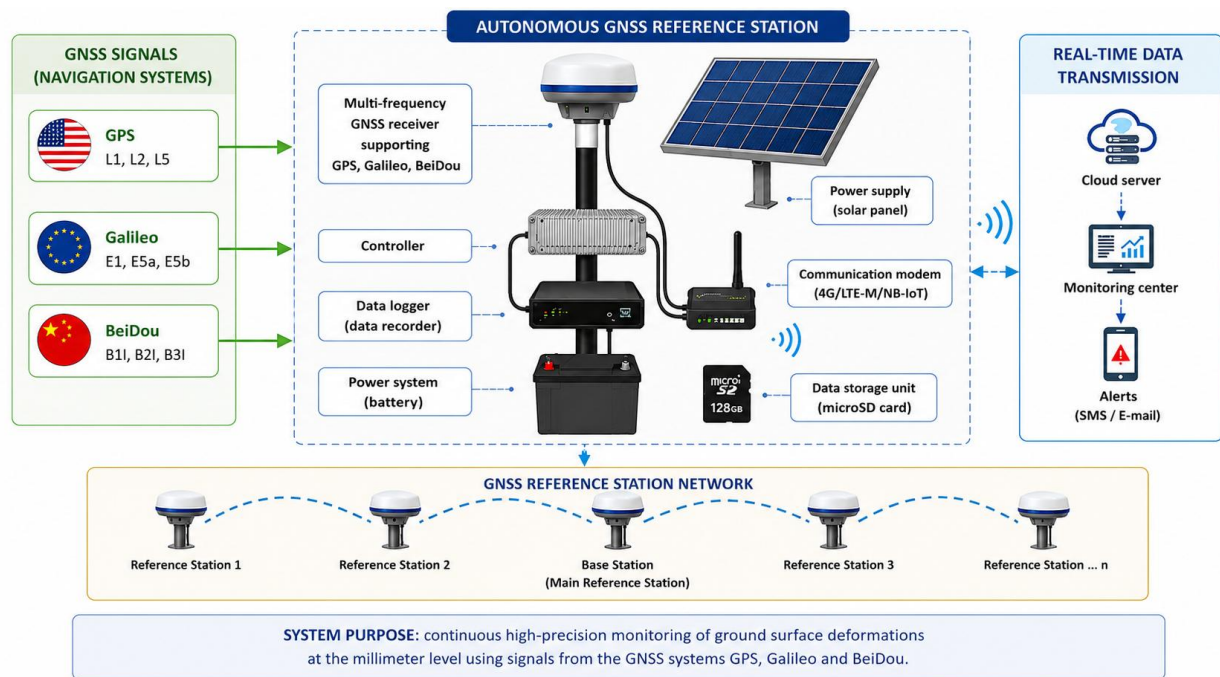


Figure 1. Structural Diagram of the Autonomous GNSS Reference Station

The software environment used in this study comprises a suite of specialized packages for GNSS observation processing and statistical analysis of coordinate data (Table 1). High-precision coordinate determination is performed using Bernese GNSS Software, GAMIT/GLOBK, Trimble Business Center, and Leica Infinity. These software packages provide automated processing of carrier-phase observations, mitigation of systematic errors, quality assessment of GNSS measurements, and precise coordinate determination in both national and global reference coordinate systems.

Spatial interpretation of the monitoring results is performed using the QGIS and ArcGIS geographic information systems. These platforms enable the generation of displacement maps, deformation contour maps, and spatial distribution models of potentially hazardous zones, thereby supporting comprehensive analysis and visualization of deformation processes.

Table 1. Functional Capabilities of the Software Used in the Study

Software	Software Class	Primary Application	Output
Bernese GNSS Software	Scientific	GNSS post-processing	Millimeter-level coordinate determination
GAMIT/GLOBK	Scientific	Time-series analysis	Displacement vectors
Trimble Business Center	Commercial	Processing of field GNSS observations	Measurement quality control
Leica Infinity	Commercial	Comprehensive processing of geodetic measurements	Network adjustment
QGIS	GIS	Spatial analysis	Deformation maps
ArcGIS Pro	GIS	Geostatistical modeling	Spatial models and deformation forecasting

The analysis of the software capabilities demonstrates that the combined use of scientific GNSS processing packages (Bernese GNSS Software and GAMIT/GLOBK) provides high-precision determination of monitoring point coordinates and reliable estimation of deformation parameters. In contrast, commercial software solutions (Trimble Business Center and Leica Infinity) facilitate efficient processing of field observations and comprehensive quality control of geodetic measurements. The

application of Geographic Information Systems (QGIS and ArcGIS Pro) enables spatial visualization of monitoring results, generation of displacement maps, digital surface models, and geostatistical analysis of deformation processes, constituting an essential component of an integrated GNSS-based monitoring system for technogenically disturbed territories.

The software framework adopted in this study includes scientific GNSS processing packages (Bernese GNSS Software 5.4 and GAMIT/GLOBK 10.7), commercial software (Trimble Business Center and Leica Infinity), time-series analysis tools (HECTOR and CATS), and GIS platforms (QGIS and ArcGIS Pro) for spatial visualization and interpretation of monitoring results.

An important practical outcome of this research is the development of an autonomous GNSS reference station, the technical design of which is protected by a Ukrainian patent application accepted for examination by the Ukrainian National Office for Intellectual Property and Innovations (UANIPIO). The proposed station integrates a multi-frequency GNSS receiver, an autonomous power supply system, wireless data transmission modules, and local data storage facilities, thereby enabling continuous high-precision monitoring of deformations in technogenically disturbed territories. The patented technical solution protects the original configuration of the station's functional components, ensuring autonomous operation, resistance to adverse environmental conditions, and long-term continuous performance under field conditions with minimal maintenance requirements.

In parallel, proprietary software for real-time deformation monitoring is currently being developed. The software is designed for automated acquisition and processing of GNSS observations collected from the monitoring network, including data filtering, displacement computation, and graphical visualization of deformation processes. The system incorporates an automatic alert module that generates warnings whenever predefined displacement thresholds are exceeded, enabling rapid response to potentially hazardous deformation trends during both the construction and operational phases of

engineering structures. The implementation of proprietary software is expected to reduce dependence on foreign commercial packages while ensuring full compliance with Ukrainian geodetic standards and regulatory requirements.

The experimental site for GNSS deformation monitoring was selected based on its representativeness of technogenically disturbed territories and the presence of long-term anthropogenic impacts capable of inducing ongoing ground deformation processes. The proposed methodology is intended for application in reclaimed mine dumps, former industrial sites, and areas affected by open-pit or underground mining activities that are considered potentially suitable for future civil or industrial development. Site selection was performed according to a comprehensive set of geodetic, geotechnical, and operational criteria to ensure the feasibility of high-precision GNSS observations. The principal site selection criteria are presented in Table 2.

Table 2. Criteria for Selecting an Experimental Site for GNSS Deformation Monitoring

Criterion	Characteristics	Significance for the Study
Territory type	Reclaimed mine dump, industrial site, undermined area	Study object
Presence of deformation	Settlement, horizontal displacement, local subsidence	Monitoring the development of geodynamic processes
Development potential	Civil or industrial construction	Assessment of site suitability for construction
Sky visibility	Satellite elevation mask angle $\geq 15^\circ$	Ensuring stable GNSS signal reception
Electromagnetic environment	Minimal level of electromagnetic interference	Reducing measurement errors
Availability of CORS stations	Distance to the nearest CORS station $\leq 30\text{--}50$ km	Improving coordinate determination accuracy
Geological conditions	Stability of the reference benchmark	Ensuring long-term stability of the reference point

A local geodetic monitoring network was established within the selected study area, consisting of one reference benchmark located outside the active deformation zone and a system of monitoring benchmarks uniformly distributed across the experimental site. The reference benchmark served as the primary control point for determining absolute coordinates, whereas the monitoring benchmarks were used to detect and quantify spatial displacements occurring within different parts of the study area.

The proposed network configuration enables the simultaneous determination of absolute coordinates of monitoring points, assessment of relative displacements between individual benchmarks, analysis of the spatial characteristics of deformation development, and generation of coordinate time series required for forecasting geodynamic processes.

The overall monitoring methodology comprises the following stages: selection of the experimental site, establishment of the autonomous GNSS monitoring network, configuration of GNSS data acquisition parameters, execution of static GNSS observations, post-processing of GNSS measurements, statistical analysis of coordinate time series, and spatial interpretation of the obtained results. The workflow of the proposed methodology is illustrated in Fig. 2.

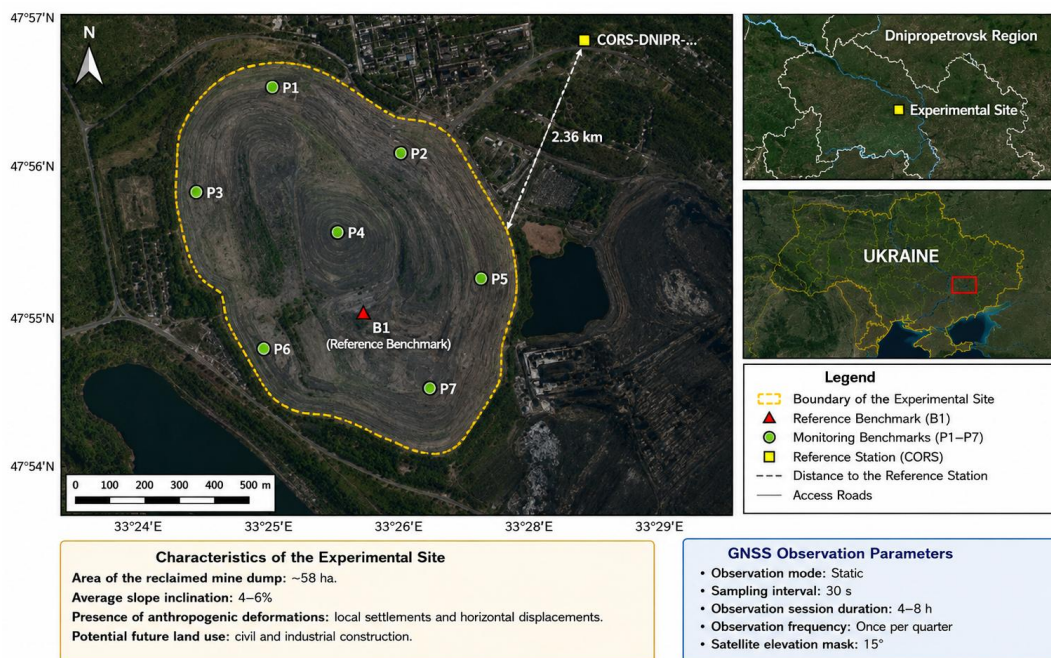


Figure 2. Experimental Site for GNSS Monitoring of a Technogenically Disturbed Territory

Field measurements were performed in the static GNSS observation mode, which is considered the most effective approach for detecting slow ground deformation processes (Table 3). Satellite signals were recorded at 30-second intervals, with the duration of each observation session ranging from 4 to 8 hours. Observation campaigns were conducted once per quarter, enabling the analysis of both seasonal variations and long-term deformation trends.

To improve the reliability and accuracy of the monitoring results, a satellite elevation mask angle of at least 15° was applied, the geometry of the satellite constellation was evaluated using the Dilution of Precision (DOP) parameter, and all observation data were recorded in the international RINEX 3.x format for subsequent high-precision post-processing.

Table 3. Parameters of Static GNSS Observations

Parameter	Value	Purpose
Observation mode	Static	Monitoring of slow ground deformation
Sampling interval	30 s	Generation of coordinate time series
Observation session duration	4–8 h	Reliable ambiguity resolution
Observation frequency	Once per quarter	Analysis of seasonal and long-term deformation trends
Minimum satellite elevation mask	$\geq 15^\circ$	Elimination of low-elevation satellite signals
Minimum number of satellites	≥ 4	Ensuring stable positioning
Preferred number of satellites	10–25	Improving coordinate determination accuracy
Maximum PDOP value	≤ 4	Control of satellite constellation geometry
Data storage format	RINEX 3.x	IGS standard for scientific GNSS data processing

The raw GNSS observation data were processed using scientific-grade GNSS software, namely Bernese GNSS Software and GAMIT/GLOBK. The processing workflow included pre-processing with gross error detection and elimination, generation of double-differenced carrier-phase observations to mitigate systematic errors, and

resolution of integer carrier-phase ambiguities using the LAMBDA or FARA algorithms [7, 12].

Displacements were determined as the differences between the coordinates of corresponding monitoring benchmarks obtained during two consecutive observation campaigns. Vertical displacements (ΔH) were calculated from the Up component in the local topocentric coordinate system. Horizontal displacements were represented by the North (ΔN) and East (ΔE) coordinate components, while the resultant horizontal displacement vector was calculated as: $D = \sqrt{(\Delta N^2 + \Delta E^2)}$.

Typical time series of vertical displacements recorded at the monitoring benchmarks for the experimental site are presented in Fig. 3.

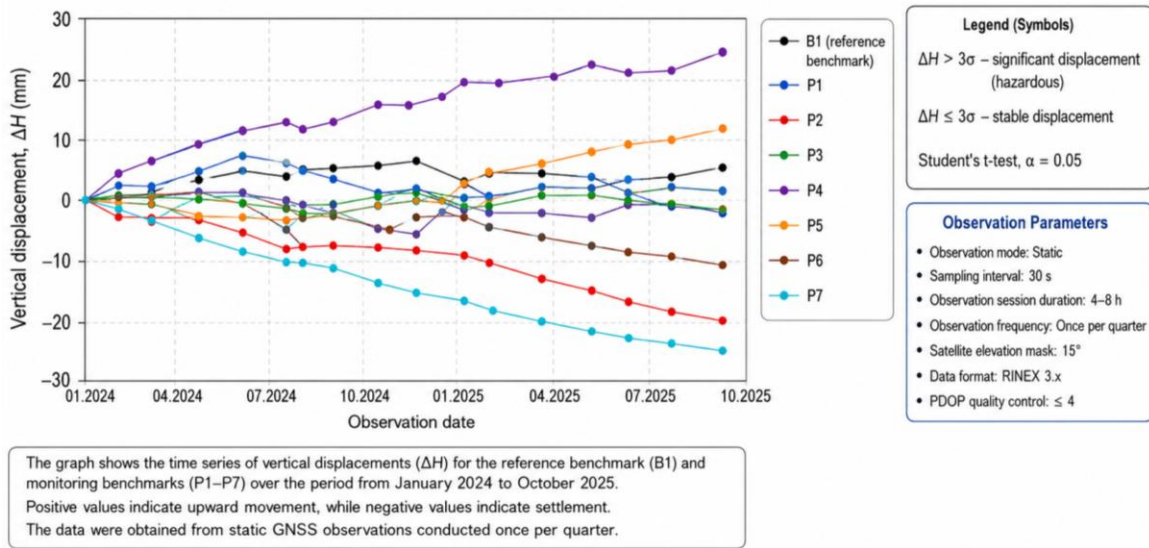


Figure 3. Time Series of Vertical Displacements of GNSS Monitoring Benchmarks (Model Data, 2024–2025)

Statistical assessment of the reliability of the obtained results is an essential stage of GNSS data processing, as it enables the discrimination between actual deformation processes and random measurement errors. Following network adjustment, the root mean square errors (RMSEs) of the coordinates are determined for each monitoring benchmark, providing quantitative estimates of the accuracy of the calculated spatial positions.

The primary criterion for identifying deformation is whether the measured displacement exceeds the level of random measurement uncertainty. In high-precision geodetic practice, the three-sigma (3σ) criterion is commonly adopted, according to which a displacement is considered statistically significant if its absolute value exceeds three times the corresponding standard deviation. For the vertical component, this condition is expressed as

$$|\Delta H| > 3\sigma\Delta H, \quad (1)$$

and for the resultant horizontal displacement as

$$|D| > 3\sigma D, \quad (2)$$

where:

ΔH is the vertical displacement of a monitoring benchmark between two consecutive observation campaigns;

D is the magnitude of the horizontal displacement vector;

$\sigma\Delta H$ and σD are the standard deviations (root mean square errors) associated with the determination of the corresponding displacement components.

The application of the 3σ criterion provides a confidence level exceeding 99.7%, indicating that the detected displacement is highly unlikely to result from random measurement errors and therefore represents an actual deformation of the ground surface or engineering structure. Consequently, this criterion has become a standard tool in high-precision geodetic monitoring because it significantly reduces the probability of false deformation detection.

To further verify the statistical reliability of the obtained results, Student's t-test was applied at a significance level of $\alpha = 0.05$. This statistical test evaluates whether the differences between the coordinates determined during two consecutive observation campaigns are statistically significant. If the calculated test statistic (t_{obs}) exceeds the corresponding critical value (t_{crit}) for the appropriate number of degrees of freedom at the 0.05 significance level, the null hypothesis of no

displacement is rejected, and the detected movement is considered statistically significant.

The combined application of the three-sigma criterion and Student's t-test provides a high level of confidence in the interpretation of GNSS monitoring results. The integration of these statistical methods makes it possible not only to quantify spatial displacements but also to assess their statistical significance, which is essential for forecasting deformation development, evaluating the stability of technogenically disturbed territories, and supporting engineering decision-making related to the safe operation, rehabilitation, or future construction development of the investigated sites [8, 9].

Presentation of the main research material. The accuracy of GNSS-based deformation monitoring was evaluated using two complementary approaches: internal accuracy assessment, based on network adjustment residuals, and external validation, performed through comparison with the results of precise geometric levelling or terrestrial laser scanning. Figure 4 presents a comparison of the accuracy achieved by the principal geodetic monitoring techniques.

Static GNSS observations provide horizontal positioning accuracy of $\pm 1\text{--}3$ mm and vertical accuracy of $\pm 3\text{--}8$ mm, representing an optimal balance between measurement precision and operational efficiency for deformation monitoring of technogenically disturbed territories. These accuracy characteristics satisfy the requirements of high-precision geodetic monitoring and support reliable detection of both horizontal and vertical ground displacements, making GNSS an effective tool for engineering surveys, construction control, and long-term monitoring of geodynamic processes [8–10].

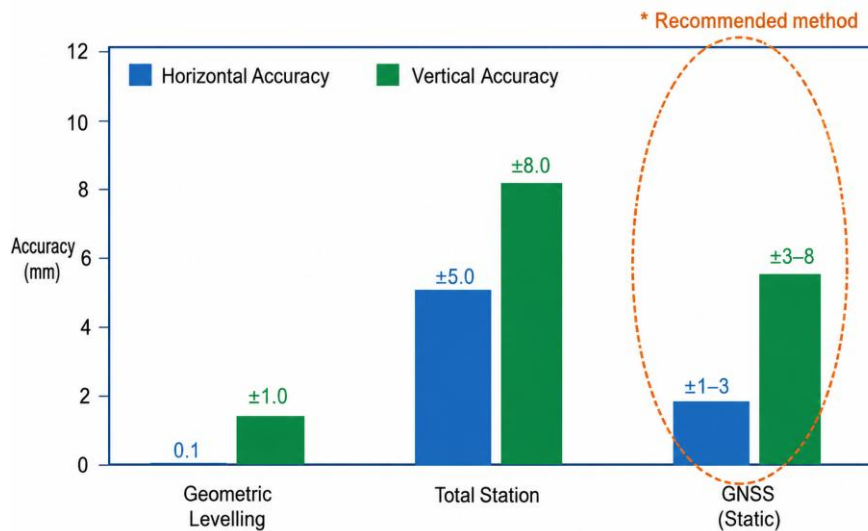


Figure 4. Comparison of the Accuracy of Geodetic Deformation Monitoring Methods (RMSE, mm)

The root mean square errors (RMSEs) obtained for the coordinate determination of the GNSS monitoring benchmarks are presented in Table 4.

Table 4. Root Mean Square Errors of Coordinate Determination for the GNSS Monitoring Benchmarks

Benchmark	σ_N (mm)	σ_E (mm)	σ_U (mm)	σ_{3D} (mm)
P1 Base	0,8	0,9	2,1	2,4
P2	1,1	1,2	3,8	4,1
P3	0,9	1,0	3,2	3,5
P4	1,3	1,4	4,5	4,9
P5	1,0	1,1	3,5	3,8

To improve positioning accuracy, the following approaches were applied: integration with the Ukrainian CORS (Continuously Operating Reference Stations) network, referencing to the International GNSS Service (IGS) network, and the stacking method for averaging the results of multi-epoch GNSS data processing. The reliability of the monitoring results is further enhanced through the structured storage of reference station telemetry together with each measurement epoch, ensuring complete traceability

of the observation conditions and improving the quality of long-term deformation analysis.

The economic feasibility of the proposed monitoring system represents an important factor in assessing its practical implementation. The cost of a single cycle of conventional geodetic monitoring (precise levelling combined with total station measurements) for a site covering approximately 1–2 ha typically ranges from UAH 15,000 to 25,000. In contrast, an autonomous GNSS-based monitoring system, following the initial investment of approximately UAH 80,000–120,000 for a network consisting of 6–8 monitoring benchmarks, provides continuous automated monitoring with minimal additional operating costs. Consequently, the proposed system is expected to achieve a payback period of approximately 1–2 years under regular operation.

According to industry statistics, the costs associated with eliminating emergency situations caused by unforeseen foundation deformations are, on average, five to ten times higher than the costs of implementing a preventive geodetic monitoring system. Therefore, the proposed GNSS monitoring methodology is not only technically effective but also economically justified for ensuring the long-term safety and reliability of civil and industrial construction projects.

Conclusions. The conducted research confirmed the high effectiveness of Global Navigation Satellite System (GNSS) technologies for deformation monitoring of technogenically disturbed territories intended for future construction development. The proposed methodology, combining static GNSS observations, high-precision post-processing of satellite data, and statistical evaluation of the obtained results, provides reliable determination of spatial displacements of monitoring benchmarks with millimetre-level accuracy.

The accuracy assessment demonstrated that the reliability of GNSS-based deformation monitoring should be evaluated using two complementary approaches. The first is internal quality control, based on the analysis of network adjustment residuals, root mean square errors (RMSEs) of the estimated coordinates, and network adjustment

quality indicators. The second is external validation, performed by comparing GNSS-derived results with independent geodetic techniques, including precise geometric levelling and terrestrial laser scanning (TLS). This integrated approach provides a comprehensive assessment of deformation reliability while minimizing the influence of systematic measurement errors.

A comparative analysis of contemporary geodetic monitoring methods demonstrated that the static GNSS technique achieves horizontal positioning accuracy of $\pm 1\text{--}3$ mm and vertical accuracy of $\pm 3\text{--}8$ mm, fully satisfying the requirements for monitoring slow ground deformation processes. Unlike conventional surveying methods, GNSS technology enables the simultaneous determination of three-dimensional coordinates for a large number of monitoring points, supports continuous automated observations, and covers extensive areas without requiring intervisibility between monitoring stations.

The study also demonstrated that the integration of GNSS observations with precise geometric levelling, terrestrial laser scanning, and modern Geographic Information System (GIS) technologies significantly improves the reliability of deformation assessment. The combined use of these complementary techniques provides mutual verification of monitoring results, enables continuous spatial representation of deformation processes, and establishes a robust information framework for predicting future geodynamic changes.

Therefore, the proposed GNSS-based deformation monitoring methodology can be recommended for geodetic support of construction projects on technogenically disturbed territories, monitoring the condition of engineering structures, reclaimed mine dumps, open-pit mines, tailings storage facilities, and other potentially hazardous sites. Practical implementation of the proposed approach will contribute to improving engineering safety, ensuring the timely detection of hazardous deformations, and supporting informed decision-making regarding the operation, maintenance, and future development of construction sites.

A promising direction for future research is the integration of autonomous GNSS monitoring benchmark networks with continuous remote monitoring systems, GIS-based information platforms, and artificial intelligence (AI)-based prediction algorithms. Such integration will enable real-time detection of critical deformation changes, improve the forecasting of geodynamic hazards, and enhance risk management during the construction and long-term operation of civil and industrial infrastructure.

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Є.Ю. Березан, Є.Г. Хлиповка

GNSS-МОНІТОРИНГ ДЕФОРМАЦІЙ ПОРУШЕНИХ ТЕРИТОРІЙ ДЛЯ ПОТРЕБ БУДІВНИЦТВА

***Анотація.** У статті розглянуто актуальне науково-прикладне завдання підвищення ефективності геодезичного забезпечення будівництва на техногенно порушених територіях шляхом впровадження сучасних технологій глобальних навігаційних супутникових систем (GNSS). Значна частина територій, що зазнали впливу гірничодобувної діяльності, характеризується розвитком повільних деформаційних процесів, які можуть негативно впливати на стійкість основ будівель і споруд, інженерних мереж та об'єктів інфраструктури. У зв'язку з цим виникає необхідність створення високоточної системи моніторингу, здатної забезпечити своєчасне виявлення просторових зміщень земної поверхні та прогнозування розвитку небезпечних геодинамічних процесів.*

Метою дослідження є наукове обґрунтування та розроблення комплексної методики GNSS-моніторингу деформацій техногенно порушених територій, орієнтованої на використання у процесі інженерних вишукувань, проєктування,

будівництва та експлуатації об'єктів цивільного і промислового призначення. Запропонована методика базується на застосуванні автономних GNSS-реперних станцій, високоточних статичних супутникових спостережень, сучасних програмних комплексів обробки GNSS-вимірювань та методів статистичного аналізу часових рядів координат.

У роботі запропоновано конструкцію автономної реперної станції, яка об'єднує багаточастотний багатосистемний GNSS-приймач, систему автономного електроживлення на основі сонячних панелей, контролер керування, модуль бездротової передачі інформації та блок локального збереження даних. Запропоноване технічне рішення забезпечує можливість тривалого безперервного функціонування мережі моніторингу без постійного обслуговування персоналом. Оригінальність конструкції підтверджується патентним рішенням, що забезпечує практичну цінність запропонованої системи.

Обґрунтовано вибір оптимальних параметрів організації статичних GNSS-спостережень, включаючи тривалість сеансів вимірювань, інтервал реєстрації супутникових сигналів, періодичність циклів спостережень, вимоги до геометрії супутникового сузір'я та критерії оцінювання якості отриманих результатів. Розроблено алгоритм обробки GNSS-даних із використанням програмних комплексів Bernese GNSS Software, GAMIT/GLOBK, Trimble Business Center та Leica Infinity, що забезпечує автоматизоване визначення координат контрольних реперів, формування часових рядів зміщень та оцінювання їх статистичної достовірності.

Ключові слова: GNSS-моніторинг, деформації інженерних споруд, геодезичний моніторинг, супутникові вимірювання, геодезичний контроль, точність вимірювань, автоматизована обробка даних, економічна ефективність моніторингу.