ANNOTATION

Dissertation for the Degree of Doctor of Philosophy (PhD) in the educational program «8D07302– Geoinformatics» by Nurzhan Khamit on the topic: «Development of a methodology for Geodynamic processes of the Almaty metro network using aerospace and geodetic methods»

In the first chapter, the analysis of the construction and operational conditions of the metro demonstrates that underground structures operate within a complex geodynamic environment influenced by both natural and anthropogenic factors. This necessitates the application of scientifically grounded methods for assessing their stability and the use of permissible deformation criteria. Contemporary studies emphasize the importance of transitioning to an integrated monitoring system that combines remote sensing (InSAR), instrumental measurements (GNSS, leveling), laser scanning, and digital modeling to accurately detect and forecast hazardous deformations. In this process, the integration of GIS technologies with modular digital modeling enables the consideration of spatially complex structures and the rapid updating of model parameters based on real-world data, while global experience demonstrates that satellite interferometry can determine vertical and horizontal displacements with millimetric precision. The analysis underscores the need to establish a unified scientific and methodological framework for integrating monitoring methods, coordinating geodetic and satellite technologies, applying advanced deformation prediction models, and assessing risks, thereby justifying the relevance of developing a comprehensive geodynamic monitoring methodology for the Almaty metro.

An analysis of the geodynamic, climatic, engineering-geological, and hydrogeological conditions of Almaty city revealed that the study area is characterized by a highly complex geological structure, increasing seismic activity, and location within the Almaty basin, which is affected by tectonic faults and differential vertical movements, directly influencing the stability of underground structures. The sharply continental climate and seasonal temperature fluctuations, along with soil freezing and thawing processes, further contribute to the formation of deformations in both surface and underground structures. The engineering-geological composition of the area consists of Quaternary alluvial-proluvial deposits overlying Paleogene–Neogene strata, including clayey, sandy, fine-grained, and boulder-bearing rocks. These data provide a basis for substantiating design decisions, selecting structural schemes, and developing measures to protect underground facilities from adverse geodynamic and hydrogeological influences.

The analysis of the development stages of the metro demonstrates the strategic significance of exploiting underground space under conditions of rapid urban growth and increasing transport loads, as well as the necessity of assessing geodynamic risks associated with tunnel deepening and implementing modern monitoring methods. International experience confirms the effectiveness of an integrated approach combining digital modeling, satellite interferometry, unmanned technologies, and terrestrial laser scanning. On this basis, the materials of Chapter 2 provide a

scientific and methodological foundation for further study of deformation processes and the stress–strain state of Almaty metro tunnels, substantiating the need for comprehensive geodynamic monitoring in the vicinity of the “Saryarka” and “Bauyrzhan Momyshuly” stations.

According to Chapter 3, the integration of geodetic and geoinformatic methods represents the most effective approach for assessing geodynamic processes in the Almaty metro area, as the safe operation of underground structures requires a comprehensive consideration of natural and anthropogenic influences. Multisensor monitoring, based on the principle of “field measurements + modeling,” allows for the identification of spatiotemporal deformation patterns and the early detection of hazardous zones. GNSS, leveling, total station surveys, and deformation markers provide precise measurements of both relative and absolute displacements of surface and underground points. UAV-based photogrammetry enables rapid monitoring of terrain and object changes along the metro alignment, updates the topographic base through orthophotos, DSM/DEM, and 3D models, and supplements GIS databases. Subsurface polygonometry, as a primary method for geometric tunnel control, establishes a planimetric–altimetric network and ensures normative accuracy, while leveling data characterize the overall stability of the tunnel’s longitudinal profile and the local nature of observed changes. The use of 3D GIS and CAD platforms facilitates the complete cycle of spatial data collection–processing–analysis–decision-making and forms the basis of an integrated monitoring system combining UAV photogrammetry, terrestrial geodetic observations, and 3D laser scanning with digital modeling, enabling early identification of hazardous areas, improved justification of engineering decisions, and enhanced operational safety of metro facilities.

A comprehensive monitoring scheme for the stress–strain state of tunnel structures along the “Saryarka – B. Momyshuly” section was established, and the integration of surface and subsurface observations with GIS analysis and digital modeling demonstrated the ability to more fully and reliably assess geodynamic conditions and tunnel stability. The application of InSAR/PSI methods complements subsurface measurements, allowing the identification of spatial patterns of deformations across large areas and monitoring dynamic changes along the metro alignment. Processing of Sentinel-1A data indicated the potential to identify hazardous zones during the period 2020–2025. The proposed complex, “subsurface geodesy + 3D/GIS modeling + digital modeling + InSAR/PSI,” forms the methodological basis for generating geomechanical risk maps, isolating areas with high rates of vertical and inclined displacements, localizing stress concentration zones, comparing calculated and observed deformations, and prioritizing enhanced monitoring and engineering interventions. Digital modeling revealed that stresses concentrate along the tunnel lining contour and diminish with distance, while the stress–strain characteristics at depths of approximately 32 m and 19.5 m differ, supporting the need for differentiated monitoring for varying depths and the application of individualized trigger thresholds.

The basis and initial data for the development of the topic. The basis for the development of the dissertation research topic "Development of a methodology

for geodetic monitoring of geodynamic processes of the Almaty metro based on digital technologies" is the need for scientifically based safety, stability and reliable operation of underground structures in a complex geodynamic environment of a megalopolis [10].

The intensive development of Almaty's underground space, the expansion of the metro network, and the high density of urban construction necessitate the use of modern approaches for monitoring geodynamic processes. Timely detection of hazardous changes in the stress–strain state of tunnels and rock masses requires the implementation of a comprehensive monitoring system. The primary data for the methodology include field geodetic observations, high-precision GNSS measurements, aerospace, geophysical, and geological materials, as well as analytical models. Integrating these data within a unified GIS-based digital platform enables comprehensive deformation analysis and the construction of spatiotemporal models of geodynamic processes, which is particularly relevant under conditions of increasing geodynamic activity, engineering-geological complexity, and stricter safety requirements.

Justification of the need for research work. The expansion of the metro network in Almaty, including the "Saryarka" and "Momyshuly" branches, leads to intensive exploitation of underground space and increases the impact of geodynamic effects—such as ground displacement, rock mass vibrations, and anthropogenic and hydrogeological changes—on tunnel stability. Consequently, an integrated geodetic monitoring methodology employing high-precision GNSS, automated stations, and GIS is required. This methodology enables the assessment of deformations, identification of hazardous zones, and ensures the safety of metro operations as well as the sustainable development of future branches.

Information about the metrological support of the dissertation.

The accuracy of the obtained results is confirmed through the use of an integrated set of geodetic and digital methods that provide multi-channel monitoring of geodynamic processes within the Almaty metro network area. The study employed instrumental monitoring of displacements in underground structures, time-series analysis of GNSS measurements, aerospace imagery, and contemporary methods of mathematical modeling of the stress–strain state of rock masses under urban development conditions.

The relevance of the topic. The underground sections of the metro network traverse areas with complex engineering-geological conditions and densely built urban zones, and their construction and operation impact residents, infrastructure, and engineering facilities, imposing stringent environmental protection requirements.

A system for monitoring and predicting ground movements and deformations is essential for the timely identification of hazardous geodynamic processes and their comparison with permissible deformations of structures. Achieving this objective requires modern geodetic and aerospace technologies that provide high-precision, continuous, and real-time monitoring.

The development of geodynamic monitoring for the Almaty metro establishes a reliable instrumental system that integrates GNSS, electronic total stations, UAVs,

digital terrain models, and GIS data, ensuring the safe operation of underground structures and the sustainable development of urban infrastructure.

The novelty of the thesis topic is the development of a comprehensive methodology for the study and monitoring of geodynamic processes in the zone of influence of the Almaty metro, based on the integration of geodetic, satellite and digital technologies.

For the first time, a method is proposed that provides for a comprehensive application:

- integrated multiscale data from ground-based, satellite, and aerospace observations into a single digital monitoring platform used to assess the stability of underground subway structures;
- forecasting of deformations of the Earth's surface and ensuring the safety of operation of metro facilities.
- geoinformation technologies for spatial analysis of deformations and construction of a digital model of a geodynamically active territory;
- modern software systems for modeling deformation processes and estimating dynamic changes in the array;
- integration of field observations, satellite measurements, aerospace survey data and digital processing algorithms into a single monitoring system for geodynamic processes.

The purpose of the study is to develop a method for determining the parameters of the zone of influence of geodynamic displacements and deformations that occur during the construction and operation of tunnels of the Almaty metro, based on the integration of geodetic and aerospace methods.

The object of the study is. the sections of geodynamic influence of the lines of the Almaty metro on the directions "Saryarka" and "Momyshuli".

Research objectives, their place in the performance of research work in general:

1. To study the existing methods of forecasting displacements and deformations of the Earth's surface during the construction of subway tunnels, taking into account the geological and man-made factors of the Almaty region.
2. To develop an algorithm for integrating data from instrumental observations, satellite monitoring, and geoinformation systems to build a digital model of deformations of underground structures and surfaces.
3. To substantiate the parameters of the zone of influence of displacements and deformations of the Saryarka and Momyshuli branches, based on numerical modeling and analysis of observations.
4. To introduce methods of geoinformation analysis (GIS) for spatial assessment of geodynamic and deformation processes in the zone of influence of the Almaty metro, as well as for modeling and visualization of potentially dangerous sections of underground and surface infrastructure.

The tasks set are consistent and logical, determine the internal unity of research work and are aimed at achieving the set research goal.

The research methodology is based on a comprehensive analysis and generalization of the results of geodetic and aerospace observations of geodynamic

processes in the zone of influence of the Almaty metro. The research uses methods of high-precision GNSS measurements, satellite radar interferometric monitoring (InSAR), instrumental observations, and digital data processing to identify, model, and interpret deformations of the Earth's surface and underground structures.

Provisions to be defended

The following provisions are submitted for the defense of the thesis:

– The stability of underground subway structures is determined by the geological structure and mechanical properties of the soil mass, which vary significantly with the depth of the tunnels.;

- zones of possible deformations during the construction and operation of subway tunnels are determined based on modeling that takes into account the spatial variability of soil and rock properties along both the tunnel route and the depth of its occurrence;

- The developed mathematical model of deformations of underground subway structures, based on the integrated integration of geodetic observations, GIS analysis data and monitoring of Earth surface displacements, optimizes geodynamic control technologies and increases the reliability of assessing the stability of underground structures.

Publications and approbation of the work. The results obtained during the dissertation work: in the Civil Engineering Journal (Q1), which is part of the Scopus database and the Web of Science, one article was published in 2025. During the academic year, Al-Farabi Kazakh National University published a dissertation for the international conference of young scientists and students "Farabi Alem" and one article for the X anniversary International Youth Forum "Green Bridge from generation to Generation".

Structure and scope of the dissertation: the thesis consists of an introduction, 4 chapters, a conclusion, a list of references from 133 titles and 2 appendices. The work is presented on 122 pages of typewritten text, contains 49 figures, 9 tables.