

Geodynamic Processes Monitoring of Subway Infrastructure Using Geodetic and Remote Sensing Methods

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Abstract

This article examines the development of a methodology for monitoring geodynamic processes during the construction of the Almaty metro using an integrated approach that incorporates geodetic methods, laser scanning, and aerospace technologies. The study aims to enhance the safety of underground structures in the context of complex engineering-geological conditions and high-density urban environments. Monitoring was conducted at the "Saryarka" and "Bauyrzhan Momyshuly" stations, employing underground polygonometry, aerial surveys with unmanned aerial vehicles (DJI Mavic 3 multispectral), laser scanning (Faro Focus 3D X), and finite element numerical modeling (PHASE 2, AutoCAD Civil 3D). The geodetic work covered a 3201-meter section with the installation of 34 benchmarks, ensuring a relative measurement error of no more than 1:30,000. Laser scanning achieved an average point cloud density of 7 mm, enabling the creation of precise 3D tunnel models, identification of deviations from the design axis, and determination of critical stress zones. The study revealed that at a depth of 32.28 m, the maximum vertical stress reached 11.2 MPa, and horizontal stress was 2.7 MPa. At a depth of 19.58 m, the vertical stress reached 10.5 MPa, while the horizontal stress was 2.47 MPa. The maximum concentration of stresses in critical zones reached 20 MPa. The use of UAVs and aerospace technologies facilitated the creation of a highly accurate digital terrain model and the identification of potential deformation zones. The findings confirm the necessity of regular monitoring in dense urban and seismically active areas and demonstrate the potential of integrating modern technologies to improve the precision and efficiency of geodynamic assessments. The proposed methodology can be applied not only to metro construction but also to other underground structures, including mining industry facilities, both in Kazakhstan and internationally.

Keywords: Geodynamic Processes; Monitoring; Massif's Stress-Strain State; Deformation; Subway.

1. Introduction

The modern stage of underground urban infrastructure development, including the subway, is accompanied by an underground construction increase in scale and depth. This is especially relevant for fast-growing megacities such as Almaty, where the underground space development is becoming a necessity in conditions of limited surface resources and high building density. In recent years, the traffic jam problem in Almaty has become much worse - during rush hour, the average speed has dropped due to the city's rapid population growth. Between 2019 and 2024, the population increased by 1.5 times, the number of vehicles by 3.8 times, and the number of cars per 1,000 residents increased by 2.8 times. Growing demands for construction safety and the need to comply with design parameters require the integration

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of geodynamic analysis into monitoring systems. Various engineering solutions and complexes are used to assess deformation processes.

In global practice, in megacities with dense historical development (London, Paris, Moscow), new subway lines are built at a 30–80 m depth to avoid conflict with existing infrastructure and geologically unstable zones. In Istanbul, Tokyo, and Hong Kong, subway lines pass through high seismic-activity zones, requiring the enhanced use of resilience technologies (for example, seismic isolation hangers and tunnel reinforcement) [1, 2].

A prerequisite for this research is the widespread geodynamic issue of earth's surface subsidence, which has attracted the attention of scientists and engineers worldwide. This phenomenon is actively discussed at international scientific forums and has taken on global significance [3]. The need for continuous and high-precision monitoring is increasing, especially given increasingly complex seismo-tectonic conditions, making this issue relevant both nationally and internationally. For example, following damage to the Daikai and Kamisawa subway stations during the 1995 Hyōgo-ken Nanbu earthquake in Japan, scientific interest in the seismic resilience of underground infrastructure increased significantly [4, 5].

The main research gaps noted in the literature are the absence of a reliable algorithm for quantitative assessment and the choosing methods problem; traditionally, displacements in industrial zones were tracked using classical geodetic methods. The high cost and limited applicability of these methods are gradually being displaced by aerospace technologies, which are particularly effective in hard-to-access areas for analyzing geodynamic processes in underground structures. Our research aim is to justify the need for regular and continuous geodynamic monitoring under conditions of intensive subway development and high-rise construction in Almaty City, where large-scale and tall structures are erected within short timeframes (1–2 years). Special attention is paid to the relevance of comprehensive research studies in densely built urban environments, which is a key factor in making effective decisions for the rational development of underground space.

Accordingly, the man-made risk assessment related to the underground infrastructure exploitation is aimed at identifying potential sources of man-made damage and evaluating their impact on the environment. Identifying such risks involves detecting vulnerable elements characteristic of a particular structure and analyzing possible failure mechanisms. Risk analysis should be especially directed toward identifying “hot spots” or hazard areas and developing scientifically based recommendations to ensure public safety in areas affected by underground structures [6].

Accelerated urbanization and growing demand for transport infrastructure are raising requirements for the design and construction of underground structures—especially subway tunnels. However, the justified adoption of decisions on geodynamic monitoring is hampered by insufficient knowledge of underground objects in densely built-up urban areas [7–9] (see Figure 1).

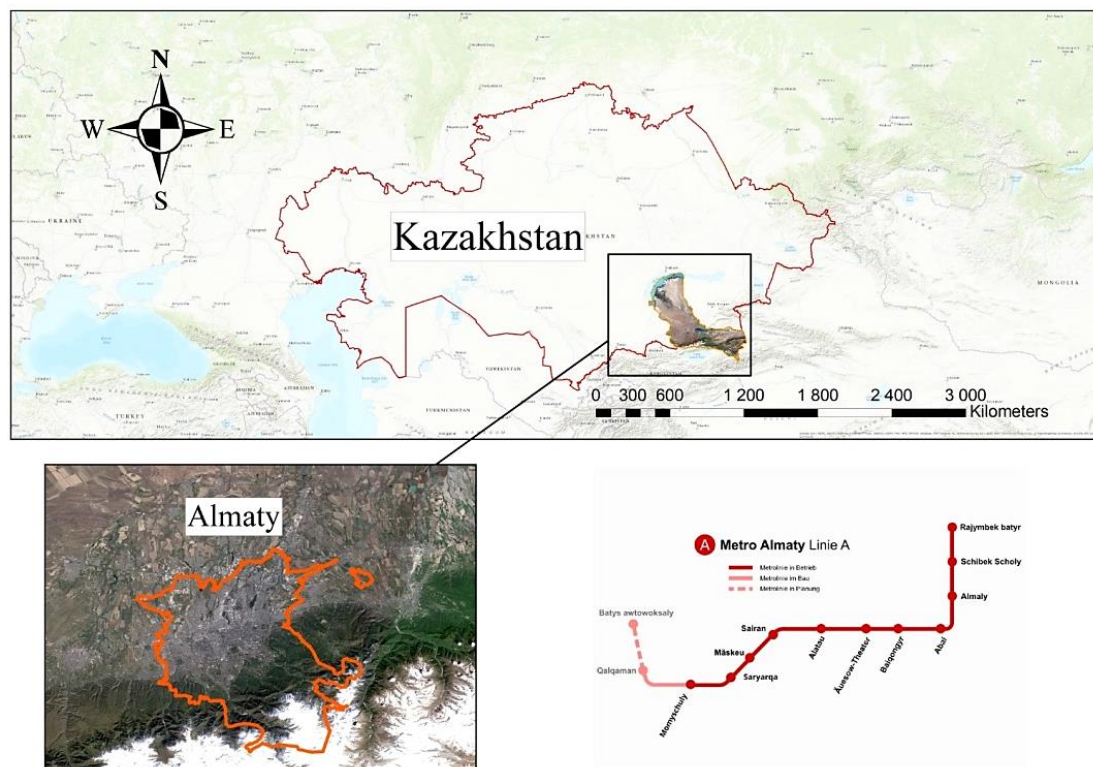


Figure 1. Main subway lines

This research significance is confirmed by the fact that similar methodologies have been successfully used to assess the risk of unforeseen deformations in existing underground structures in major metropolises with well-developed subway systems, such as London (UK), Paris (France), Berlin (Germany), Tokyo (Japan), New York (USA), as well as in nearby countries—Moscow, Saint Petersburg (Russia), Tashkent (Uzbekistan), and Baku (Azerbaijan) [10–12].

The relevance of developing an integrated methodology for assessing the underground infrastructure safety is conditioned by the need for long-term monitoring under intensive construction conditions, as in Almaty. Effective control requires a combination of numerical modeling (e.g., the finite element method) and modern observation technologies, including radar interferometry, UAVs, satellite data, and terrestrial laser scanning—especially in conditions of a limited number of benchmarks and traditional geodetic monitoring's high costs [13].

Almaty is Kazakhstan's largest metropolis, designated as a city of republican importance and serving as the country's leading financial, cultural, educational, and tourism center. Under the national program, the city is being developed as an international financial center to promote economic growth and the competitive financial cluster creation. To improve the ecological situation and reduce transportation load, the subway network is being actively expanded: in the future its length is expected to reach 50 km [14]. The recently commissioned Saryarka and Bauyrzhan Momyshtuly stations extended the existing line, connecting the city center with residential areas on the outskirts—these areas are the focus of the present geodynamic research (see Figure 2).

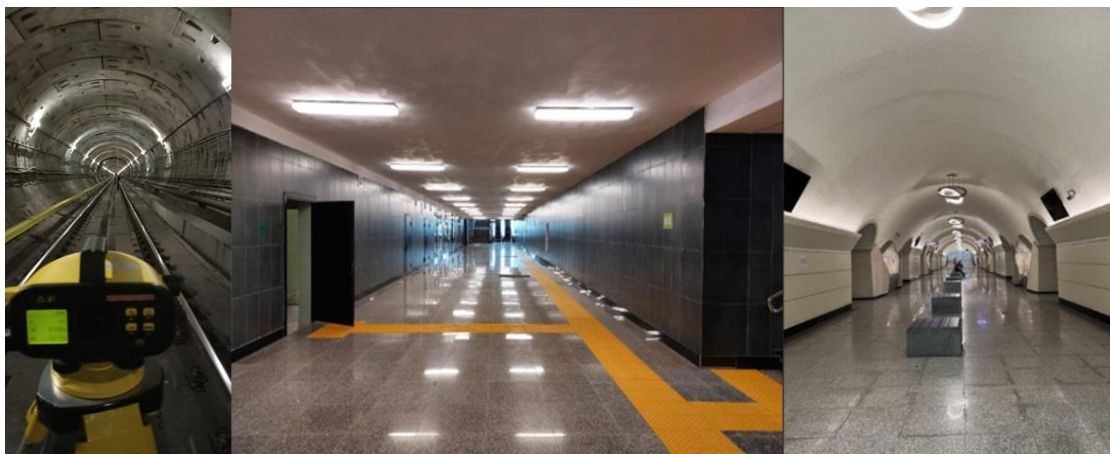


Figure 2. Subway lines of Saryarka and Bauyrzhan Momyshtuly stations

One of the key factors influencing the urban development effectiveness is the complex interaction of surface and underground processes, which, in the absence of proper control, can lead to dangerous situations.

2. Literature Review

Accelerated urbanization and increasing demand for transport infrastructure impose increasingly stringent requirements on the underground facilities' design and construction, especially subway tunnels [15–17]. Justified decision-making in the geodynamic monitoring field is hindered by the insufficient research of complex underground objects in densely urbanized environments [18–20]. Deformation monitoring has key importance in researching geodynamic phenomena accompanying subway construction and exploitation, so far as obtained results directly affect engineering decisions aimed at ensuring the stability of underground structures. In densely built urban environments and complex engineering-geological conditions typical for Almaty, natural variability in soil and rock properties can cause significant deformations and potential accidents, demanding a comprehensive monitoring approach [21, 22].

From 2017 to 2023, using SBAS-InSAR technology based on Sentinel-1 satellite data, ground surface vertical displacements in Almaty have been assessed. The research aim was to identify the relationship between deformations and active faults. Subsidence zones of up to -57 mm/year and uplift reaching $+40$ mm/year were identified, including mixed deformation zones. Five infrastructure objects susceptible to subsidence were discovered, indicating tectonic activity's effect on urban stability [23, 24]. The research is not accompanied by verification by ground methods (e.g., GPS, high-precision leveling, or laser scanning), which may reduce the accuracy of quantitative displacement estimates.

Huang et al. [12], the multi-temporal coherent analysis of goals The InSAR (PS-InSAR) method was used based on PalSAR data (2007–2010) to evaluate subsidence in the eastern expansion zone of Shanghai's Subway Line 2 (29.9 km). Three deformation areas with subsidence rates up to -30 mm/year were identified, particularly near Longyang Road and Chuansha stations, related to active construction and reconstruction. Also, deformation of coastal dams was noted. The study did not consider seasonal or temporal subsidence factors.

Research dedicated to deformation monitoring due to underground subway construction in Istanbul in the period from 2015 to 2018, using the constant scattering method PS-InSAR based on Sentinel-1 data, used geometric leveling and GNSS methods. The work highlights the limitations of traditional monitoring during the construction period only and proposes satellite monitoring as a method of control after the commissioning of facilities. This study took into account long-term displacement dynamics, including post-construction periods—rare in practice—but was limited to a single district of Istanbul and did not cover the entire subway network [25].

In the study by Kobayashi et al. (2024), dedicated to the Noto Peninsula earthquake in Japan, high-precision analysis of crustal deformations was conducted using SAR data and GNSS observations. The main focus was on transient deformation and instantaneous shift caused by the earthquake with a 7.5 magnitude that occurred on 1 January 2024. As a result of GNSS measurements, a recorded westward displacement of the peninsula's northern part by ~2 m, as well as rises of up to 1 m at a number of stations. Interferometric analysis (InSAR) and the pixel shift technique allowed us to obtain a more detailed picture of the deformation field than is possible using only ground-based observations. The most significant uplift (~4 m) occurred at the northwestern tip of the peninsula, correlating with fault structure and epicenter location. A limitation was the emphasis on vertical rather than horizontal displacement, which requires further elaboration [26].

Ando et al. (2025) article, in the journal *Earth, Planets and Space*, dedicated to the M7.5 earthquake analysis on the Noto Peninsula (Japan) in 2024. The authors are using a three-dimensional bent (nonplanar) fault geometry model to explain the shear and uplift spatiotemporal distributions. The research demonstrates that complex fault geometry has a decisive impact on the crustal deformation mechanism. This is important for predicting such events and interpreting geodetic data [27]. Authors in Quinteros-Cartaya et al. [28] present MagEs—a deep-learning model able to evaluate earthquake magnitudes based on high-frequency (1 Hz) GNSS station data. MagEs is integrated into the SAIPy package, combining event detection (DetEQ) and magnitude estimation. Training was conducted on synthetic data simulating Chilean subduction-region earthquakes and validated with real events. The model achieves magnitude estimates in seconds using data from stations within 3° of the epicenter with acceptable errors (~0.1). The article is based mainly on synthetic data, modeling the Chilean subduction region, which may limit the transferability of the model to other tectonic conditions. In this work, the advantage is the magnitude operational assessment (within a few seconds)—critical for early warning systems.

Li & Xu [29] propose a new method—QVCBI (Quadratic Variational Causal Bayesian Inference)—to classify building damage states after strong seismic events based on InSAR data. The model allows us to differentiate different classes of damage to buildings (from “no damage” to “collapse”), handling noise and secondary effects (landslides, subsidence). Integrating USGS data about geotechnical risk and building vulnerability functions, QVCBI achieves high accuracy (AUC 0.94–0.96) when processing data across five major earthquakes (Haiti 2021, Puerto Rico 2020, Zagreb 2020, Italy 2016, and Ridgecrest 2019). The method ensures accelerated processing (> 40% time reduction) while maintaining high precision without the need for extensive verification sampling.

Though primarily aimed at buildings, it can be adapted for areas adjacent to underground infrastructure—for example, tunnel-induced subsidence. International experience analysis in the application of satellite and ground geodetic technologies shows that deformation monitoring plays a key role in ensuring the stability of underground transport infrastructure under dense urban development and complex engineering-geological conditions. Using SBAS-InSAR and PS-InSAR technologies based on Sentinel-1 and PaISAR, as demonstrated in research in Shanghai, Istanbul, and Almaty, allows for high-precision identification of precipitation as well as the rise of the earth's surface, including post-construction deformations, often missed by traditional monitoring.

Of particular importance for Almaty are approaches that integrate satellite and ground-based methods (GNSS, leveling), as in the research studies devoted to the earthquake on the Noto Peninsula (Japan), where it was possible to construct detailed displacement models caused by tectonic processes. This is especially relevant given the seismic hazard of the region and the fact that the subway lines run close to active faults. Furthermore, modern developments in machine learning, such as MagEs and QVCBI, demonstrate the potential for rapid analysis and infrastructure status assessment using GNSS and InSAR data. These methods provide not only high accuracy but also real-time applicability, critical for early-warning systems and rapid response.

Such a comprehensive approach—combining satellite, ground, and intelligent analysis methods—provides a robust foundation for assessing and forecasting deformation processes in areas of metro construction and operation in Almaty. This lays the groundwork for forming an effective monitoring system aimed at enhancing the safety of urban underground infrastructure. The theoretical basis for this research is based on the interdisciplinary integration of principles from geomechanics provisions, soil stress-strain theory, modern geodetic and remote sensing monitoring methods, as well as geoinformation modeling. This approach allows for a comprehensive characterization of geodynamic processes emerging during subway construction and operation in densely built urban areas such as Almaty.

The focus is on the development and implementation of high-precision spatiotemporal monitoring methods for ground surface and engineering structure deformations induced by anthropogenic effects. This is especially relevant for underground transport systems located in complex geological-geotechnical conditions and sensitive to subsurface water dynamics, soil settlement, and vibration loads from rolling stock.

From a theoretical point of view, ground surface deformations in cities located in seismically and tectonically active regions (like Almaty) are interpreted as a result of interactions between endogenous (fault activity, tectonic motion) and exogenous (infrastructure loading, drainage, water extraction) factors. The adopted approach draws on geomechanics, geodynamics, and engineering geodesy concepts, supplemented with data on geological cross-sections, fault zones, and the region's seismotectonic structure.

The following key tasks are solved within the theoretical approach framework:

- Assessment of changes in the stress-strain state of soils surrounding the subway under conditions of long-term operation;
- Detection of local and regional deformations using geodetic measurements (GNSS, leveling);
- Modeling of the interaction "soil-water-structure" taking into account the saturation of rocks, fluctuations in the level of groundwater and the impact of vibration loads;
- Development and implementation of a geoinformation environment for the integration, analysis and visualization of multiscale monitoring data;
- Assessment of potential risks and predicting the development of dangerous deformation processes based on numerical modeling (finite element method) and models calibration based on natural observations.

The proposed theoretical approach establishes a scientific basis for comprehensive monitoring and analysis of geodynamic processes in the influence zone of Almaty's metro, aiming to improve engineering safety, infrastructure resilience, and optimization of technical oversight systems.

3. Material and Methods

Figure 3 shows a research method's block diagram for modeling the workflow, briefly displaying the methodology stages under the design and operation of underground structures in the conditions of a complex engineering and geological urban environment structure. The method was developed using Almaty subway sections as an example, where there are increased risks of deformation due to the interaction of man-made loads with natural geodynamic processes. This approach's main goal is to optimize the parameters of subway operation in areas with potential soil instability and increased seismicity. The development is aimed at reducing the deformation or destruction risks of underground infrastructure elements, as well as preventing emergency situations. The combined impact of natural and man-made factors contributing to the deformation processes' development in the subway route area includes:

- Soil instability in tectonic fault zones;
- Additional loads from urban development and engineering communications;
- The impact of groundwater and seasonal humidity fluctuations;
- Vibration loads during construction and operational work.

The scheme includes the stages of collecting and preparing input data, constructing a 3D geoinformation model of the surface and underground space, numerical modeling of stress-strain state, and integration with the monitoring system to substantiate engineering decisions. This visualization helps to more clearly represent the research approach and the logic of the work.



Figure 3. Research methodology flowchart

Taking these factors into account allows us to more accurately predict the design solutions reliability within the framework of further subway development.

3.1. Advanced Monitoring Techniques in Underground Construction

Risk management is an important part of assessing operational risks and combating them, a set of measures to prevent dangerous situations. In this regard, the specialized geoinformation system creation for managing man-made risks [30] using modern, topographic-geodetic, and aerospace technologies, laser scanning, and geomechanical research, as well as improving known and developing new methods, will increase the safety of exploiting ground and underground structures.

In modern research studies related to the excavation work impact assessment on subway construction, special attention is given to numerical and experimental approaches. One of the key methods is numerical modeling, which allows us to analyze the structures and surrounding soil deformation and stress states. For example, PLAXIS 3D software is used for detailed modeling of the excavation process and its impact on adjacent structures, such as subway tunnels, by Ye et al. [18].

The finite element method (FEA), widely used in this field, provides the ability to divide complex structures into smaller elements, which allows for accurately predicting stress and strain distribution [31, 32]. At the same time, using the discrete element modeling (DEM) makes it possible to simulate soil behavior at the particle level, which is especially important for analyzing complex interactions between soil and structure [33]. Experimental methods include physical testing, for example, laboratory model development to research the subway tunnels' deformation and destruction mechanisms under soil subsidence conditions. These approaches provide empirical data that complement and verify the numerical modeling results.

Additionally, dynamic numerical methods are used to account for the soil and water interaction. They allow us to research phenomena such as soil subsidence under the train vibration influence, which is especially topical for saturated soft clays [34]. Synthetic aperture radio-locating interferometry (TS-InSAR) is actively used for monitoring subsidence and deformation, providing high accuracy in observing changes in the earth's surface. This method allows detecting even minimal surface movements, making it indispensable in dense urban areas [13, 35]. Innovative construction methods deserve special attention, such as SCJB, which combines open-notch shafts and jack boxes. This approach minimizes the environmental and urban transport impacts under subway construction.

Finally, using field observations supported by 3D geomechanical modeling contributes to a better understanding of sedimentary processes and the reliable solutions development for underground construction. An integrated approach combining numerical methods, field data, and experimental research studies provides a more complete understanding of deformation and destruction mechanisms in complex geological conditions [36].

3.2. Critical Analysis of Methodology

At present, this topic is particularly relevant for countries with industrially developed infrastructure and complex tectonic structures, including Kazakhstan, where the influence of tectonic and man-made factors on the environment, as well as the harmful effects of earthquakes or accidents at industrial engineering structures, has greatly increased.

The study of geodynamic processes and their component, “modern movements of the Earth's crust,” which has become an area of scientific interest across all Earth sciences [37, 38], emerged relatively recently—around the mid-20th century—and began to develop rapidly worldwide. The complexity of solving problems in geodynamics when researching real processes, combined with a lack of experimental material, led to the fact that, at the initial stage of experimental data accumulation, researchers in the Earth sciences worked independently from one another in studying geodynamic processes. However, when analyzing their results, each researcher inevitably faced the need to integrate the findings of geodynamic studies from various Earth science disciplines at the interpretation stage.

At the same time, it is known that underground structure construction does not always lead to negative consequences expressed in the damage form to individual elements of buildings or structures on the surface, and that, if necessary, the underground construction impact can be mitigated by using various protective measures or changing the technological mode. The final engineering solution should be based on the predicted deformation values of the earth's surface and rock mass caused by the underground structure construction.

The first attempts to predict the earth's surface deformations were made in Bayramov et al. [39] and Karasev and Belyakov, which were later supplemented in the works of Attewell [40], Mair et al. [41], and O'Reilly & New [42]. The forecast methods proposed by these authors are mainly based on the field observation results, which were generalized in the analytical dependencies form.

A common disadvantage of these methods is the uncertainty in choosing the parameters of analytical dependencies, the range of which is quite wide, and the authors do not offer clear recommendations on the choice of numerical indicators. As a result, these methods are used either for preliminary prediction of deformations of the earth's surface,

which makes it possible to identify areas of influence of the construction of underground structures, or they are used in well-studied construction sites where there is a foundation for field studies.

The general disadvantage of these methods lies in the uncertainty associated with selecting parameters for analytical dependencies, whose range of variation is quite wide, and the authors of these works do not provide clear recommendations for choosing numerical indicators. As a result, these methods are used either for preliminary forecasting of earth surface deformations—allowing the identification of influence zones during underground structure construction—or in well-studied construction sites where additional opportunities for natural research exist.

A significant number of researchers have developed methods for predicting the earth's surface behavior based on analytical approaches. Among these, the most notable works are [43, 44]. The main limitation of the methods presented in these studies for predicting earth surface deformations lies in their simplified approach to both describing the process of constructing underground structures and representing the mechanical behavior of the surrounding rock mass. In recent years, attempts have been made to account for various soil behavior characteristics, such as anisotropic deformation properties [45]; however, the models have remained relatively simple and have not fully addressed the shortcomings inherent in earlier studies in this field. Consequently, these methods have not found wide application in tunnel design practice and are used mainly for verifying numerical solutions and in academic research.

At present, the prediction of earth surface deformations is mainly carried out based on numerical modeling of underground construction. This progress has been facilitated by the development of concepts related to soil deformation processes that account for the anisotropy of their strength and deformation properties [46, 47], as well as the emergence of advanced behavior models representing such characteristics [48, 49]. Various methods have been developed for predicting earth surface deformations during underground structure construction, both through shield tunneling and different modifications of mining methods.

Numerical modeling of underground structure construction should be performed while considering the specific construction technology, allowing for detailed tracking of changes in the stress state trajectory of the surrounding rock mass and the bearing elements of fortification structures, as well as modifications in mechanical properties and the moment when the lining begins operation. To achieve this, the problem under consideration must be divided into stages, the number of which depends on the level of detail required to account for the specific characteristics of construction operations.

For example, under the conditions of St. Petersburg, the stope size during the construction of station tunnels for pylon-type subway stations is 0.75 m, with the lining installed after excavation within each stope. The total length of the three station tunnels is 450 m. Therefore, to conduct a detailed numerical model of subway station construction, it is necessary to divide the solution into at least 600 stages. Considering that the lining installation and soil excavation are usually modeled as two separate stages, the total number of calculation stages will double. It should also be noted that a subway station, in addition to station tunnels, includes a variety of other underground mining operations [50].

The problem of mutual influence among a complex of underground mining operations within a subway station must be solved in a spatial formulation, using a preliminary number of finite elements approximating the actual station geometry—ranging from 350,000 to 500,000 elements. In this case, the elements must be at least of the second order to ensure sufficient accuracy of the solution. Considering the above, the duration of the problem-solving process becomes quite significant (lasting several weeks, and even longer when complex environmental behavior models are applied), which greatly limits the practical application of this approach [51, 52].

As the accuracy and efficiency of geodetic measurements continue to improve, the range of problems to be addressed is expanding—an area in which modern geodesy can make a significant contribution.

3.3. Method Applying on the Researching Object

Geodetic methods are the primary and most modern techniques for researching geodynamic processes. Their application allows for the simultaneous measurement of all deformation marks located within underground tunnels, enabling the determination of mutual displacements between any two observed marks. Additionally, individual displacements can be identified based on reference points with known and fixed coordinates. Beyond these advantages, the combination of modern geodetic measurement methods and specialized mathematical processing techniques makes it possible to monitor and detect the displacements not only of deformation marks but also of the main reference points [53].

Unmanned aerial vehicles (UAVs) are ideal for rapid monitoring of subway route areas during terrain observation stages. The aerial photographs obtained are particularly valuable for tracking potential trends in the area—such as development, modification, transformation, and dynamics—allowing for prompt decision-making and effective analysis of the object's condition.

Before commencing survey operations using UAVs, geodetic marks were installed within the study area, and their coordinates were determined using GNSS technology (Figure 4).

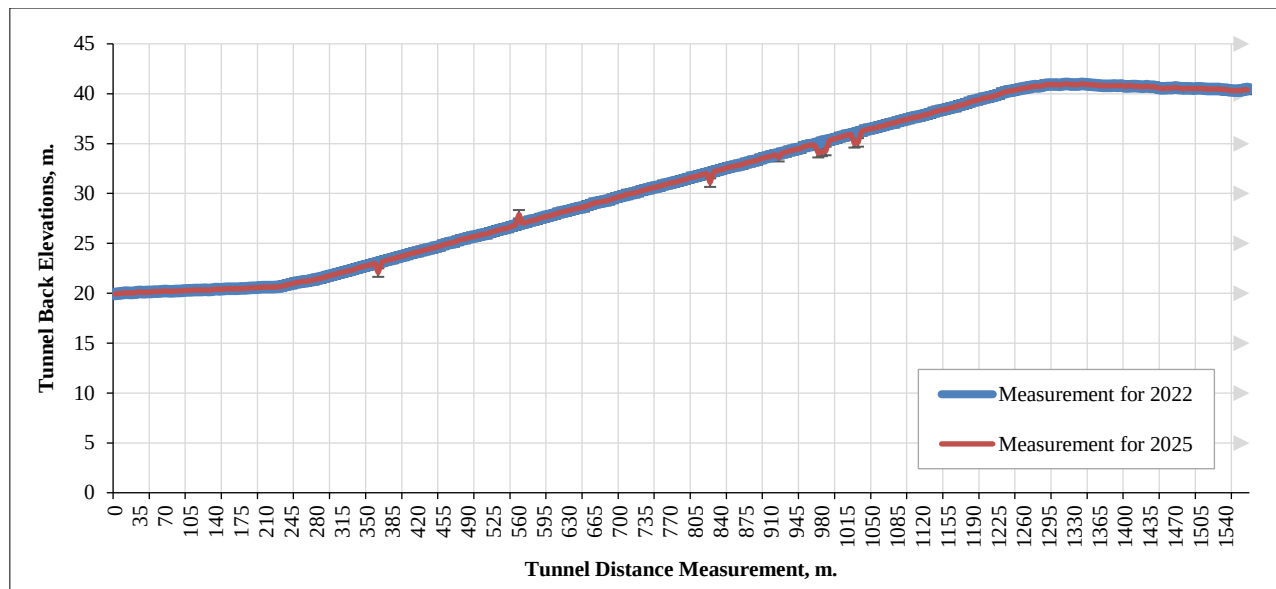


Figure 4. Marker coordinates and indicators graphs

In our research a DJI Mavic 3 multispectral (quadcopter) was applied (Figure 5). Drones, along with the newest three-dimensional modeling systems, will be used at every monitoring stage.



Figure 5. DJI Mavic 3 multispectral

The quality of information obtained from UAV aerial photographs largely depends on the choice of software used for their processing. Modern software packages for UAV data processing—such as Agisoft, Erdas Imagine Photogrammetry, and AutoCAD REPAC—employ local adaptive algorithms and various modifications of these algorithms. A distinctive feature of these algorithms is their direct image processing within a “sliding window”, the size of which typically does not exceed 4000×3000 pixels. This approach enables relatively fast processing without requiring additional information about interference parameters or effective signals. To enhance the visual perception of images, it is necessary to adjust pixel brightness so that it is distributed uniformly across the full range whenever possible.

In such cases, the resulting image appears high-contrast. However, in the original image, this condition is typically not met due to the limited dynamic range of signal intensities, which is constrained by the communication channel’s throughput. Considering the above criteria for UAV images, the Agisoft PhotoScan application was selected. The main advantages of this program are that orthophoto plans obtained through photogrammetric processing are suitable for updating topographic maps at scales of 1:2000 and smaller, while terrain models generated from oriented pairs of aerial photographs can be used to update relief data on topographic plans.

In real-world applications, Agisoft PhotoScan is implemented by installing the program on a portable computer, to which any GPS device can be connected. The GPS-Link tool, included in the standard package, allows communication between the program and the GPS receiver.

A significant advancement in the expansion of 3D model applications has been the ability to create measurable 3D models—referred to here as *photogrammetric models*—which can represent spatial information within a defined coordinate system and allow for the measurement of individual point coordinates. A rapidly developing scientific field, 3D GIS, now provides fundamentally new possibilities for managing spatial information and assessing man-made risks. The creation of realistic photogrammetric 3D terrain models is a crucial prerequisite for developing such 3D GIS systems.

4. Results

4.1. 3D Terrain Modeling Based on UAV and Photogrammetric Data

Monitoring of geodynamic processes in the Almaty subway is aimed at identifying and assessing deformation changes in the Earth's crust, which arise both as a result of the construction and operation of underground structures and under the influence of natural factors, including tectonic movements. Particular importance is given to the control of displacements and changes in the stress–strain state of the rock mass near tunnels and subway stations.

To address these issues, modern geodetic, geophysical, and aerospace methods are employed, enabling the detection of even minor displacements with high accuracy. These include high-precision geodetic measurements, GNSS observations, laser scanning, and seismometric monitoring. Since geodynamic processes pose a potential threat to the stability of underground structures and the safety of passenger transportation, establishing an effective observation system is a priority task (Figure 6).

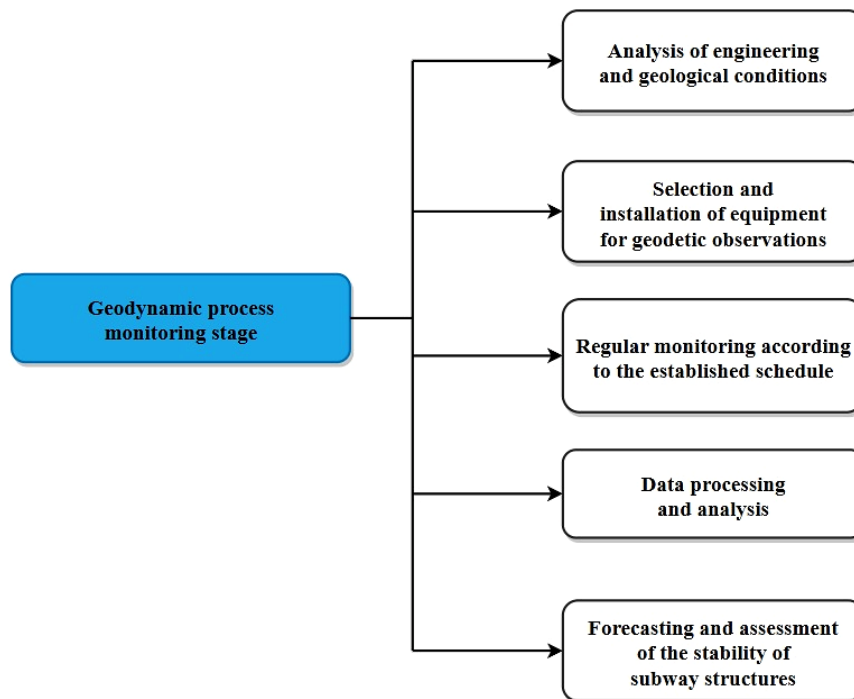


Figure 6. Geodynamic modeling stages and influence of deformation zones determination

Currently, the following geodynamic risks have been identified during the Almaty subway underground structures operation, capable of affecting the tunnels' stability and the functioning of the entire system safety:

- Local deformation processes activation in zones of tectonic faults crossing the subway route;
- Development of instability in the surface and deep soil layers, especially in areas with increased water saturation and poorly cemented rocks;
- Displacements of engineering-geological blocks caused by dynamic loads from rolling stock and fluctuations in groundwater levels;
- Potential for sudden collapses or subsidence due to stress redistribution around underground workings;
- The impact of seismic vibrations typical for the Almaty region, which increases the tunnel structures' destabilization risk.

Spatial data about terrain and urban features can be obtained through geodetic measurements, topographic maps, or laser scanning, but aerial photogrammetric surveys remain the most complete and effective method for creating accurate 3D terrain models. Although various institutions have begun to create such models, problems remain associated with obtaining and processing aerial photographs. In this research, a photogrammetric method was developed that combines aerial and terrestrial digital imagery to improve modeling efficiency. The orthophotomap in GeoTIFF format was created based on UAV images with embedded coordinate marks (Figure 7). Since each UAV image contains coordinate and elevation metadata, creating orthophotomaps and terrain models becomes an easy task.

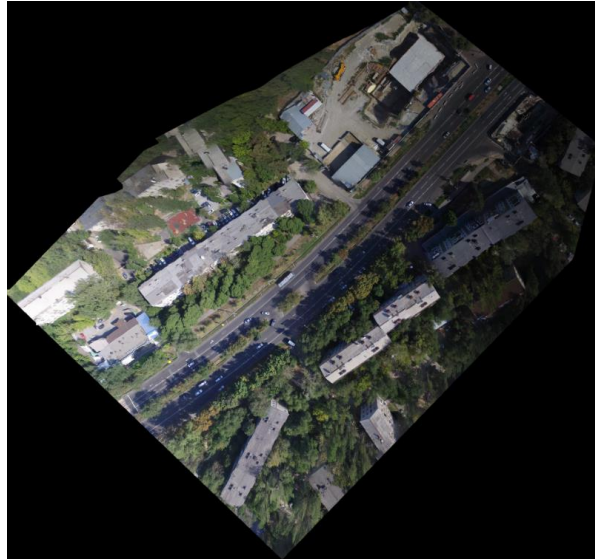


Figure 7. Territory orthophotoplan

Spatial data on terrain and urban objects can be obtained through geodetic measurements, topographic maps, or laser scanning; however, photogrammetric aerial imaging remains the most comprehensive and efficient method for generating accurate 3D terrain models. While various institutions have begun creating such models, challenges remain regarding aerial data acquisition and processing.

In this study, a photogrammetric method was developed that integrates aerial and ground-based digital imagery to improve modeling efficiency. An orthophotoplan in GeoTIFF format was created using UAV images, with embedded coordinate tags (Figure 7). Since each UAV photo includes metadata on coordinates and elevation, generating orthophotos and terrain models becomes a manageable task. Due to the fact that each photograph taken by a UAV contains information about the coordinates and set of height points, the orthophotoplan and terrain model creation at the processing stage is not such a labor-intensive task. Executing all the conditions and also meticulously collecting initial information for processing, a high-quality and exact digital terrain model is obtained, which will inure as a basis for further geomonitoring development in the subway area (Figure 8).

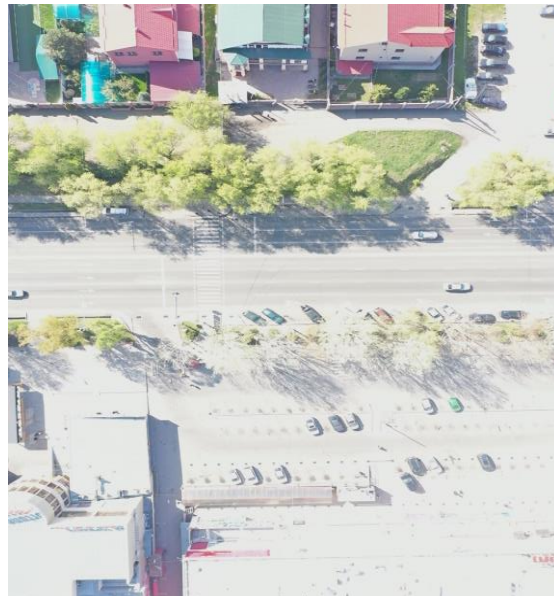


Figure 8. Aerial photography data processed using the program Agisoft PhotoScan

A 3D Point Cluster is a form of 3D visualization and represents one of the stages in creating an accurate real 3D model image of the research object. It serves as the starting point of digital reality—a spatial map of points that captures a larger or more complete picture to form an exact model of a specific area. Figure 9 illustrates the transformed point cluster data used to represent the object. The advantage of this method lies in the fact that the grid retains the original point data and operates more efficiently.



Figure 9. Creating points cluster models

This represents the starting point of digital reality—a spatial map of points designed to capture a broader and more complete picture in order to form an accurate area model. Figure 10 illustrates the transformed point cluster data used to represent the object. The advantage of this method lies in the fact that the grid retains the original point data and operates more efficiently.

Most GIS and CAD systems can utilize geotags and instantly display a GeoTIFF file as a coordinate-based layer. A digital terrain model (DTM), presented in DEM (Digital Elevation Model) format, is represented as a GeoTIFF file in which the elevation at each precise point is determined by variations in pixel brightness. Many GIS and CAD systems can use DEM files exported from PhotoScan.

This modeling approach allows for a high-quality visualization of the complete positional layout and facilitates detailed analysis of coordinate calculations within the subway area—particularly for the Saryarka and Bauyrzhan Momyshuly stations. These analyses were conducted as part of a comprehensive monitoring framework of geodynamic processes and structured into two main stages: surface-level and underground tunnel sections. Figure 10 illustrates this modeling process.

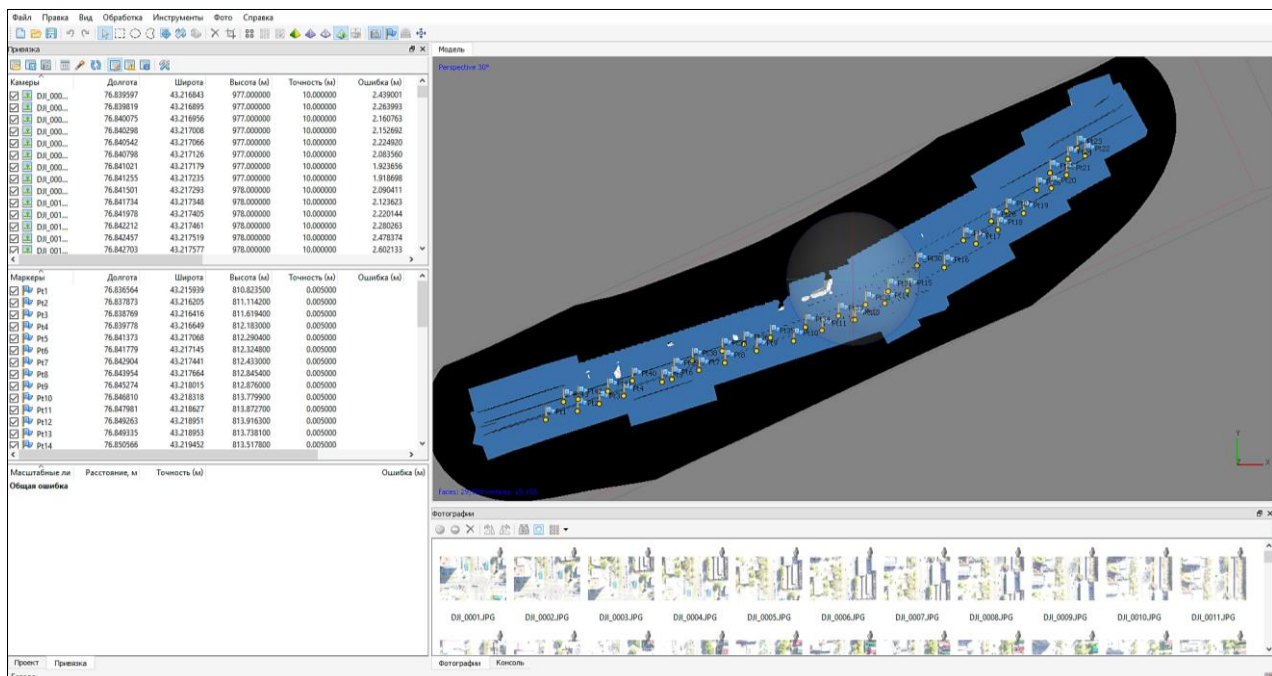


Figure 10. Coordinate indicators model based on aerial photography data

4.2. Underground Geodetic Surveys and Polygonometry

An underground geodetic survey spanning 3,201 meters was conducted in April–May 2023. A total of 34 permanent geodetic benchmarks were established. Angular measurements were conducted via the iteration method using the Leica 06 Plus, and linear distances were measured with an electronic tacheometer. Elevation differentials were recorded at 464 points for deformation analysis (Figure 11).

Angular and linear measurements for determining all sign coordinates were conducted twice—at different times and independently. For comparison purposes, altitude mark surveys were carried out in February and March 2018. Underground polygonometry serves as the foundation for the precise transfer of all tunnel structures to their actual project dimensions. The main indicators scheme enables the creation of a continuous chain of triangles. At the same time, underground polygonometric points function as underground altitude benchmarks. The relative discrepancy in polygonometric increments does not exceed $1:30,000$, and the permissible angular discrepancy complies with the condition $f = 6\sqrt{n}$.

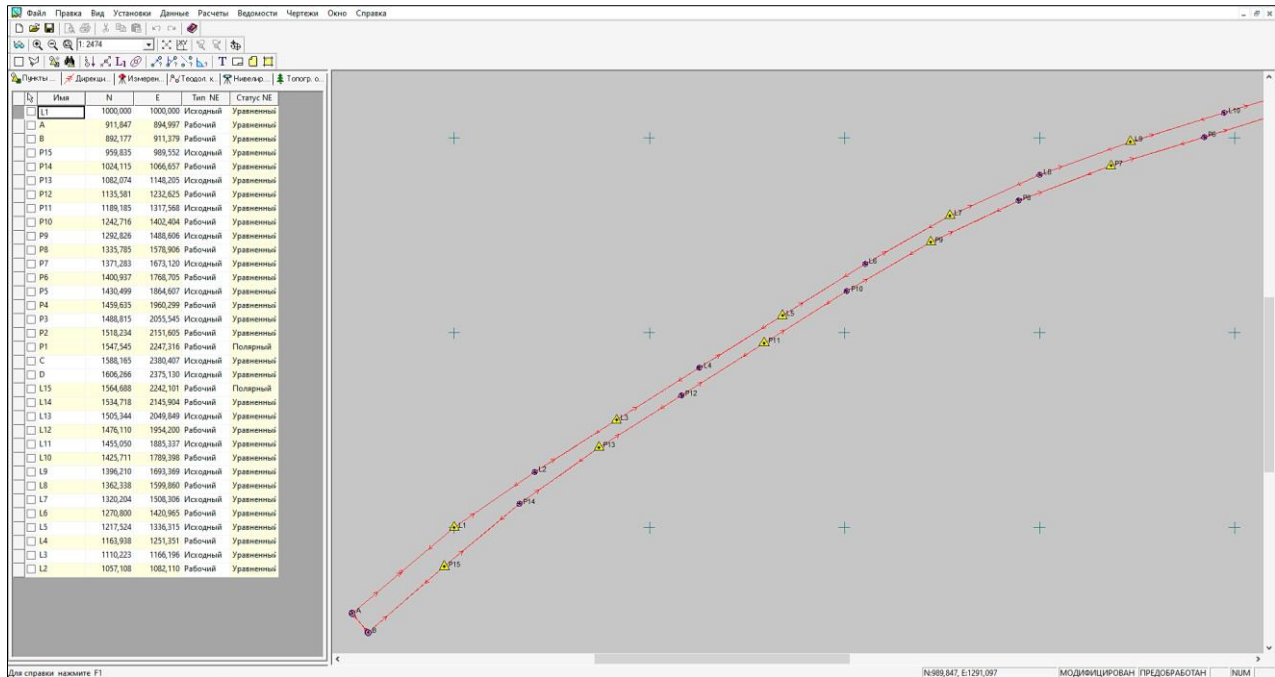


Figure 11. Coordinate Underground polygonometry scheme

Overall, the reference geodetic network was constructed with an accuracy that meets the requirements for supporting subway construction. Deviations in the interpretation of underground polygonometry orientation do not exceed $3''$, ensuring the feasibility of tunneling operations using navigation systems. The entire complex of geodetic works was performed in accordance with regulatory standards, without any technological violations, and the reference engineering and geodetic polygonometric network—both in plan and profile—achieved an accuracy of ± 5 mm [54].

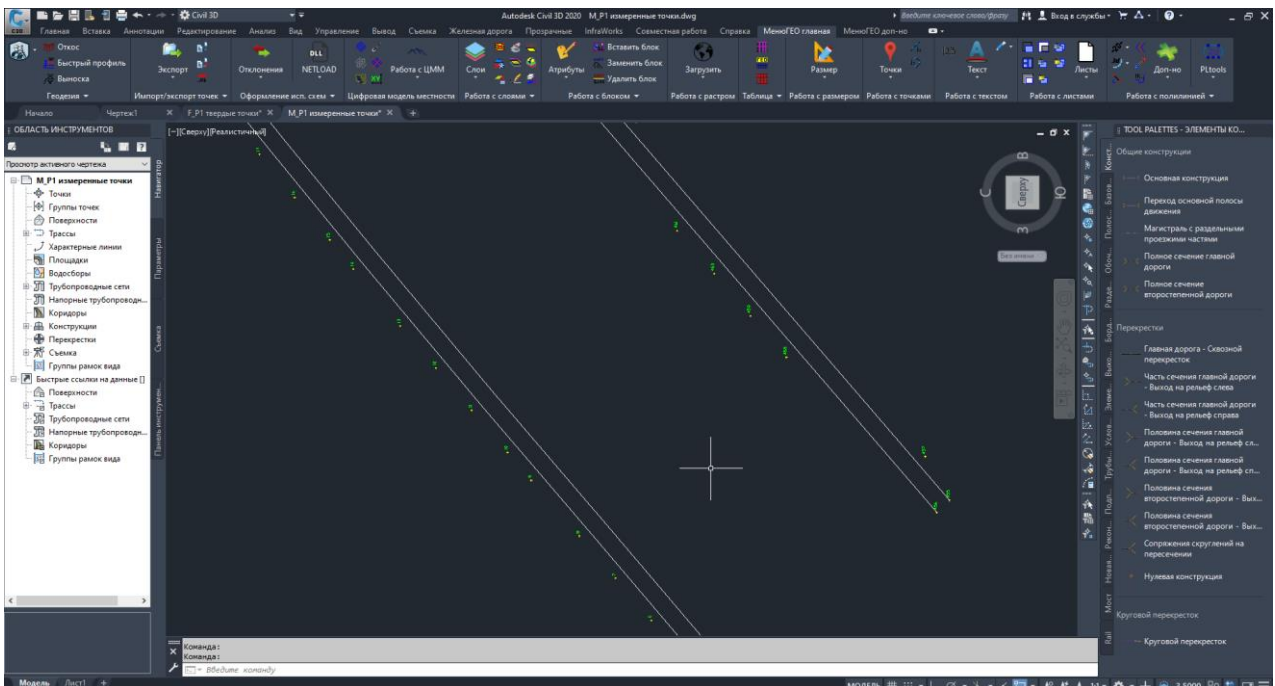


Figure 12. Tunnels model in the Saryarka and Bauyrzhan Momyshtuly direction

A key feature of modern geodetic maintenance in subway construction using geoinformation systems is the extensive use of modeling. In general, geodetic work in subway construction adopts an integrated approach based on geoinformation models and technologies. This essentially replaces traditional geodetic methods with geoinformatics techniques that integrate geodetic measurements into geospatial data. Furthermore, well-established technologies are systematically applied using accumulated expertise, as illustrated in Figures 12 and 13, where a dual-tunnel model is simulated using AutoCAD software.

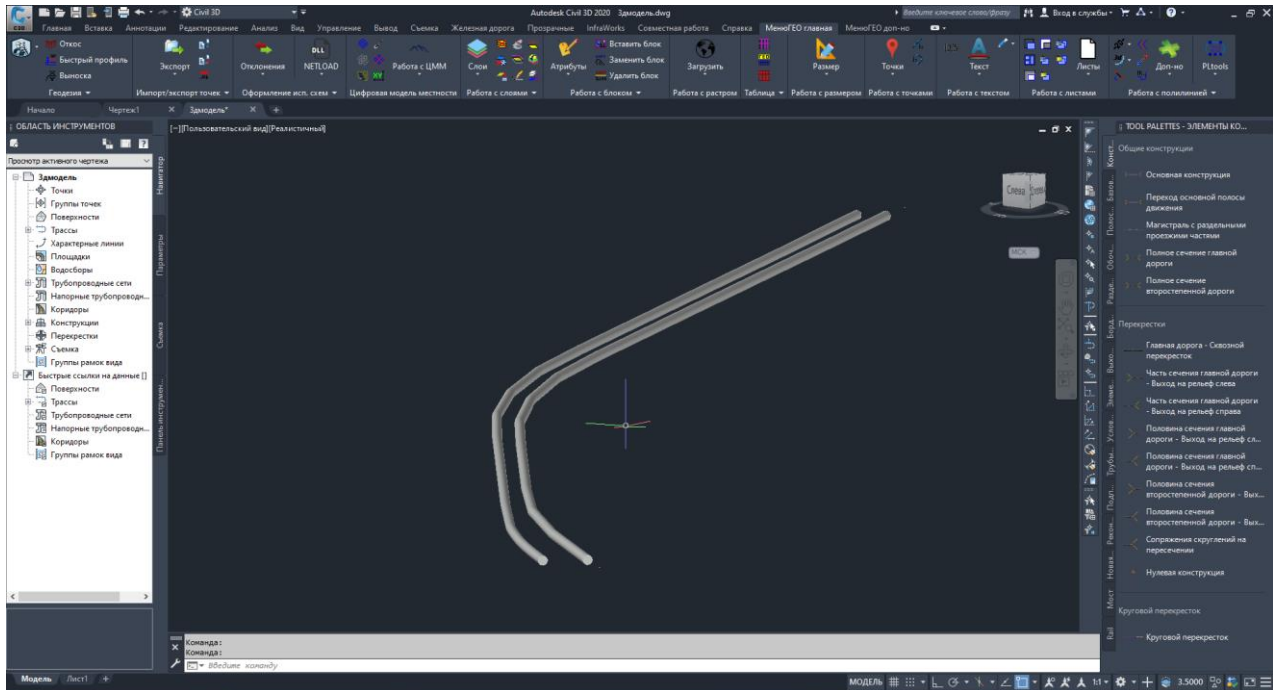


Figure 13. Tunnels model along the subway axis

The simulation of stress zones was conducted using a geomechanical analysis complex. Initial input included tunnel geometries and soil physical-mechanical characteristics (Table 1). Investigated tunnel depths were: Saryarka – 32.280 m, Momyshuly – 19.580 m, and Vent Trunk Saina – 31.560 m. The stratigraphy included sandy loam, clay loam, and gravel soils, each with specified geomechanical properties.

4.3. Numerical Modeling of Stress–Strain States

The depths from the surface were investigated as follows: 32.280 m (Saryarka), 19.580 m (Momyshuly), and 31.560 m (Vent Trunk Saina), representing the upper boundary of the studied area. The enlarged fragment of the area indicates that the massif consists of sandy loam, clayey loam, and pebble soil. The properties of each layer are defined in accordance with Table 1.

Table 1. Soils physical and mechanical characteristics

Soil name	Density, (t/m ³)	Internal friction angle, (degrees)	Specific adhesion, (kPa)	Deformation module, (mPa)	Poisson's coefficient	Protodyakonov's coefficient
Sandy loam	1.64-1.74	22	36	18	0.3	1.0
Clayey loam	1.66-1.75	24	35	14	0.35	1.0
Pebble soil	2.17-2.26	35	34	68	0.27	1.2-1.7

Novelty: The main stresses and displacements are the most informative characteristics for assessing the stress–strain state of the massif. The distribution of the largest principal stresses is typical for an extended cavity.

The stress–strain state modeling was carried out using the licensed PHASE2 software developed by Rocscience. For this purpose, a topographic survey was performed at each of the studied stations, followed by the construction of a terrain model using AutoCAD Civil 3D software (Figures 14 to 31).

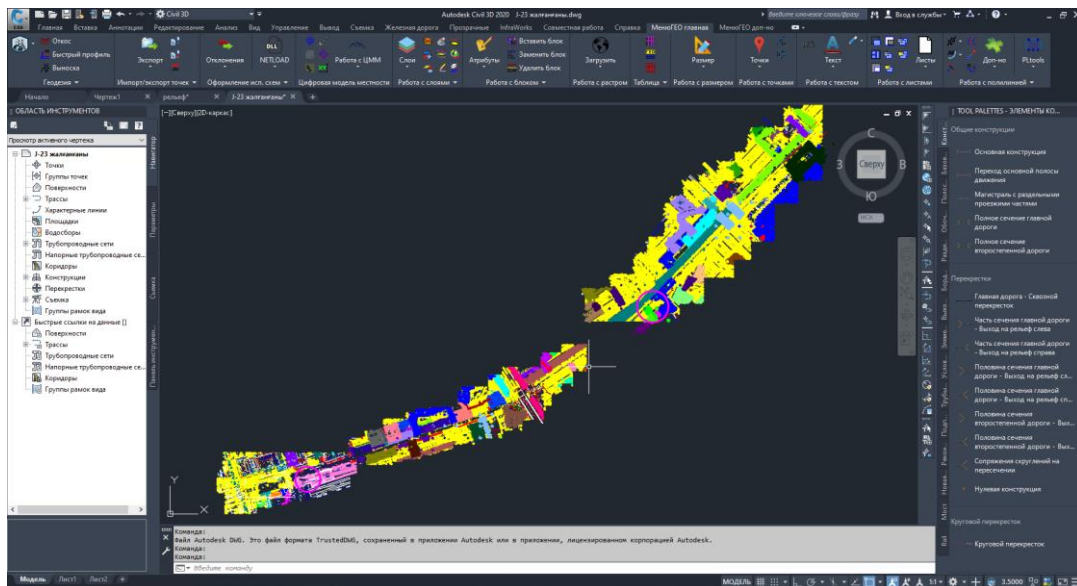


Figure 14. Subway surface topographical plan at Saryarka and Bauyrzhan Momysuly stations

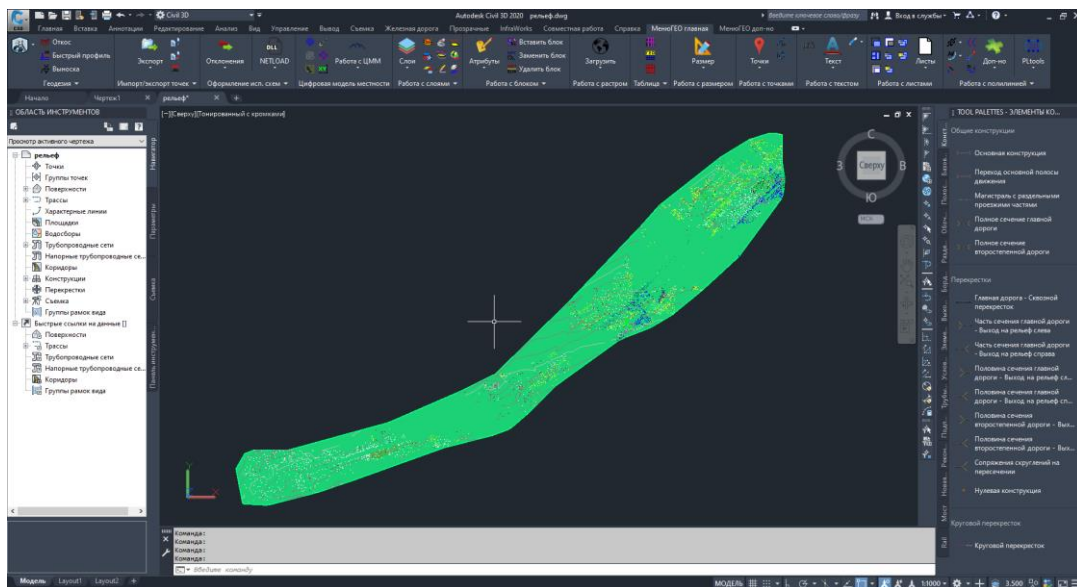


Figure 15. The subway surface plan and their heights made in the AutoCAD Civil 3D program

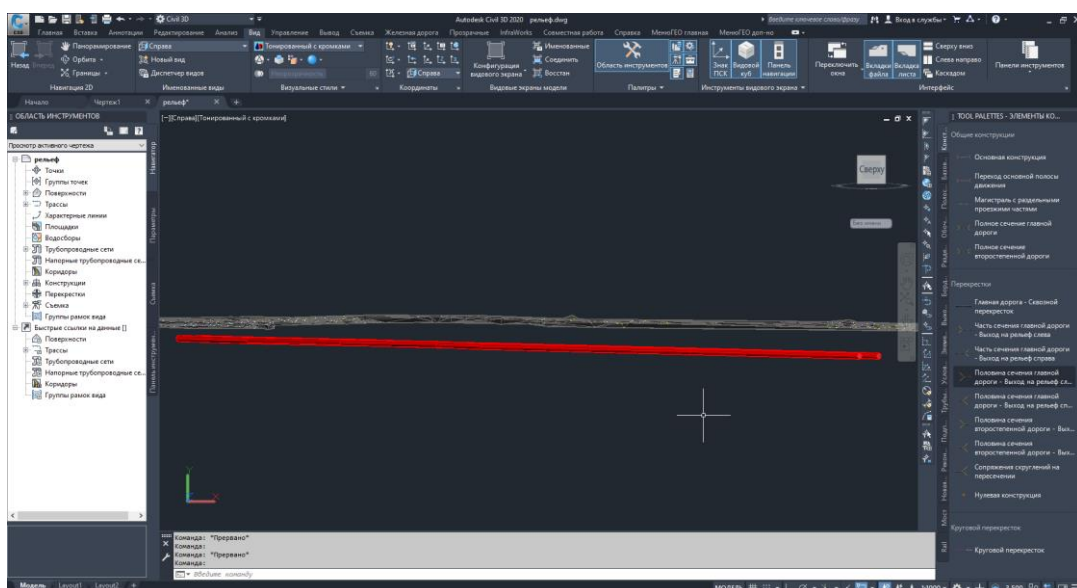


Figure 16. Engineering and geometric 3D model of a subway tunnel structure

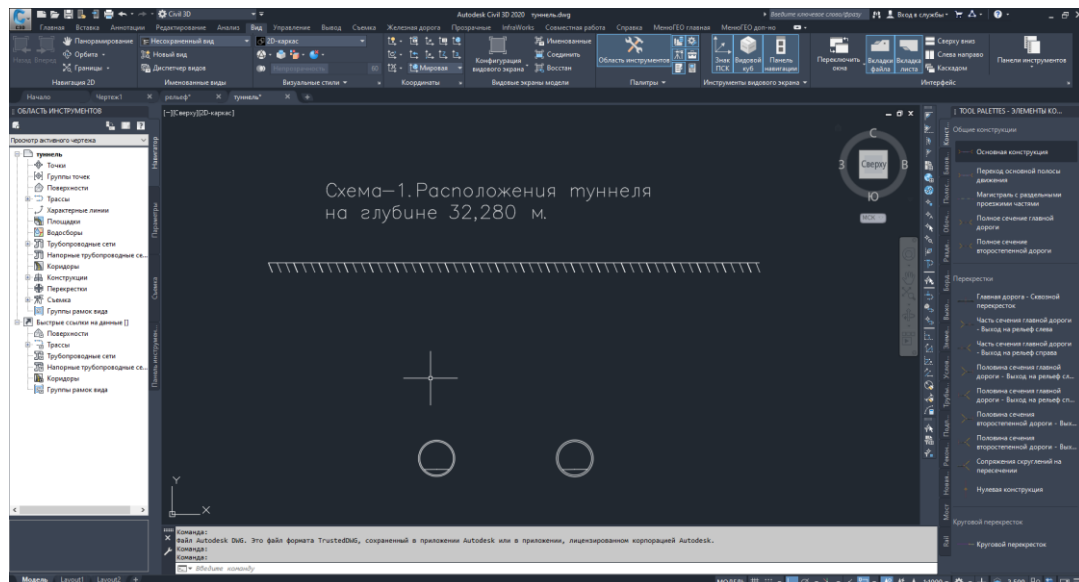


Figure 17. Underground space fragment in the Saryarka station area at a 32.28 meters depth

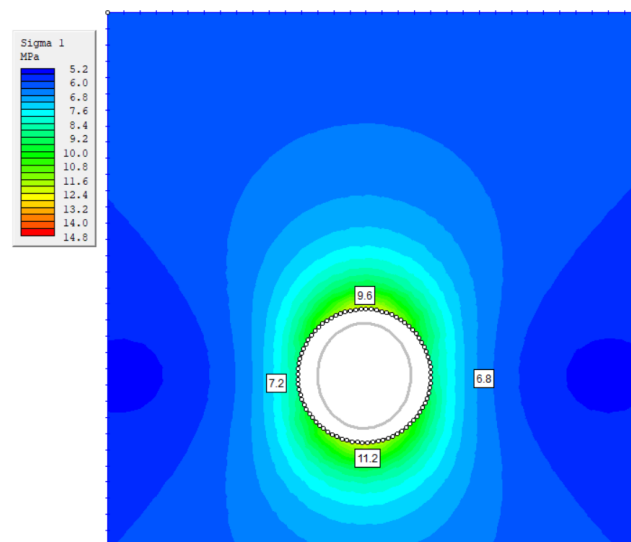


Figure 18. Impact of vertical stress in a tunnel 6.8-11.2 MPa, at 32.28 meters depth

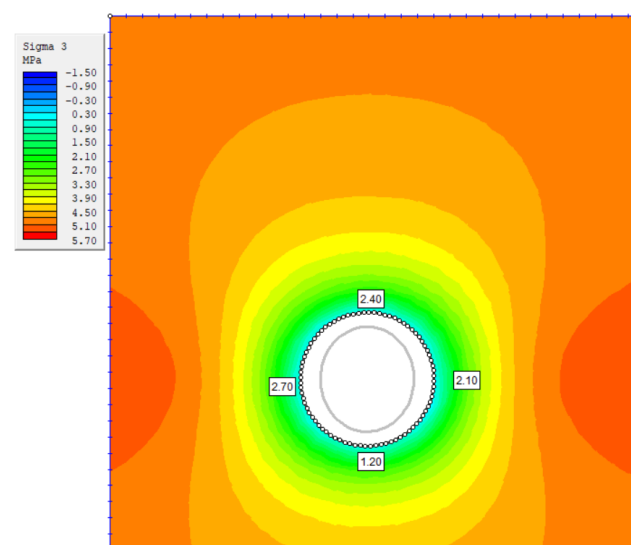


Figure 19. Impact of horizontal stress in a tunnel 2.1-2.7 MPa, at 32.280 meters depth

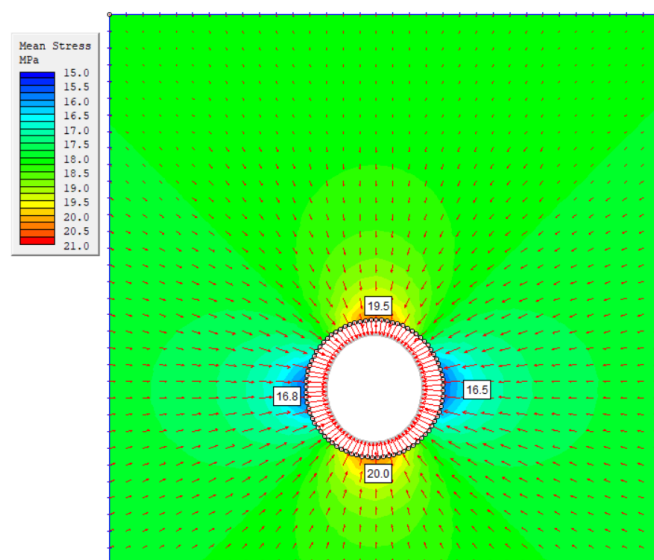


Figure 20. Dynamic change of stress field 16.8-20 MPa around tunnel at 32.28 meters depth

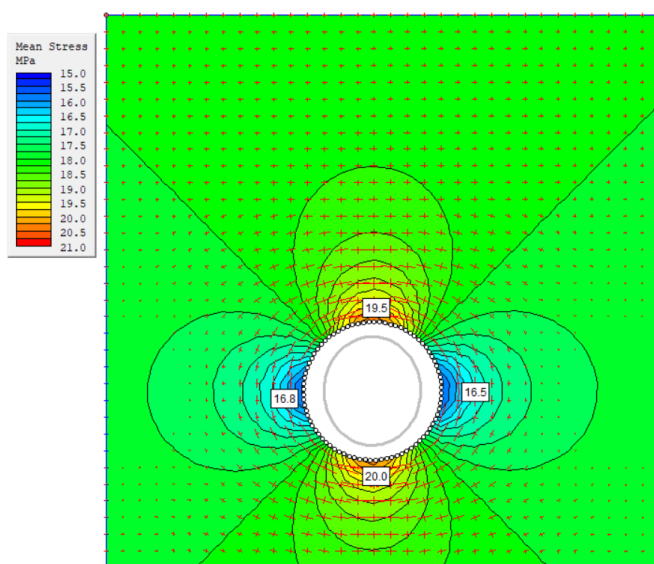


Figure 21. Fracture direction and stress distribution 16.8–20.0 MPa at 32.28 meters depth

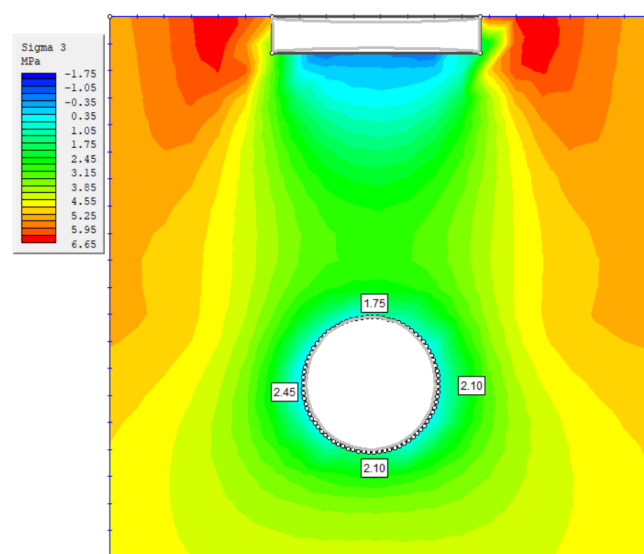


Figure 22. Maximum horizontal stress impact in a tunnel 1.75-2.45 MPa, at 32.280 meters depth

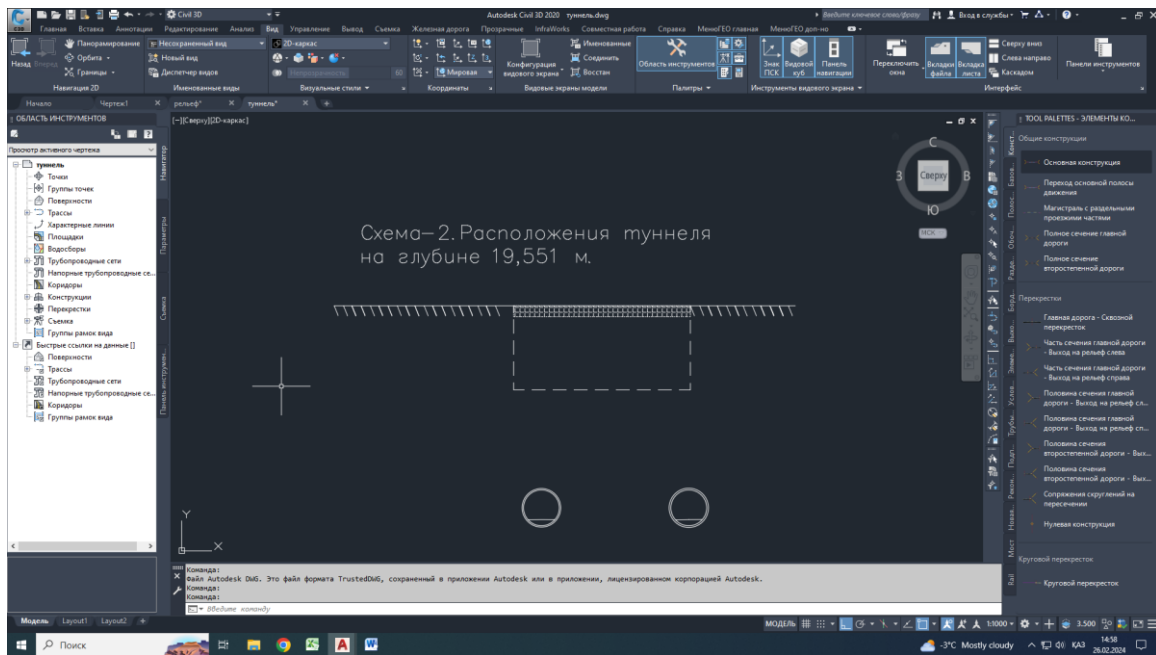


Figure 23. The 2nd subway line investigated section, Abay Avenue and Saina Street, includes a bridge and a tunnel, at 19,55 meters depth

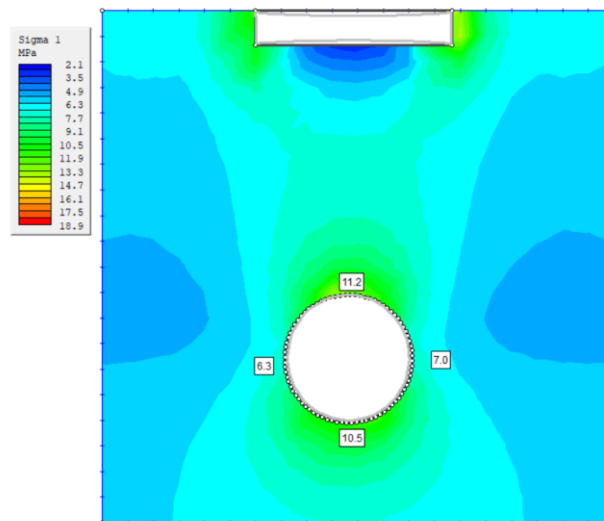


Figure 24. Vertical stress impact in a tunnel 6-11.2 MPa, at 19.55 meters depth

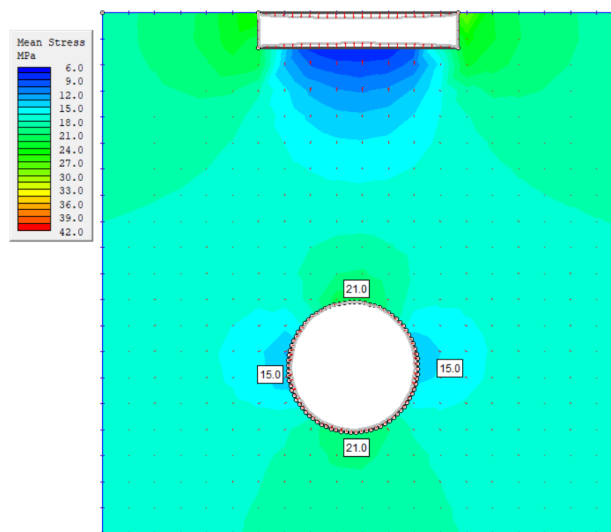


Figure 25. Stress field's dynamic change 15-21 MPa around tunnel at 19.55 meters depth

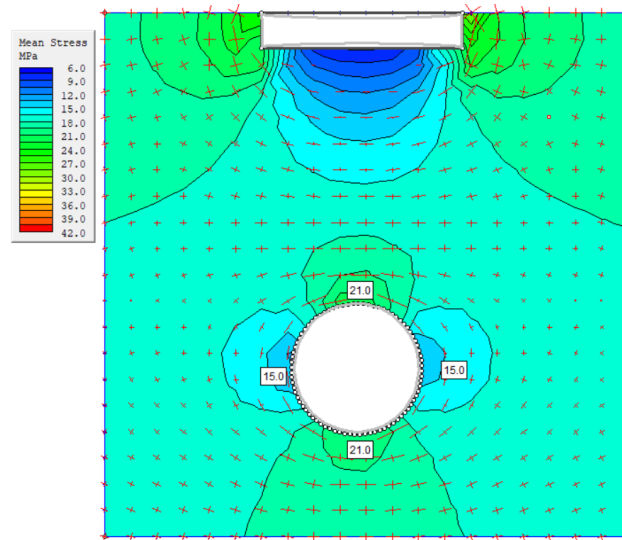


Figure 26. Fracture direction and stress distribution 15-21 MPa at 19.55 meters depth

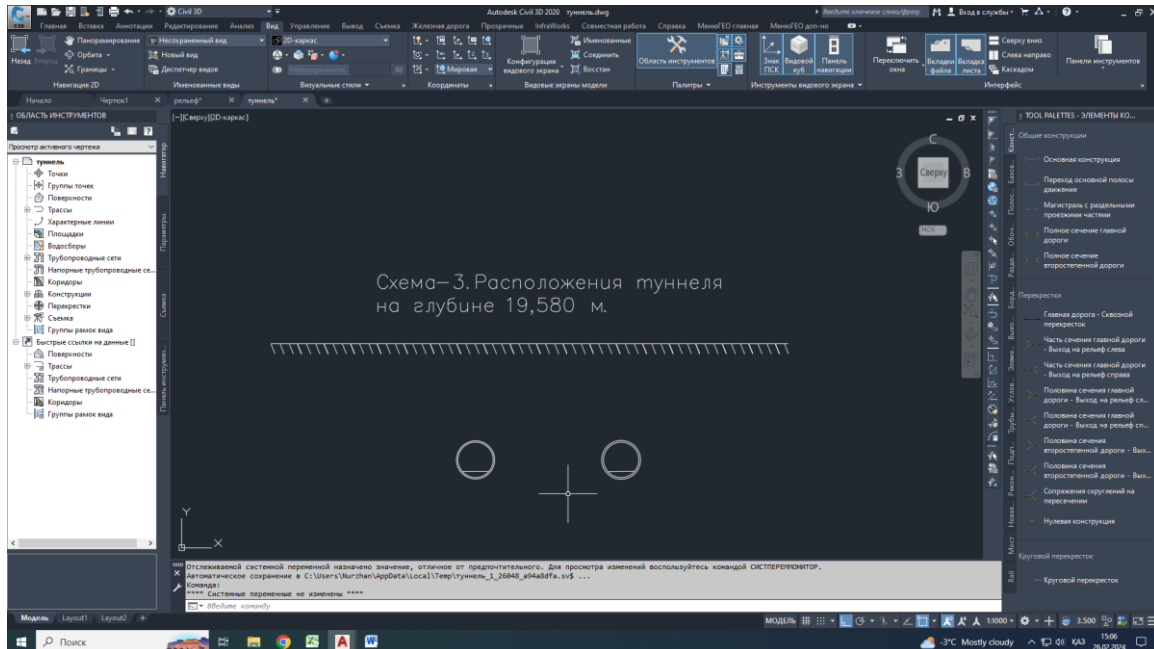


Figure 27. The 3rd metro line section researching, Abay Avenue and Momysuly Street, tunnel depth 19.58 meters

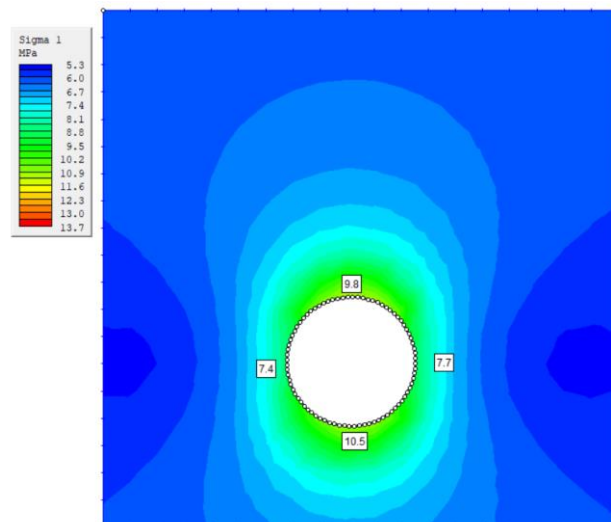


Figure 28. Vertical deformations in the tunnel at depth 19.58 meters under tension 7.7–10.5 MPa

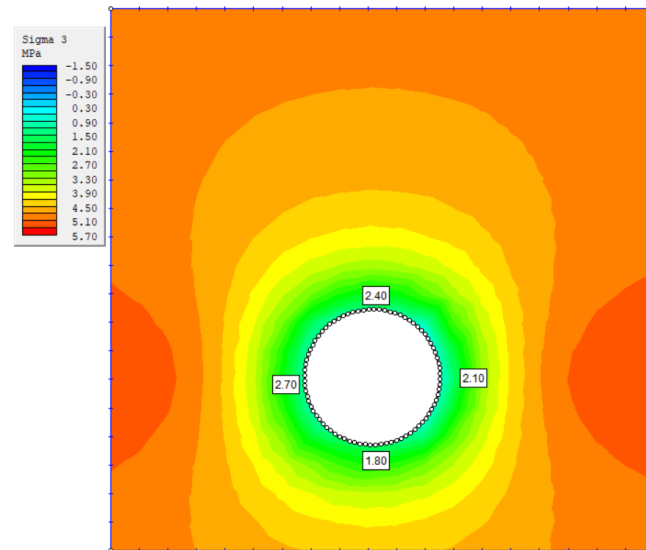


Figure 29. Horizontal deformations in the tunnel at 19.58 meters depth at maximum stress 1.8-2.47 MPa

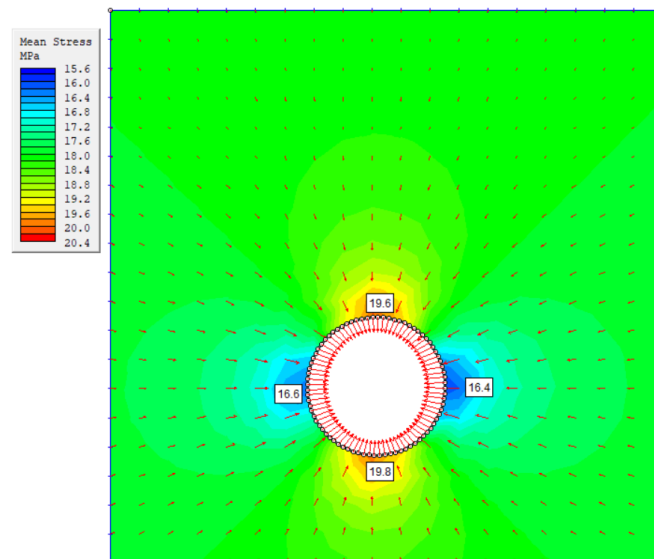


Figure 30. Deformations dynamic distribution in a tunnel at 19.58 meters depth under tension 16.6-19.58 MPa

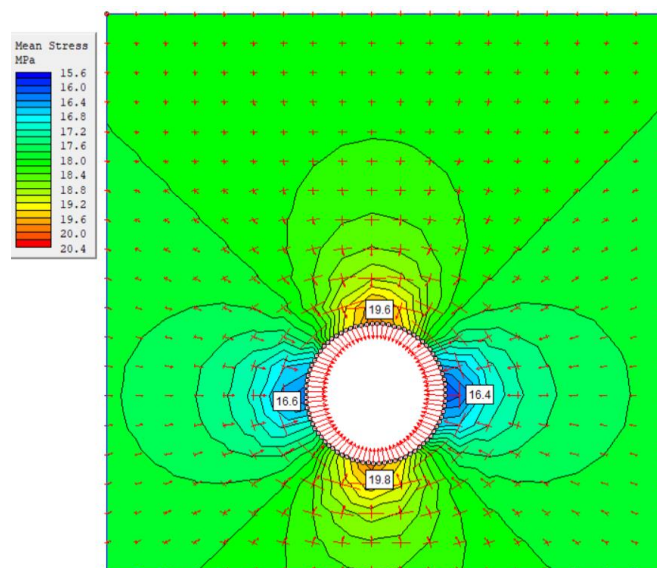


Figure 31. Fracture direction and stress distribution 15-21 MPa at 19.58 meters depth

The materials presented in Figures 14 to 16 illustrate the key results of geodynamic monitoring conducted during the construction of the Almaty subway, which was implemented under complex engineering and geological conditions within a densely developed urban environment. Figure 14 shows the topographic plan of the subway surface in the Saryarka and Bauyrzhan Momyshtuly station areas, prepared in AutoCAD Civil 3D. This visualization enables a clear representation of the terrain and the distribution of engineering structures, which is critically important for subsequent modeling of the massif's stress-strain state.

Figure 15 presents a digital surface plan with elevation marks created in AutoCAD Civil 3D, providing a three-dimensional representation of the terrain. Such models serve as a foundation for geomechanical analysis and numerical modeling, as variations in relief and elevation significantly influence the stress distribution within the rock mass and affect the behavior of tunnel structures.

Figure 16 depicts the tunnel's engineering geometric 3D model, constructed based on geodetic data, laser scanning, and finite element numerical modeling using PHASE2 software. This model enables the analysis of critical stress zones and the identification of potential deformation risks or displacements. The integrated use of aerospace technologies, laser scanning, and geodetic methods ensures high visualization accuracy and enhances the prediction of geodynamic processes, which is particularly important for maintaining the stability of underground structures in the seismically active Almaty region. A 3D model of the subway tunnel was developed using coordinate data (Figure 16).

Figure 17 illustrates a fragment of the underground space in the Saryarka station area, located at a depth of 32.28 meters, where the position of the tunnel and its engineering elements is visualized, defining the geometric layout of the mine workings. This image serves as the basis for conducting numerical modeling of the rock mass stress-strain state around the tunnel.

Figures 18 and 19 show the distribution of vertical (6.8–11.2 MPa) and horizontal (2.1–2.7 MPa) stresses around the tunnel lining. These data were obtained using the finite element method in the PHASE2 program and indicate the uneven stress state of the massif, determined by the geomechanical properties of the soil and the embedment depth. Figure 20 illustrates the dynamic changes in the stress field, reaching 16.8–20 MPa, which indicates the presence of localized high-stress areas that are potentially dangerous in terms of fracture formation or tunnel lining deformation. Figure 21 visualizes the directions of fracture propagation and the distribution of stresses, allowing the identification of critical areas where the progression of deformation processes may occur. Figure 22 demonstrates the influence of maximum horizontal stresses (1.75–2.45 MPa), confirming the significant impact of lateral soil pressure on tunnel stability.

The obtained results were interpreted considering the complex engineering and geological conditions of Almaty, where intense urbanization and seismic activity necessitate comprehensive monitoring and numerical modeling to ensure the safety of subway operations. The research highlights the importance of integrating surveying methods, laser scanning, and geomechanical analysis to identify potential risk areas and enhance the reliability of underground structures.

Figure 23 presents the section of the Almaty subway's 2nd line located along Abay Avenue and Saina Street, including a bridge and tunnel at a depth of 19.55 meters. As noted in this study, such areas require increased attention due to the complex interaction between surface and underground structures within dense urban environments and under the influence of regional seismic activity. Figure 24 shows the distribution of vertical stresses ranging from 6 to 11.2 MPa, identified through our measurements using the finite element method in PHASE2. These values indicate localized stress zones that may contribute to deformation processes in the tunnel lining. Figure 25 shows the dynamic changes in the stress field with magnitudes ranging from 15 to 21 MPa around the tunnel. In this study, such areas are interpreted as potentially dangerous zones, where the development of plastic deformations is possible—particularly at points of contact with bridge structures.

Figure 26 demonstrates the directions of fracture propagation and stress distribution contours. The research findings indicate that maximum stresses are concentrated in the upper part of the massif and along the tunnel sides, emphasizing the necessity of monitoring possible displacements. Thus, the obtained data confirm that geodynamic monitoring and stress-strain state modeling, as applied in this study, are essential for ensuring the safe operation of Almaty's underground infrastructure.

Figure 27 illustrates the third subway line section under investigation, located in the Abay Avenue and Momyshtuly Street area, where the tunnel lies at a depth of 19.58 meters. The study notes that such areas are characterized by a complex stress-strain environment, which requires regular monitoring. Figure 28 shows the distribution of vertical deformations under stresses ranging from 7.7 to 10.5 MPa. The measurements indicate that maximum vertical deformations are concentrated in the tunnel roof zone, which could potentially lead to subsidence

or local damage to the lining. Figure 29 presents the horizontal deformations at maximum stresses of 1.8–2.47 MPa. These values are interpreted as resulting from lateral soil pressure, which increases the load exerted on the tunnel walls.

Figure 30 illustrates the dynamic distribution of deformations within a 16.6–19.58 MPa stress range, revealing localized zones of stress concentration that may necessitate reinforcement measures. Figure 31 shows the directions of fracture development and the spatial distribution of stresses (15–21 MPa), which, according to this study, may serve as indicators of potentially critical deformation processes. The integrated approach, based on finite element modeling, laser scanning, and aerospace data, enabled us to enhance prediction accuracy and develop recommendations for improving tunnel stability in this study.

This article presents a comprehensive investigation of the stress–strain state of the rock mass in the construction and operation zones of the Almaty subway. The objects of research included the “Saryarka” and “Bauyrzhan Momyshuly” station sections, as well as areas along Abay Avenue, Saina Street, and Momyshuly Street. The studies were conducted based on topographic surveys, three-dimensional laser scanning, and numerical modeling using the finite element method in PHASE2 and AutoCAD Civil 3D software environments.

Figures 14–16 present topographic plans and engineering–geometric 3D models of tunnel structures. This work highlights that such models enable more accurate relief assessment, the identification of potentially hazardous deformation zones, and serve as a foundation for geomechanical analysis.

In the “Saryarka” station area (Figures 17–22), at a depth of 32.28 meters, vertical stresses ranging from 6.8–11.2 MPa and horizontal stresses between 2.1–2.7 MPa were recorded. The dynamic stress variation reached 16.8–20 MPa, indicating the presence of local potential deformation zones. The research identified that fracture propagation predominantly occurs along the tunnel arch, associated with load redistribution within the rock mass.

On the 2nd subway line section (Figures 23–26), located along Abay Avenue and Saina Street at a depth of 19.55 meters, the data show vertical stresses ranging from 6–11.2 MPa and a dynamic stress field variation of 15–21 MPa. The study emphasizes that in such areas, engineering structures like bridges can significantly affect stress redistribution, leading to complex interactions between underground and above-ground structures.

On the 3rd subway line section in the Abay Avenue and Momyshuly Street area (Figures 27–31), where the tunnel lies at a depth of 19.58 meters, the measured vertical deformations ranged from 7.7–10.5 MPa and horizontal deformations from 1.8–2.47 MPa. The dynamic deformation distribution reached 16.6–19.58 MPa. The study shows that maximum stresses are concentrated in the upper and lateral zones of the tunnel, posing a risk of plastic deformation and fracture formation.

Thus, the results obtained in our study confirm the necessity of integrating modern geodetic monitoring methods, laser scanning, and numerical modeling for the timely identification of high-risk zones and ensuring the safe operation of Almaty’s underground infrastructure. This article emphasizes that such an approach can serve as a model for monitoring and analyzing geodynamic processes in other megacities with high seismic activity and complex engineering and geological conditions.

4.4. Laser Scanning and Tunnel Deviation Mapping

In the previous chapters of this paper, a comprehensive interpretation of the numerical simulation results of the rock mass stress–strain state in the construction and operation zones of the Almaty subway stations was presented. In this research, special attention was given to identifying stress concentration zones, determining possible fracture propagation directions, and assessing the dynamics of deformation processes at various tunnel depths. However, for complete verification of the obtained data, calculation and modeling methods alone are insufficient. Therefore, this study includes the next key research stage — high-precision laser scanning of the tunnel space.

Chapter 4.4 describes the application of laser scanning and the construction of tunnel deviation maps. This article highlights that for large cross-section mine workings constructed in low-cohesion soils, there is a high probability of surface subsidence and the formation of unstable zones around the structures in cases where soil pressure compensation is inadequate. To ensure the operational stability of the structures, it is critically important to follow the technological sequence of tunnel construction and to timely install temporary and permanent supports with adequate load-bearing capacity.

The research data required an additional surveying method — tunnel scanning, which was conducted using a Faro Focus 3D X phase laser scanner (Figures 32 and 33). Before scanning, reference marks were installed along the tunnel,

and their coordinate positions were determined by our geodetic team using a Leica TC 06 Plus tachometer. The scanning was performed from three stations, achieving an average point cloud density of 7 mm.

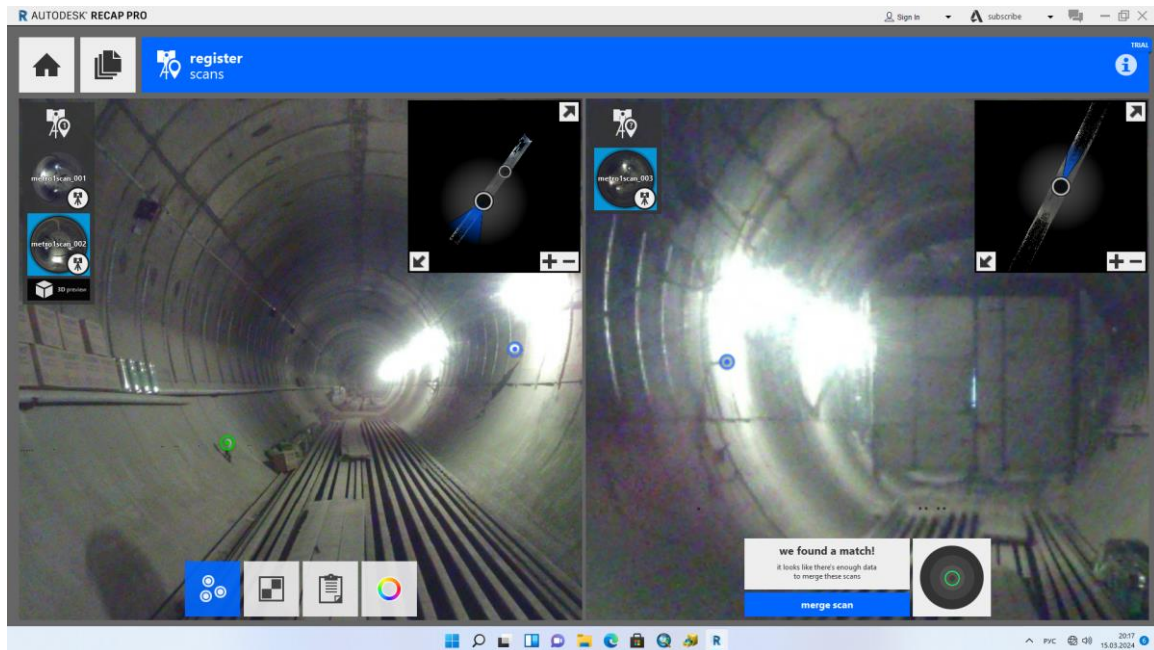


Figure 32. Tunnel scanning and connection results

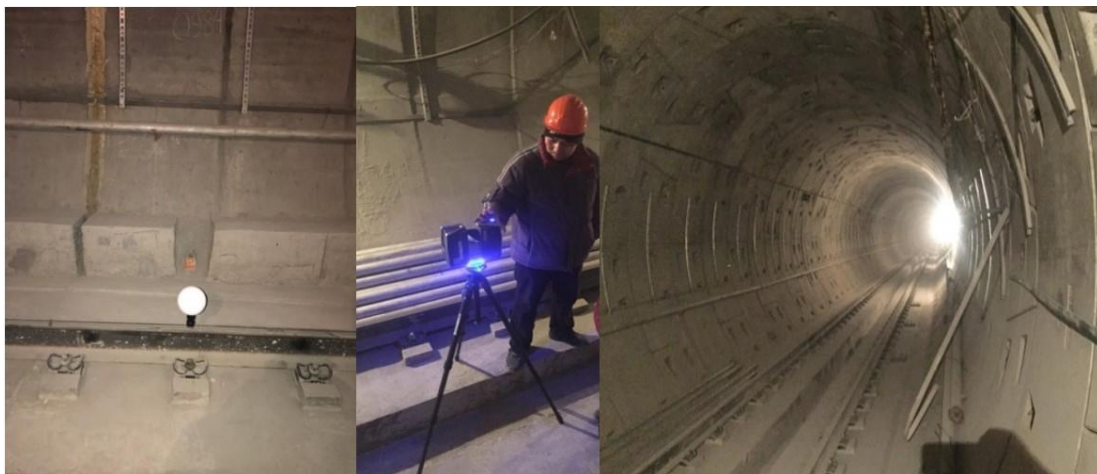


Figure 33. Tunnel scanning with a Faro Focus 3D X phase laser scanner

The primary objective of any laser scanning process is to obtain accurate and up-to-date data on the condition, location, and state of the research model as quickly as possible. This information is then converted into one or more standard output data formats during the subsequent processing stages.

The research was conducted using ReCap software, and the following tasks were completed:

- Alignment of scanning clusters using planar reference marks;
- Positioning of the tunnel based on the exact coordinates provided by the client;
- Creation of a TIN (Triangulated Irregular Network) model of the tunnel;
- Calculation of actual tunnel deviations relative to the projection axis and cross-sections.

Figure 33 presents the geodetic scanning results for the Saryarka and Bauyrzhan Momysuly subway stations. The alignment deviations between point clusters are expressed as percentages. The allowable deviation values depend on the distance between the spherical markers (reference points) and their visibility during the survey. The figure illustrates the deviation data during alignment (Figures 34 and 35), verifying the accuracy of our route and the 3D tunnel model.

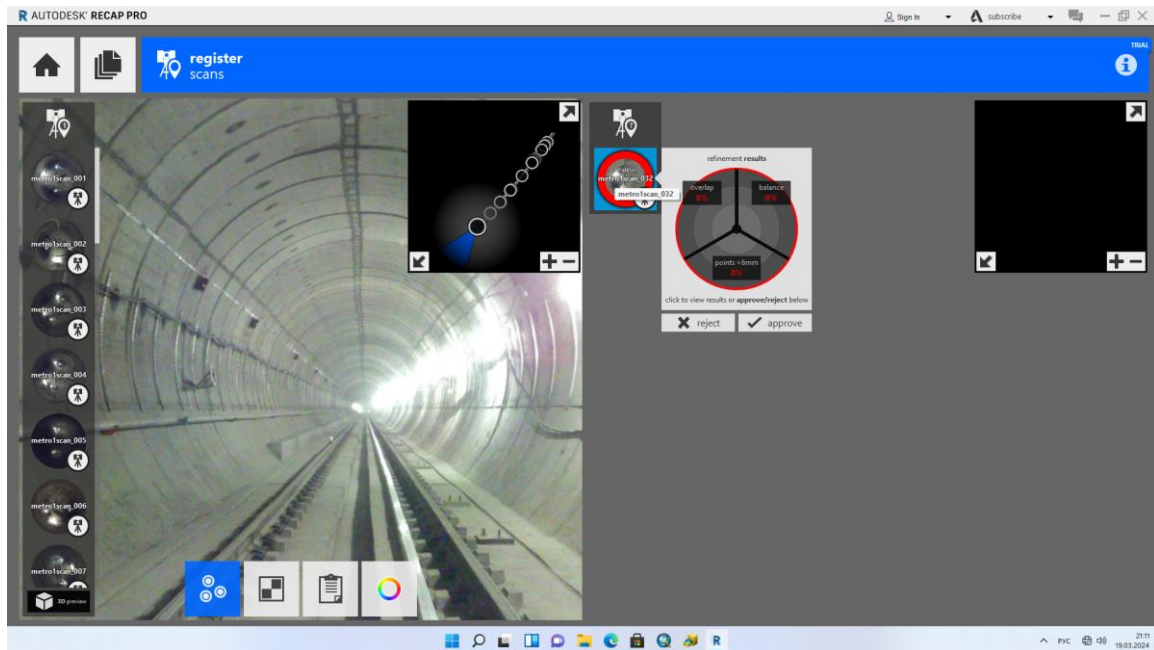


Figure 34. Tunnel location on the diagram and photo

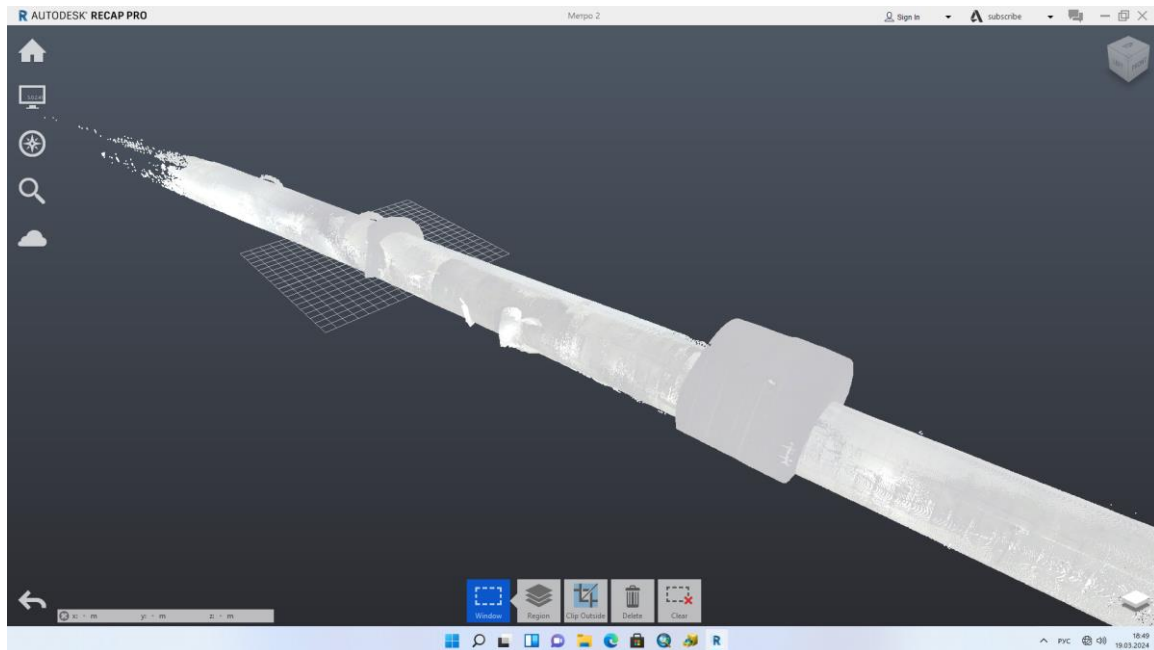


Figure 35. Points cluster in 3D Saryarka and Momyshty stations image

As a result of constructing cross-sections, a digital 3D model of the actual tunnel and the project model were obtained, along with tunnel section drawings showing deviations from the M 1:20 project and a deviation map presented in the form of a gradient fill. The rapid advancement of modern technologies has made geodetic work significantly more efficient than it was even a decade ago. Today, the key factors are speed, accessibility, and the precision of measuring equipment. The laser scanner has become an essential tool for specialists across a wide range of professional fields.

5. Conclusion

5.1. Research Novelty

This study proposes a new approach to geodynamic research under conditions of complex geological structures and urbanized territories, typical of the Almaty subway construction area. Taking into account the specifics of engineering interactions between structures and the surrounding geoenvironment, including the transition from a natural massif to a man-made disturbed zone, the proposed method enables a more accurate prediction of earth surface displacement vectors and underground tunnel structural element movements under man-made loads. This, in turn, enhances prediction reliability and ensures a higher level of safety during both the construction and operation of underground structures.

When developing the model, the spatial configuration of the underground structure complex was considered, along with the variability of engineering and geological conditions, including the presence of tectonic fault zones and soil heterogeneity. Such models, although rarely developed, are capable of accounting for both geomorphological and anthropogenic characteristics of the urban environment. They allow for a more realistic assessment of the behavior of soil masses and subway structures, particularly in areas with a high deformation risk, thereby significantly improving forecast accuracy and design reliability.

5.2. Theoretical Contribution

An analysis of literary sources by both foreign and domestic authors, as well as practical experience in using comprehensive monitoring systems—integrating mine surveying, topographic-geodetic, aerospace, and geomechanical observations of underground and above-ground structure deformations—has shown that the choice of methods depends on site-specific characteristics, development conditions, and tunnel depth. The research conducted aimed to determine the optimal parameters of geodynamic influences, resulting from natural and anthropogenic factors in the Saryarka and Momyshuly station areas, using geodetic and geomechanical methods. The development of models to simulate the stress-strain dynamics of the rock mass and surface along the new subway lines will contribute to improving monitoring methods and regulating subway development. The resulting 3D visualization serves as a crucial stage in creating an accurate digital 3D model of the studied object, forming the starting point of digital reality—a spatial point map that captures a comprehensive and detailed representation of the area.

5.3. Practical Significance

The practical significance of this research lies in the development of a comprehensive methodological approach to geomonitoring the Almaty subway under complex geological structures and dense urban environments. Considering the specific features of the subway section—irregular terrain, heterogeneous soil mass, and the region's high seismicity—the proposed geodetic and aerospace-based monitoring methodology allows for highly reliable predictions of both surface and subsurface behavior. This, in turn, supports well-founded engineering decisions aimed at reducing man-made risks, such as deformation, leakage, subsidence, or structural damage to tunnels and stations. Implementing this approach contributes to enhancing the sustainability and safety of the Almaty subway's design, construction, and operation.

5.4. Future Research Directions

Future research will focus on extending this methodology for use in the construction and operation of various underground structures, including mineral resource development within the Republic of Kazakhstan and abroad, where subway construction and operation are actively underway.

6. Declarations

6.1. Author Contributions

Conceptualization, Y.K., G.J., and N.K.; methodology, Y.K. and N.K.; software, Y.K., N.K., and Z.K.; validation, Y.K. and N.A.; formal analysis, Y.K., G.J., and N.K.; investigation, Y.K., G.J., K.K., S.Z., Z.K., N.K., and N.A.; resources, Y.K., G.J., and N.K.; data curation, Y.K., G.J., and N.K.; writing—original draft preparation, Y.K. and G.J.; writing—review and editing, Y.K., G.J., and N.K.; visualization, Y.K., G.J., and N.K.; supervision, Y.K., G.J., and N.K.; project administration, Y.K., G.J., and N.K.; funding acquisition, Y.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

- [1] Kobayashi, T. (2024). Nationwide crustal deformation monitoring by SAR satellite. Proceedings of the 44th UJNR (United States–Japan Natural Resources) Earthquake Panel Meeting, Tokyo, Japan..
- [2] Suito H. (2024). Postseismic deformation caused by the 2024 Noto Peninsula earthquake. Proceedings of the 44th UJNR Earthquake Panel Meeting. Tokyo, Japan.
- [3] Bek, A. A., Nurpeisova, M. B., & Ormanbekova, A. (2016). Assessment of the technical condition of engineering structures. LAR LAMBERT Academic Publishing, ALMATY, Kazakhstan.
- [4] Yoshida, N. (2009). Damage to subway station during the 1995 Hyogoken-Nambu (Kobe) earthquake. Earthquake Geotechnical Case Histories for Performance-based Design, 373-389.
- [5] Wang, J., Luo, Z., Zhou, L., Li, X., Wang, C., & Qin, D. (2024). Surface Deformation Monitoring and Subsidence Mechanism Analysis in Beijing based on Time-series InSAR. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 10(1), 233–239. doi:10.5194/isprs-annals-X-1-2024-233-2024.
- [6] Yu, A., Mei, W., & Han, M. (2021). Deep learning based method of longitudinal dislocation detection for metro shield tunnel segment. Tunnelling and Underground Space Technology, 113. doi:10.1016/j.tust.2021.103949.
- [7] Hattanji, T., Koga, W., Kawano, T., Harada, S., Furuichi, T., Doshida, S., & Tanaka, Y. (2024). Human impacts on infilling rates of hollows in landslide-prone areas of western Japan: Estimation from radiocarbon dates and high-resolution DEMs. Earth Surface Processes and Landforms, 49(1), 277–290. doi:10.1002/esp.5672.
- [8] Karaca, Ş. O., Erten, G., Ergintav, S., & Khan, S. D. (2024). Anthropogenic problems threatening major cities: Largest surface deformations observed in Hatay, Türkiye based on SBAS-InSAR. Bulletin of the Mineral Research and Exploration, 173(173), 235-252.. doi:10.19111/bulletinofmre.1298494.
- [9] Jiang, Y., & Yu, X. (2025). Space-based long term condition monitoring of cold region pavement with PS-InSAR. Journal of Infrastructure Preservation and Resilience, 6(1), 4. doi:10.1186/s43065-024-00110-2.
- [10] Perkins, O., Alexander, P., Arneth, A., Brown, C., Millington, J., & Rounsevell, M. (2024). Litigation challenging over-reliance on carbon dioxide removal requires quantitative feasibility assessment. EGU General Assembly Conference Abstracts, 5662. doi:10.5194/egusphere-egu24-5662.
- [11] Palanisamy, S., Lobón, U., Cabrera, Humberto., Albiol, D., Batalla, A., Camafort, M., & Bento, L. (2024). Monitoring of Tunnels in Urban Environments: Complementing InSAR with in situ instrumentation. Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization, 18-21 June, 2024, Barcelona, Spain.
- [12] Huang, C., Tan, L., Liu, J., & Yan, K. (2024). Multi-Temporal-InSAR Ground Deformation Mapping of Beijing Subway Network Based on ALOS-2 and Sentinel-1 Data. Polish Journal of Environmental Studies, 1-15. doi:10.15244/pjoes/194592
- [13] Wang, R., Yang, M., Dong, J., & Liao, M. (2022). Investigating deformation along metro lines in coastal cities considering different structures with InSAR and SBM analyses. International Journal of Applied Earth Observation and Geoinformation, 115. doi:10.1016/j.jag.2022.103099.
- [14] Pernebek, K., Abdibek, A., Soltabayeva, S., & Nurpeisova, M. (2022). Monitoring of deformations of structures in the metro construction zone. The Scientific Heritage, 89, 141–144. doi:10.5281/zenodo.6575898.
- [15] Hou, Y. M., Wang, J. H., & Zhang, L. L. (2007). Three-Dimensional Numerical Modeling of a Deep Excavation Adjacent to Shanghai Metro Tunnels. Computational Science – ICCS 2007, 1164–1171. doi:10.1007/978-3-540-72588-6_184.
- [16] Liu, B., Xu, W., Zhang, D., & Zhang, Q. (2022). Deformation behaviors and control indexes of metro-station deep excavations based on case histories. Tunnelling and Underground Space Technology, 122. doi:10.1016/j.tust.2022.104400.
- [17] Luo, Z., & Das, B. M. (2016). System probabilistic serviceability assessment of braced excavations in clays. International Journal of Geotechnical Engineering, 10(2), 135–144. doi:10.1179/1939787915Y.0000000021.
- [18] Ye, S., Zhao, Z., & Wang, D. (2021). Deformation analysis and safety assessment of existing metro tunnels affected by excavation of a foundation pit. Underground Space (China), 6(4), 421–431. doi:10.1016/j.undsp.2020.06.002.
- [19] Zhang, W., Zhang, R., Wu, C., Goh, A. T. C., Lacasse, S., Liu, Z., & Liu, H. (2020). State-of-the-art review of soft computing applications in underground excavations. Geoscience Frontiers, 11(4), 1095–1106. doi:10.1016/j.gsf.2019.12.003.
- [20] Zhang, Y. C., Guang-hua, Y. A. N. G., & Jie, Y. A. O. (2010). Numerical simulation and analysis of effect of excavation of foundation pits on metro tunnels. Chinese Journal of Geotechnical Engineering, 32(S1), 109-115.

- [21] Tan, D., Li, A., Ji, B., Duan, J., Tao, Y., & Luo, H. (2023). Ground deformation monitoring for subway structure safety based on GNSS. *Buildings*, 13(11), 2682. doi:10.3390/buildings13112682.
- [22] Bayramov, E., Sydyk, N., Nurakynov, S., Yelisseyeva, A., Neafie, J., & Aliyeva, S. (2024). Quantitative assessment of urban surface deformation risks from tectonic and seismic activities using multitemporal microwave satellite remote sensing: a case study of Almaty city and its surroundings in Kazakhstan. *Frontiers in Built Environment*, 10. doi:10.3389/fbuil.2024.1502403.
- [23] Bayramov, E., Sydyk, N., Nurakynov, S., Yelisseyeva, A., Neafie, J., & Aliyeva, S. (2024). Quantitative assessment of urban surface deformation risks from tectonic and seismic activities using multitemporal microwave satellite remote sensing: a case study of Almaty city and its surroundings in Kazakhstan. *Frontiers in Built Environment*, 10. doi:10.3389/fbuil.2024.1502403.
- [24] Qu, F., Lu, Z., Zhang, Q., Bawden, G. W., Kim, J. W., Zhao, C., & Qu, W. (2015). Mapping ground deformation over Houston–Galveston, Texas using multi-temporal InSAR. *Remote Sensing of Environment*, 169, 290–306. doi:10.1016/j.rse.2015.08.027.
- [25] Halicioglu, K., Erten, E., & Rossi, C. (2021). Monitoring deformations of Istanbul metro line stations through Sentinel-1 and levelling observations. *Environmental Earth Sciences*, 80(9), 361. doi:10.1007/s12665-021-09644-0.
- [26] Kobayashi, T. (2024). SAR-detected crustal deformation and topographic changes of the 2024 Noto Peninsula earthquake. *Proceedings of the 44th UJNR Earthquake Panel Meeting*, Tokyo, Japan.
- [27] Ando, R., Fukushima, Y., Yoshida, K., & Imanishi, K. (2025). Nonplanar 3D fault geometry controls the spatiotemporal distributions of slip and uplift: evidence from the Mw 7.5 2024 Noto Peninsula, Japan, Earthquake. *Earth, Planets and Space*, 77(1). doi:10.1186/s40623-025-02187-9.
- [28] Quinteros-Cartaya, C., Quintero-Arenas, J., Padilla-Lafarga, A., Moraila, C., Faber, J., Li, W., Köhler, J., & Srivastava, N. (2025). A deep learning pipeline for large earthquake analysis using high-rate global navigation satellite system data. *Earth Science Informatics*, 18(4), 516. doi:10.1007/s12145-025-02023-4.
- [29] Li, X., & Xu, S. (2025). Multi-class Seismic Building Damage Assessment from InSAR Imagery using Quadratic Variational Causal Bayesian Inference. *arXiv Preprint*, arXiv:2502.18546. doi:10.48550/arXiv.2502.18546.
- [30] Yang, Y. F., Liao, S. M., Liu, M. B., Wu, D. P., Pan, W. Q., & Li, H. (2022). A new construction method for metro stations in dense urban areas in Shanghai soft ground: Open-cut shafts combined with quasi-rectangular jacking boxes. *Tunnelling and Underground Space Technology*, 125. doi:10.1016/j.tust.2022.104530.
- [31] Xu, Y., Xia, M., Zhang, W., Li, Z., & Zhang, Z. (2022). Risk assessment of an existing metro tunnel in close proximity to new shield tunnels following construction. *Journal of Engineering*, 2022(1), 5774764. doi:10.1155/2022/5774764.
- [32] Huang, Q., Miao, C., Yuan, Y., Qu, Y., & Gou, Y. (2023). Failure analysis of metro tunnel induced by land subsidence in Xi'an, China. *Engineering Failure Analysis*, 145. doi:10.1016/j.engfailanal.2022.106996.
- [33] Zhou, F., Zhou, P., Li, J., Lin, J., Ge, T., Deng, S., Ren, R., & Wang, Z. (2022). Deformation characteristics and failure evolution process of the existing metro station under unilateral deep excavation. *Engineering Failure Analysis*, 131. doi:10.1016/j.engfailanal.2021.105870.
- [34] Qian, W., Qi, T., Zhao, Y., Le, Y., & Yi, H. (2019). Deformation characteristics and safety assessment of a high-speed railway induced by undercutting metro tunnel excavation. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(1), 88–98. doi:10.1016/j.jrmge.2018.04.014.
- [35] Zhang, B., Liao, X., Zhang, J., Xiong, S., Wang, C., Wu, S., ... & Li, Q. (2023). Megalopolitan-scale ground deformation along metro lines in the Guangdong-Hong Kong-Macao Greater Bay Area, China, revealed by MT-InSAR. *International Journal of Applied Earth Observation and Geoinformation*, 122, 103432. doi:10.1016/j.jag.2023.103432.
- [36] Nepeina, K., Bataleva, E., & Alexandrov, P. (2023). Electromagnetic Monitoring of Modern Geodynamic Processes: An Approach for Micro-Inhomogeneous Rock through Effective Parameters. *Applied Sciences*, 13(14), 8063. doi:10.3390/app13148063.
- [37] Savchyn, I., & Bilashuk, A. (2023). Differentiation of Recent Geodynamic Processes within the Carpathian Mountains Based on GNSS Data. *International Conference of Young Professionals “GeoTerrace-2023”*, 1–5. doi:10.3997/2214-4609.2023510011.
- [38] Kaftan, V. I., Melnikov, A. Yu., & Dokukin, P. A. (2025). Evolution Of Inner Crustal Displacement Deficit According To the GPS Data in Connection with Seismicity in the Period Of 2014–2024 And The Mw=7.4 Hualien Earthquake, Taiwan. *Geodynamics & Tectonophysics*, 16(1), 0812. doi:10.5800/gt-2025-16-1-0812.
- [39] Bayramov, E., Sydyk, N., Nurakynov, S., Yelisseyeva, A., Neafie, J., & Aliyeva, S. (2024). Quantitative assessment of urban surface deformation risks from tectonic and seismic activities using multitemporal microwave satellite remote sensing: a case study of Almaty city and its surroundings in Kazakhstan. *Frontiers in Built Environment*, 10, 1502403. doi:10.3389/fbuil.2024.1502403.
- [40] Attewell, P. (1978). *Ground movements caused by tunnelling in soil*. Pentech Press, London, United Kingdom.

- [41] Mair, R. J., Gunn, M. J., & O'reilly, M. P. (1982). Ground movement around shallow tunnels in soft clay. *Tunnels & Tunnelling International*, 14(5). doi:10.1016/0148-9062(83)90434-5.
- [42] O'Reilly, M. P., & New, B. M. (1983). 831153 Settlement above tunnels in the United Kingdom — their magnitude and prediction. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 20(1), A18. doi:10.1016/0148-9062(83)91768-0.
- [43] Selby, A. R. (1988). Surface movements caused by tunnelling in two-layer soil. *Geological Society Engineering Geology Special Publication*, 5, 71–77. doi:10.1144/GSL.ENG.1988.005.01.05.
- [44] Lu, A. zhong, Zeng, G. sen, & Zhang, N. (2021). A complex variable solution for a non-circular tunnel in an elastic half-plane. *International Journal for Numerical and Analytical Methods in Geomechanics*, 45(12), 1833–1853. doi:10.1002/nag.3244.
- [45] Kaftan, V. I., Gvishiani, A. D., Manevich, A. I., Dzeboev, B. A., Tatarinov, V. N., Dzeranov, B. V., ... & Losev, I. V. (2024). An Analytical Review of the Recent Crustal Uplifts, Tectonics, and Seismicity of the Caucasus Region. *Geosciences*, 14(3), 70. doi:10.3390/geosciences14030070.
- [46] Alain, G., & Bengio, Y. (2016). Understanding intermediate layers using linear classifier probes. *arXiv Preprint*, arXiv:1610.01644. doi:10.48550/arXiv.1610.01644.
- [47] Chen, K., Wang, J., Pang, J., Cao, Y., Xiong, Y., Li, X., ... & Lin, D. (2019). MMDetection: Open mmlab detection toolbox and benchmark. *arXiv preprint arXiv:1906.07155*. doi:10.48550/arXiv.1906.07155.
- [48] Clevert, D. A., Unterthiner, T., & Hochreiter, S. (2015). Fast and accurate deep network learning by exponential linear units (Elus). *arXiv preprint*, arXiv:1511.07289, 4(5), 11.
- [49] Nikolov, I., & Madsen, C. (2016). Benchmarking Close-range Structure from Motion 3D Reconstruction Software Under Varying Capturing Conditions. *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2016, Lecture Notes in Computer Science*, 10058, Springer, Cham, Switzerland. doi:10.1007/978-3-319-48496-9_2.
- [50] Petrov, D. N., Demenkov, P. A., & Potemkin, D. A. (2010). Numerical modelling of the lining stress state of column stations without lateral platforms. *Journal of Mining Institute*, 185, 166-170.
- [51] Tao, Y., & Rao, J. (2022). Construction analysis of Guiyang Metro passing across Guiyang Railway Station in karst zone. *Tunnelling and Underground Space Technology*, 126. doi:10.1016/j.tust.2022.104541.
- [52] Zwaan, F., Alves, T. M., Cadenas, P., Gouiza, M., Phethean, J. J. J., Brune, S., & Glerum, A. C. (2024). (D)riftng in the 21st century: key processes, natural hazards, and geo-resources. *Solid Earth*, 15(8), 989–1028. doi:10.5194/se-15-989-2024.
- [53] Cao, X. G., Yang, J. L., Meng, X. L., & Zhang, W. C. (2014). Subway Tunnel Cross-Section Surveying Based on Ground 3D Laser Scanning Data. *Advanced Materials Research*, 1079–1080, 296–299. doi:10.4028/www.scientific.net/amr.1079-1080.296.
- [54] Kupreeva, E., & Pronina, L. (2021). Geodetic support of subway construction using navigation systems. *Journal of Omsk State Agrarian University*, 1(24), 1-5.