

Features of Improving the Accuracy of Surveying for Shield Tunneling of the Second Stage of the Tashkent Metro

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Abstract

The article discusses the features of improving the accuracy of mine surveying during shield tunneling in the second stage of the Tashkent Metro. Modern technical tools and methods of mine surveying have been investigated, including high-precision electronic total stations, laser scanning, automated observation stations, and the integration of satellite and inertial technologies. The importance of continuous deformation monitoring—such as the installation of observation marks, regular leveling, and displacement analysis—is emphasized. This approach enables prompt responses to potential threats and enhances the safety of construction operations. At the same time, the use of comprehensive measurement technologies that ensure high-precision navigation of the shield complex is highlighted. The practical part of the study includes an analysis of accuracy characteristics obtained in specific sections of the second stage of the metro. Data on the mutual docking of tunnels—performed with minimal deviations—confirm the effectiveness of the proposed solutions. Thanks to the timely correction of total station data, it was possible to achieve minimal deviations when entering the disassembly chamber. It is concluded that significant improvements in surveying accuracy are achievable through the integrated use of modern technologies and optimization of measurement techniques. The experience presented demonstrates the effectiveness of combining classical observation methods with modern geodetic technologies to enhance the accuracy and reliability of underground construction. The results are of scientific and practical interest and can be applied in the design and construction of underground structures in dense urban environments and complex geotechnical conditions.

1. Introduction

The development of subways in large megacities requires highly accurate engineering and geodetic work. This is especially relevant for Tashkent, where the density of urban development, diverse geological conditions, and high real estate prices increase the requirements for the quality of tunnel construction. The construction of the second phase of the Yunusabad Line of the Tashkent Metro required high-precision mine surveying to prevent accidents and minimize risks to the city's infrastructure. The second stage of the Yunusabad Line included the construction of connecting tunnels between stations located in difficult geological and hydrogeological conditions. Modern tunnel-boring complexes (MTBK) were used, which operate using the method of mechanized shield boring with simultaneous construction of the lining.

The requirements for the accuracy of surveying work were as follows. When tunneling underground tunnels, the permissible deviations from the design axis are limited: in plan – up to ± 50 mm, in height – up to ± 30 mm. In this regard, the task of improving the accuracy of surveying is of paramount importance.

2. Methods

The following methods and technologies were used to ensure high accuracy in the mine surveying support of the metro construction.

1. Construction of a high-precision geodetic basis. To ensure accuracy in the construction area, the following was performed: creation of a reference network of 4th class accuracy; conducting precision measurements with high-precision total stations (angular error of $1'' - 2''$, rangefinder error of up to $1 \text{ mm} + 1 \text{ mm/km}$); using electronic levels to transfer altitude marks. The stability of the geodetic network was constantly checked using repeated observations.

2. High-precision shield navigation. The following systems were used in the tunnel: automated MTBK navigation systems based on gyroscopic theodolites (inertial navigation); an optical navigation system using reflectors mounted on the shield; regular verification of the shield's position through ground-based tachometric observations through vertical shafts and technological windows.

3. Accounting for the effects of ground surface deformations. To control settlements and building deformations, the following were performed: monitoring of surface settlement marks; using optical levels of the 1st class of accuracy; laser scanning of building structures near the excavation zone. This allowed for the timely detection of critical deformations and the adjustment of the excavation process.

4. Innovative approaches. In some areas, the following technologies were used: GNSS technologies for external control of the ground network coordinates; 3D laser scanning of tunnels for control of the lining shape; and the use of inclinometers for monitoring the movement of soil masses.

The specific features of the second stage of construction included: the need to work in a limited time frame ("window") while the metro was operational; adapting the methods to the limited space and vibrations caused by traffic; and combining traditional total station methods with automated MTBK navigation systems.

The layout of the tunnel route of the second stage of the Yunusabad line of the Tashkent Metro is shown in Figure. 1. The works were performed in the Metrostroy coordinate system and in the Pariysky elevation system.

The following types of geodetic and surveying work were performed at the tunnel route facility:

- search for the starting points of tunnel triangulation of the metro system, high-altitude reference points and points of basic ground polygonometry;
- reconnaissance of points of the satellite geodetic network;
- laying of ground tunnel triangulation points with an accuracy of 1:35,000, the type of center is Metrostroy;
- satellite determination of coordinates at 9 points of ground tunnel triangulation (accuracy 1:35,000).

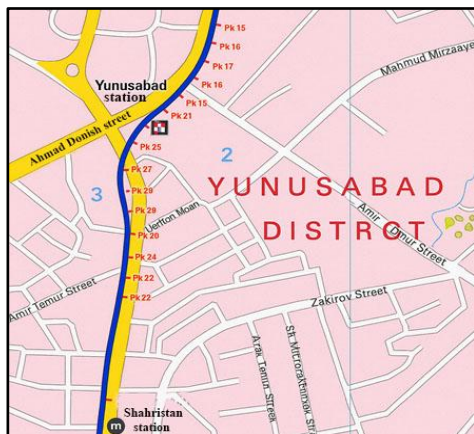


Figure 1. Plan diagram of the tunnel route of the second stage of the Yunusabad line of the Tashkent metro, which are being built using a shield method.

Class II leveling was performed using a double traverse based on ground tunnel triangulation points (accuracy of 1:35,000) over a 3.8 km section.

The leveling courses were laid along the tunnel and tied to the marks and reference points of the I and II classes of the state leveling network.

Figure 2-3 shows the schemes of satellite ground tunnel triangulation and II class leveling network, performed as part of the construction of the second stage of Yunusabad line of Tashkent Metro [1,2].

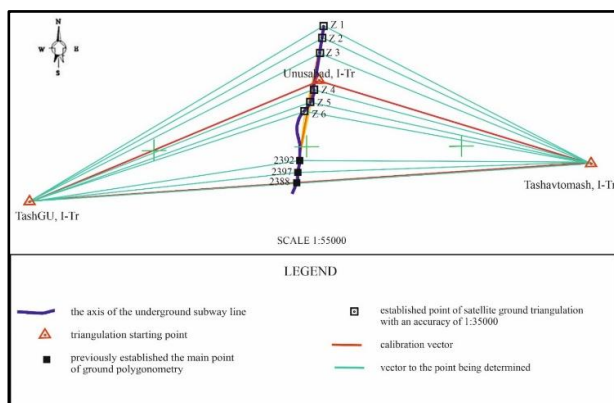


Figure 2. Scheme of satellite ground-based tunnel triangulation for creating reference networks during the construction of the second stage of the Yunusabad Line of the Tashkent Metro

The facility has created a tunnel triangulation of 1:35,000 accuracy using satellite technology GNSS instead of traditional ground polygonometry. The network includes three I-T triangulation reference points: Yunusabad, TashAvtoMash and

TashGU. From these points, the coordinates of nine points grouped into three clusters were determined using satellite observations.

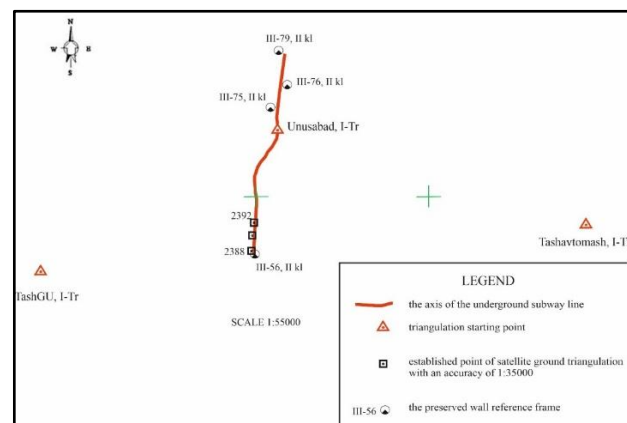


Figure 3. Class II leveling scheme for satellite ground tunnel triangulation points

The method of observations was as follows. The measurements were carried out in the morning and evening hours, which reduces the influence of temperature gradients. The height of the antenna above the center of the point was measured with an accuracy of 1 mm before and after each session, the final value of the antenna height was determined as the average. The centering of the antenna was provided with an accuracy of 1-2 mm [2,3,4].

The satellite measurements were processed in two stages.

The preprocessing was performed in the Trimble Business Center software in accordance with the receiver operating instructions. The final processing and network alignment is also performed at the Trimble Business Center. The equalization was carried out on the basis of three starting points of the I-T category (Tashavtomash, Yunusabad, Tashgu). The final coordinates were obtained as the average value from two independent measurement sessions.

3. Results

A posteriori qualimetric indicators of the accuracy of the coordinates of the "tunnel triangulation" points, obtained using the "min-max" rule, are given in Table 1.

The observation cycle	M _s , min/max, mm	Ehe average square error of the directional angle, min/max, sec		Relative weakness error, min/max	
	received	received (% of additional)	acceptable	received (% of additional)	Acceptable
session 1	1-2	0,000-0,582 (100%)	0,7	1: 36651* - 1: 8329015 (100%)	1:350 00
session 2	1-2	0,000-0,086 (100%)	0,7	1: 43110** - 1: 7142011 (100%)	1:350 00

Note: * is the value of the relative error for the first morning observation session; ** is the value of the relative error for the second evening observation session.

Table 1. A posteriori qualimetric indicators of points

As a result of the performed a posteriori quality assessment based on the measurement difference between the two observation sessions, the average square errors in determining the points were: $M_x=+2$ mm; $M_y=+4$ mm; $M_r=+5$ mm.

Qualimetric indicators of the surface tunnel triangulation network for deviations from the average value of ordinates and abscissas of points are given in Table 2 [2].

Deviation from the average value	Number of points meeting the tolerance, point (%)		
	up to M_x , M_y	from M_x , M_y up to $2M_x$, $2M_y$	from $2M_x$, $2M_y$ to $3M_x$, $3M_y$
Abscissa of points	3 (6)	6 (1)	15 (2)
Ordinate of points	3 (6)	6 (2)	10 (1)

Table 2. Qualimetric indicators of the ground tunnel triangulation network

The geodetic network of points of the "Ground Tunnel Triangulation" network, built with an accuracy of 1:35,000 and defined in the "static" mode, provides the required accuracy characteristics of the identified geodetic elements with a high margin of reliability. The obtained parameters make it possible to use this network as a planned basis for performing a full range of executive surveys, as well as for monitoring deformations at the second stage of construction of the Yunusabad line of the Tashkent Metro [2,5].

Class II leveling has been performed at the tunnel route facility. The class II leveling network is laid along the points of the satellite "Ground tunnel triangulation" (9 points) and consists of 3 single passages (Figure 3) based on the initial reference points of Class II. Class II leveling is performed with digital Trimble Dini 03 levellers complete with barcode rails. Class II leveling was performed in the forward and reverse directions according to the points of the "Ground tunnel triangulation". The length of the sighting beam did not exceed 65 m. The disparity of shoulders (distances) at the station did not exceed 1 m, and their accumulation in the section did not exceed 2 m. The height of the sighting beam above the surface was at least 0.3 m. In the forward and reverse directions, leveling was performed along the same route, the number of stations in the section was as equal as possible. When the leveling direction was changed, the rails changed places. The characteristics of the quality of leveling in forward and reverse courses of Class II are given in Table 3.

Line number according to the	Line and section name, section number	Length, km	Quantity tripods	The distance between the signs, km		Discrepancy of the forward and reverse stroke exceedances, mm		Average square error per 1 km of travel, mm
				The largest	Average	The received	Acceptable Value	h
1	III-79 - III-76 (1-3)	0.632	8	0.3	0.2	-0.10	3.97	0.20
2	III-76 - III-75 (4-5)	0.466	6	0.3	0.2	0.30	3.41	0.26
3	III-75 - III-56 (6-12)	2.648	33	1.1	0.4	-0.70	8.14	0.34

Table 3. Characteristics of Class II leveling quality

According to the data presented in Table 3.14, the actual qualimetric leveling indicators of class II significantly exceed the regulatory requirements: the resulting discrepancy value was 0.70 mm with an acceptable value of 8.14 mm, which

corresponds to an accuracy of 93%. The average square random error per 1 km of leveling stroke was 0.16 mm, which indicates a high stability of measurements.

Leveling of class II was performed in conjunction with leveling routes of class III using the CREDO DAT module of the CREDO software package. Equalization in the Trimble Business Center (TBC) software was used as an alternative control procedure [2,6].

	Number of lines	Number of points			Length	
		The original	Certain	Nodal	km	tripods
II	3	7	6	0	3.746	47
		High-altitude discrepancy			Number of discrepancies as a percentage of the tolerance	
		max, mm	motion	add., MM	0 - 50%	50 - 100% > 100%
		-3.550	16	8.136	3	0

Table 4. Technical characteristics of a class II leveling network

Satellite leveling is used to measure distances between points from tens to hundreds of kilometers. The current level of GNSS technology development in the Republic of Uzbekistan makes it possible to replace traditional methods with high-precision GPS leveling, which allows measurements to be carried out in short periods of time [4].

Currently, geodetic network points created by ground-based methods are used at local facilities as the base points for building local satellite networks. It should be noted that planned and high-altitude geodetic networks often exist separately: their points, as a rule, are not combined [6].

One of the key features of the creation and reconstruction of urban geodetic networks is the need to preserve the existing coordinate system [7].

For satellite measurements, it is recommended to use a differential coordinate determination method. The reference height justification should be carried out using the geometric leveling method of class II with mandatory reference to the state leveling network of classes I and II [8].

In the Republic of Uzbekistan, geodetic and cartographic activities are based on the reference reference system represented by the Krasovsky reference ellipsoid (KS-42), as well as the State Geodetic Network (SGN) and the State High-altitude Base (SHA) with reference to the 1977 Baltic Elevation System. The coordinate catalogs of the ITRF (International Terrestrial Reference Frame) points are periodically updated taking into account geodynamic processes, and the corresponding epoch is indicated [9, 10].

When creating a planned altitude justification, the satellite method is usually used to determine only the planned coordinates. The altitude position is specified by geometric leveling, since the construction of geodetic terrain models is required to obtain normal heights with satellite leveling [11].

As a result of the conducted mine surveying work, the average accuracy of the tunnel position was achieved: in plan – ± 18 mm, in height – ± 12 mm. These indicators significantly exceed the regulatory requirements, which allowed: to avoid adjustments of the design route; to minimize damage to buildings and structures; to optimize the construction process.

During the mining operations, the mine surveying service monitors the settlement of structures both on the surface and in underground workings. When constructing tunnels near buildings, the project provides for the installation of observation stations for continuous monitoring. Objects near the construction site are protected from vibrations, noise, and other negative effects, including the operation of tunnels.

Modern panel tunneling complexes, such as MTBK Herrenknecht S-1128, are equipped with pressure monitoring and face control systems. This allows timely detection of violations in the ground. Using MatLab increases the efficiency of deformation data processing, and the precipitation factor depends on the depth of the tunnel, the geology, the speed of work and the timely filling of voids.

The deformation zone is determined by geological conditions and can be 1.5–2 tunnel depths. The permissible discrepancy in the control of the reference marks is no more than 5 mm. All distillation tunnels are regularly leveled every 5 m, as well as monitoring the condition of the reference points and, if necessary, installing additional ones.

Polygonometry points of class 4 (55 pieces), located at a distance of 50–150 m, are used to control horizontal deformations. Leveling passages of class III are laid along these points, which also determine vertical precipitation. The first measurement cycle serves as the base for subsequent comparison. All cycles are repeated with a focus on land-based geodetic points.

The measurements included: determination of tunnel diameters (after 10 m on straight lines and 5 m on curved sections, accuracy ± 10 mm); leveling of the arch (accuracy ± 5 mm); control of the ellipticity of the arch (accuracy ± 5 mm using an electronic total station).

Monitoring is based on the accumulation and analysis of the coordinates of reference points installed between the rails. The data is transmitted from ground-based stations via staircases. The conditions of the tunnel and the surrounding environment affect the longitudinal and transverse settlement of the surface along the tunnel route.

When constructing long-distance tunnels using a tunneling shield with a soil weight, it is important to inject mortar into the gap between the lining and the soil in a timely manner. This ensures a tight contact, even pressure distribution, and enhances the reliability of the structure. The rock mass is characterized by natural cracks and tectonic disturbances, and anthropogenic impacts change its condition. When the permissible deformations of buildings exceed the required values, it is necessary to design measures to eliminate them [13,14,15].

The longitudinal forces in the tunnel are determined taking into account the ground resistance and deformations of the annular lining. Effective monitoring of enclosing structures should be carried out at all stages of construction and operation. The assessment of the stress-strain state of the soil is possible through geodynamic zoning, which makes it possible to identify dangerous zones and build models of the interaction of the tunnel and the massif [16,17,18].

Reinforced concrete lining can deform under its own weight, especially in the lower part, where linings and wedges are used, and in the upper part there are stacking trolleys. These loads increase the impact of rock pressure [19,20].

Accident prevention requires a comprehensive approach, from geological surveys to environmental engineering. To predict precipitation, it is necessary to take into account the parameters of the initial stress state. The calculated stress data in the lining tubing is confirmed by measurements made during construction [21,22,23].

According to regulatory documents, the permissible measurement error for accuracy class III is ± 5 mm for vertical and ± 10 mm for horizontal movements of structures.

All observations of the deformation signs were carried out using high-precision geodetic instruments: a Leica TS09 R1000 (1") total station and a Leica NA700 optical leveler.

To identify planned high-altitude deformations in the area of the right tunnel on the section of the PK20+88.65 - PK22+03.65 highway, which falls into the zone of possible and dangerous deformations, during the construction work, the following geometric leveling was performed: determination of the planned position by the method of linear-angular constructions (in polar coordinates) according to the deformation signs fixed on the route of the right tunnel, which are elements of the planned-altitude geodetic basis.

The horizontal displacement q of the deformation point in the specified area was determined as the difference between the coordinates obtained in the current and initial observation cycles. The discrepancies in the closed course were calculated using the formula: $f_{h, \text{доп.}} = 2,5 \text{ мм} \sqrt{n}$, where n is the number of stations.

Based on the results of the observations, a plan was drawn up for the location of the deformation signs of the right tunnel in the section PK20+88.65 - PK22+03.65, in the area of the reinforced concrete retaining wall of the highway bridge (see Figure. 4), and a catalog of deformation marks has been prepared (see Table. 5), reflecting the zones of propagation of deformations and their magnitudes. The spatial positions of the deformation points were determined relative to the coordinates obtained in the initial observation cycle.

№	Sign number	Type of sign	Stages from the beginning of observation, (mm)					
			I			II		
			in the plan		in the profile	in the plan		in the profile
			q_x	q_y		q_x	q_y	
1.	2404n	Reinforcement in concrete	5	6	1	-6	4	2
2.	2402n	Reinforcement in concrete	4	4	2	4	5	3
3.	TS-70	A pin in concrete	6	-5	2	3	-4	3
4.	20+75	Nail-type dowel (6x70)	7	6	-3	-9	7	-3
5.	21+00	Nail-type dowel (6x70)	-8	7	-4	8	-9	-5
6.	21+25	Nail-type dowel (6x70)	8	9	-5	9	7	-4
7.	21+50	Nail-type dowel (6x70)	8	-10	-4	8	-9	-3
8.	21+75	Nail-type dowel (6x70)	9	7	-5	7	8	-5
9.	22+00	Nail-type dowel (6x70)	-10	9	-4	9	7	-5

Table 5. Catalog of deformation marks on the site PK20+88.65 ÷ PK22+03.65

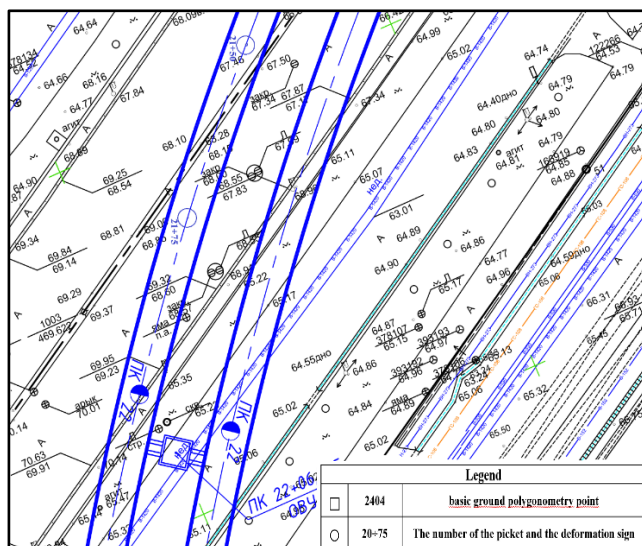


Figure 4. Layout of the deformation signs of the right tunnel of the highway on the section PK20+88.65 - PK22+03.65 reinforced concrete retaining wall of the highway bridge. 4. Layout plan for the deformation signs of the right tunnel of the highway on the section PK20+88.65 - PK22+03.65 reinforced concrete retaining wall of the highway bridge

4. Conclusion

The complex of surveying and geodetic works carried out as part of the second stage of construction of the Yunusabad line of the Tashkent metro confirmed the need and effectiveness of integrated high-precision technologies to achieve the required level of accuracy of panel tunneling in dense urban areas and difficult engineering and geological conditions.

The implementation of satellite ground-based tunnel triangulation with an accuracy of 1:35000, the use of GNSS equipment, laser scanning and digital leveling, as well as software solutions such as Trimble Business Center, CREDO DAT and AutoCAD Civil 3D, made it possible to ensure the stability of geodetic measurements, minimize errors and achieve high accuracy of spatial positioning of objects. The calculated and actual qualimetric characteristics convincingly demonstrate that the deviations obtained do not exceed the regulatory tolerances, and in some cases significantly exceed them (for example, the average speed per 1 km of leveling stroke was only 0.16 mm with an acceptable value of 2.5 mm).

Special attention was paid to monitoring deformations, which is especially important in the tunnel passage area near residential and engineering buildings. The installation of observation marks, regular leveling, control of horizontal and vertical displacements, analysis of deviations in polar coordinates relative to the initial observation cycle – all these measures made it possible to identify potentially dangerous areas in a timely manner and promptly make adjustments to the drilling process.

The use of complex surveying methods made it possible to control with high accuracy and timely introduce corrections to the navigation of the laser electronic total station, which made it easier to enter the disassembly chamber with an acceptable error in plan of +41 mm and in profile of -45 mm.

Thus, the results obtained confirm the scientific and practical importance of using integrated surveying solutions and can be recommended for use in the construction of similar facilities in

Uzbekistan and other countries with intensive urbanization and complex engineering infrastructure. A promising area remains the development of automated real-time monitoring, the integration of sensor systems into tunnel structures, as well as the expansion of the use of inertial and digital technologies, including machine learning for predicting deformations.

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