

PREDLOG LOKALNE 2D-GEODETSKE MREŽE ZA POTREBE GRADNJE PREDORSKEGA DELA BEOGRAJSKE PODZEMNE ŽELEZNICE

PROPOSED DESIGN OF LOCAL 2D GEODETIC NETWORK FOR THE CONSTRUCTION OF THE TUNNEL PART OF THE BELGRADE METRO

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IZVLEČEK

V tem delu je prikazan postopek optimizacije podzemne predorske mreže za gradnjo beogradske podzemne železnice. Pri navedenem postopku je bila uporabljena metoda predhodne ocene točnosti. Podane so teoretične osnove za matematični model predhodne analize, ki temelji na Gauß-Markovem modelu izravnave geodetskih mrež, ter za preračunavanje točnosti preboja predora. Na temelju gradbenih standardov je opravljeno preračunavanje zahtevane točnosti preboja predora kot osnovnega merila točnosti za podzemne predorske mreže. Na podlagi tehničnih parametrov za traso linije 1 beogradske podzemne železnice, ki se nanašajo na položaj osi in nivelete predora, je opredeljena oblika podzemne predorske mreže. V postopku optimizacije so analizirani različni načrti postavljanja opažev in rezultati predhodne analize za vsak načrt posebej. Glede na izbrano merilo maksimalnega prečnega pogreška preboja predora, ki znaša 4,5 centimetra, je bil nazadnje sprejet tretji načrt postavljanja opažev, s katerim je dosežen pogrešek preboja 3,5 centimetra. Sprejeti načrt postavljanja opažev obsega načrtovana merjenja horizontalnih smeri, azimutov in dolžin z vnaprej določeno natančnostjo 1" za horizontalne smeri, 3,2" za azimute in (1 mm; 1 ppm) za dolžine.

KLJUČNE BESEDE

lokalne geodetske mreže, optimizacija, Gauß-Markov model, predhodna ocena natančnosti, natančnost preboja predora

ABSTRACT

This paper presents a method of optimization of the underground network for the construction of the Belgrade metro. In the process of optimization, the method of preanalysis was used. The theoretical basis of the mathematical model of the preanalysis is given, which is based on Gauß-Markov model of geodetic networks adjustment, as well as the theoretical basis for calculating the tunnel breakthrough precision. Based on the construction standards, the calculation of the required breakthrough precision was made, as the fundamental criterion of precision for the development of the underground tunnel network. Depending on the technical parameters of the Belgrade Metro Line 1 alignment, related to the position of the axis and the longitudinal profile of the tunnel, the design of the underground tunnel network was defined. In the process of optimization, different plans of observations were analyzed, as well as the results obtained from the preanalysis for each plan individually. Based on the set criterion of maximum transverse error of the tunnel breakthrough, which is 4.5 cm, the third plan of observations was adopted as the final plan, by which the breakthrough error of 3.5 cm was achieved. The adopted plan of observations includes planned measurements of horizontal directions, azimuths, and distances, with the assumed standard deviation of 1" for horizontal directions, 3.2" for azimuths, and (1 mm; 1 ppm) for distances.

KEY WORDS

Local geodetic networks, optimization, Gauss Markov model, preanalysis, tunnel breakthrough precision

1 INTRODUCTION

Belgrade is a European metropolis in which over two million people live. Constant traffic congestions and poor infrastructure burden the city, while the existing public transportation is incapable of efficiently transporting passengers from one end of the city to another. At the same time, the suburban railway system “Beovoz” is not efficient enough due to inadequate infrastructure and outdated rolling stock. In order to improve public transportation, the decision on the metro construction has been made at the city level. On the 9th November 2012, the City Assembly adopted the Concept Study of Metro Rail Network, developed by a French company EGIS, by which the alignment of the future city metro Line 1 was defined.

A metro system is the most efficient mode of transportation in terms of energy consumption and space occupancy, in comparison to the number of passengers. Since electricity is used for its feeding, this mode of transportation is environmentally friendly because there are no pollutant emissions. Besides, efficient public transportation, such as metro, has a structuring influence on cities, i.e. it enables development of new residential areas in accordance with the increase in population. It can operate completely independently from other modes of transportation, and it is usually entirely or partially constructed in tunnels.

During the construction of complex structures, such as tunnels, geodetic surveying is inevitable. For conducting such geodetic surveying, it is necessary to develop a specific network of points, i.e. it is necessary to establish a local geodetic network (Paar, 2006). Problems that appear in the process of designing a local geodetic network are related to the network design and also choosing geodetic measurement methods in order to achieve the required precision. The objective of the designing and optimization of a local geodetic network is to make the best configuration of network points and the best plan of geodetic measurements so that the required precision is reached by having the lowest costs (Grafarend, 1974; Cross, 1985; Schmitt, 1985; Schaffrin, 1985; Kuang, 1991). Optimal design and analysis of local geodetic network are the two most important processes during its establishing (Paar, 2006). Optimal design should meet all the set up realization criteria for the geodetic network. After performing the measurements and observations in the geodetic network, collected data are processed and analyzed in order to determine the values of the unknown parameters, as well as of parameters of the network quality.

The geodetic network must be optimal in respect of geometry, precision and reliability (Seemkooei, 2001a,b). The objective is to reach the required precision of the geodetic network within certain constrains: time of measuring, available instruments and equipment, as well as financial resources. In many cases, what is needed to be achieved and what will be achieved depends on the experience of the designer of the network. After defining the network configuration and selecting measuring methods and instruments, it is possible to determine precision and reliability of the future geodetic network by using the **simulation** method of a network adjustment. If the conceived design does not fulfill the required precision criterion, development of a new design of the network is proceeded with until the required precision of the future local geodetic network is achieved by simulation.

In the design of a geodetic network, the designer tries to find the optimal solution that will meet the predefined criteria. Therefore, when it is said “well designed geodetic network”, it means it is precise, high-quality, which is described by precision and reliability (Pelzer, 1979), also homogenous, isotropic, efficient, and additionally, economically realized.

2 RESEARCH METHOD

2.1 Preanalysis of the local geodetic network

It is necessary to know the methods of preanalysis for the successful designing of a local geodetic network. Using the preanalysis, the expected positional uncertainty of the network points is determined, i.e. a weight, *a priori* determined on the basis of the predicted standard deviation, is assigned to each planned observation. Based on the results of the preanalysis, different variants of the geodetic network design can be formed through the process of optimization, using the simulation method, after which the variant that best meets the requirements is selected.

The mathematical model of the preanalysis is based on the Gauß-Markov model of adjustment of geodetic networks, which consists of a functional and a stochastic model (Kuang, 1996).

The functional model is given by the equation:

$$\mathbf{l} + \mathbf{v} = \mathbf{A}\hat{\mathbf{x}} \quad (1)$$

The stochastic model is given by the equation:

$$\mathbf{K}_{ll} = \sigma_0^2 \mathbf{Q}_{ll} = \sigma_0^2 \mathbf{P}^{-1}, \quad (2)$$

where:

\mathbf{l} – vector of measured values,

\mathbf{v} – residual vector,

\mathbf{A} – network design matrix (coefficient matrix),

$\hat{\mathbf{x}}$ – vector of the estimated values of the unknown parameters,

\mathbf{K}_{ll} – covariance matrix of measurements,

σ_0^2 – *a priori* variance of unit weight,

\mathbf{Q}_{ll} – cofactor matrix of measurements,

\mathbf{P} – weight matrix.

By applying the method of least squares, normal equations are formed. Solving these equations will provide the best estimates of the *unknowns* – increments of approximate values of unknown parameters (Koch, 1980; Rao, 1973; Searle, 1971):

$$\hat{\mathbf{x}} = \left(\mathbf{A}^T \mathbf{P} \mathbf{A} \right)^{-1} \mathbf{A}^T \mathbf{P} \mathbf{f} = -\mathbf{Q}_{xx} \mathbf{A}^T \mathbf{P} \mathbf{f}, \quad (3)$$

where \mathbf{f} is the vector of free terms.

In the process of geodetic network designing an optimal solution, in terms of the specified quality criterion – precision, should be found. A well-designed, or precise geodetic network implies a network that satisfies the required criteria: precision and reliability. These criteria can be realized through various stages of the geodetic network establishing, and this process is called *the optimization*.

Optimization of geodetic networks is one of the most difficult tasks for surveyors. *It takes a lot of knowledge and experience in order to establish a precise and reliable geodetic network.* Traditionally, optimization problems are classified into the following four orders of design (Grafarend, 1974):

- The zero-order design: selection of the optimal reference coordinate system,
- The first-order design: selection of the optimal geodetic network configuration and plan of measurements,
- The second-order design: selection of the type of measurements and their optimal weights,
- The third-order design: improving the quality of an existing geodetic network.

Using the zero-order design, the problem of determining the optimal coordinate system as the basis for calculating the unknowns of the geodetic network (position of points) and the optimal covariance matrix of the unknowns is solved. The optimal solution of the zero-order design is obtained by applying network adjustment using pseudo inversion, the so-called free network adjustment.

Optimization of the first- and the second-order designs can be performed using the **simulation method**. The basis of this method lies in the possibility of using the experience and knowledge of the surveyor to carry out „the empirical optimization” of geometry and precision of measurements in a geodetic network (Ninkov, 1989).

Within a simulation method, the starting points are initial criteria that relate to the quality of the geodetic network (homogeneity, isotropy, stakeout precision etc.). Those criteria should be satisfied in a model of designed network:

$$\mathbf{K}_{\mathbf{xx}PROJ} = \mathbf{K}_{\mathbf{xx}MODEL} \tag{4}$$

Besides significant professional experience a surveyor should have, for forming a model of a geodetic network, appropriate topographic and other field conditions, and access to adequate instruments are also needed. In order to obtain the most of quality criteria which designed network must satisfy, the variance-covariance matrix of the unknown parameters is used:

$$\mathbf{K}_{\mathbf{xx}} = \sigma_0^2 (\mathbf{A}^T \mathbf{P} \mathbf{A})^{-1} = \sigma_0^2 \mathbf{Q}_{\mathbf{xx}} \tag{5}$$

After forming the matrix $\mathbf{K}_{\mathbf{xx}}$, values of the set criteria are tested. If the set criteria are not met, specific changes must be made in the weight matrix P or design matrix A. How big these changes will be depends on the set criteria, and the knowledge and experience of the surveyor. However, the results of the next iteration should be closer to the given criteria than the previous ones. It is necessary to repeat the simulation procedure until the equation (4) is satisfied.

Optimization of the third-order design leads to possible improvement of the existing network, and it is achieved by adding new points to the network or planning additional measurements.

2.2 Calculation of the tunnel breakthrough precision

A local geodetic network must meet the highest requirements in terms of precision and reliability, which are determined by a tolerance of a tunnel breakthrough.

Tolerance of the tunnel breakthrough Δ is (Cvetković, 1970):

$$- \text{transverse } \Delta_Q = \pm 60\sqrt{L} \text{ mm}; \tag{6}$$

$$- \text{vertical } \Delta_L = \pm 23\sqrt{L} \text{ mm}; \tag{7}$$

where L is the tunnel length, expressed in kilometers (km).

The precision of the surface and underground geodetic network is defined by the construction standard for breakthrough precision. Breakthrough precision depends on the length of the tunnel and is determined by the value σ per kilometer. It can be described by the equation (Krüger, 1985):

$$s_D = \sigma \cdot L_{[\text{km}]}, \tag{8}$$

where s_D is the standard breakthrough deviation.

The breakthrough precision is needed to be verified on the basis of the breakthrough precision error. This error is determined independently from both directions of the tunnel excavation. It is invariant with the respect to the specified datum of the network, and represented by the relative error ellipse (Figure 1), which contains information on the transverse and vertical errors of the breakthrough precision (Ninkov, 1989).

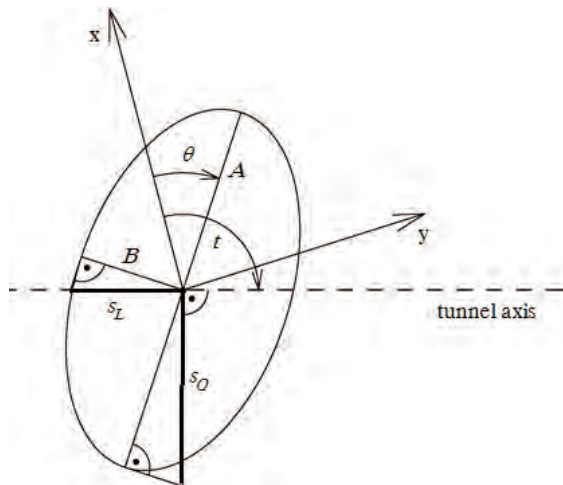


Figure 1: Relative error ellipse of the tunnel breakthrough precision.

Relative error ellipse, shown in Figure 1, is described by:

$$A = s_0 \sqrt{\lambda_1} \tag{9}$$

$$B = s_0 \sqrt{\lambda_2} \tag{10}$$

$$\tan 2\Theta = \frac{2q_{\Delta x \Delta y}}{q_{\Delta x \Delta x} - q_{\Delta y \Delta y}} \tag{11}$$

$$\lambda_{1,2} = \frac{1}{2} \left(q_{\Delta x \Delta x} + q_{\Delta y \Delta y} \pm \sqrt{(q_{\Delta x \Delta x} - q_{\Delta y \Delta y})^2 + 4q_{\Delta x \Delta y}^2} \right), \tag{12}$$

where:

A, B – semi-major axis A , semi-minor axis B of the relative ellipse,

Θ – azimuth of the major axis,

q_{ii} – the elements of the cofactor matrix $Q_{\hat{x}\hat{x}}$,

λ_1, λ_2 – the eigenvalues of the cofactor matrix $Q_{\hat{x}\hat{x}}$.

Since the relative error ellipse is independent of the distance between two points, it exists for two points whose mutual distance is approximately equal to zero, if the points are determined independently of each other. If this applies to the point of breakthrough, transverse s_Q and vertical s_L errors of the breakthrough precision will be (Ninkov, 1989):

$$\begin{aligned} s_Q^2 &= A^2 \sin^2(t - \Theta) + B^2 \cos^2(t - \Theta), \\ s_L^2 &= A^2 \cos^2(t - \Theta) + B^2 \sin^2(t - \Theta), \end{aligned} \tag{12}$$

where t is the direction of the tunnel axis.

3 CASE STUDY

3.1 Proposed design of the local 2D geodetic network for the construction of the Belgrade metro line 1

In (EGIS, 2012) the preliminary design of the Belgrade metro Line 1 is defined. The Metro Line 1 (Figure 2), as a priority, follows the corridor east – west and passes through the old center of the city. Outside the old part of the city, on the right bank of the Sava River, the highest population density is along the King Alexander Boulevard. Therefore, the alignment begins at one end of a densely populated area, at the end of King Alexander Boulevard (beside Ustanicka Street), enters the city center (the Nikola Pasic Square, the Republic Square), crosses the Sava River and passes through New Belgrade, along the busiest streets, towards the populated area of Zemun.



Figure 2: Planned Belgrade metro network – Line 1.

Through a deep tunnel, 3430 m long, the corridor passes underneath the most densely populated old part of Belgrade, which is characterized by narrow streets. There will be a maximum of four underground stations in the downtown: Varos Kapija, Akademija, Trg Republike, and Trg Nikole Pasica. The tunnel is envisaged to start in Cucuk Stanina Street and to end at the Varos Kapija station, where the metro will exit directly onto the bridge across the Sava River.

The tunnel part of the metro will be drilled by a tunnel boring machine (TBM). Since drilling will begin from two opposite ends of the tunnel, it is necessary to form the surface geodetic network. The surface network should consist of national geodetic network points and portal network points (Figure 3). Measurements in the surface network would be carried out using GNSS technology. Since it is necessary to transform the baseline results from WGS84 to the site coordinate system, at least three points from the national geodetic network, which are uniformly distributed around the designed alignment of the tunnel, should be determined in the site coordinate system. Before the tunnel excavation begins, control of the portal network should be conducted by comparing terrestrial horizontal angles with those calculated from the transformed GNSS coordinates. Also, control of every azimuth should be exercised. During the construction of the tunnel, the surface network would have to be remeasured in order to reveal possible deformation of the points.

The excavation of the tunnel will be carried out from two portals: Cucuk Stanina and Varos Kapija. Therefore, it is necessary to develop two portal networks. These two networks would be connected to the national geodetic network and would serve to connect the surface and the underground tunnel network (Figure 3).

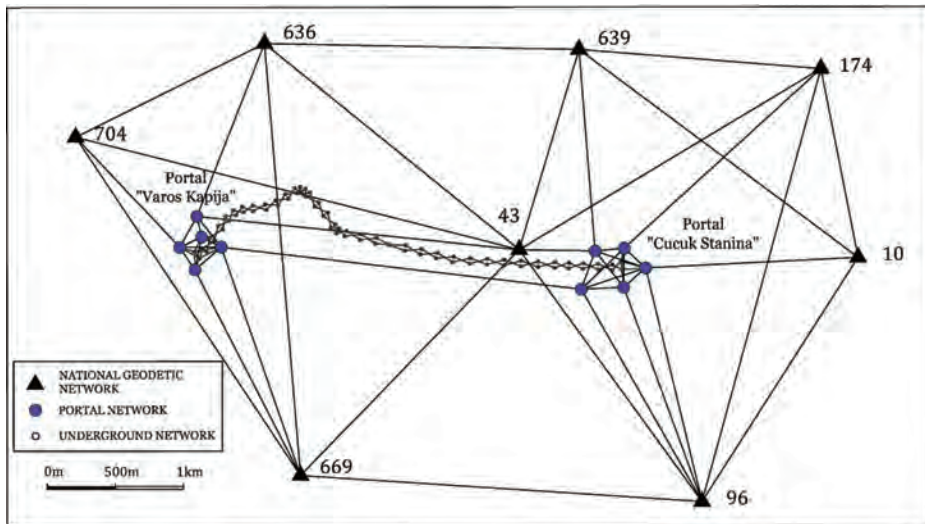


Figure 3: Schematic view of the geodetic networks.

3.2 Preanalysis of the 2D underground tunnel network

The underground network is developed for the purpose of guidance of the TBM machine and staking out the axis of the tunnel. With its configuration the precision of the tunnel breakthrough must be ensured

and other aspects of geodetic surveying, such as: connecting the surface and the underground networks (Cvetković, 1970), the precision of the initial azimuth (Zrinjski et al., 2006), reducing the impact of lateral refraction (Redovniković et al., 2011; Ingensand et al., 1998), the use of gyroscopic measurements in order to reduce the tunnel breakthrough error (Lewen, 2006) must be taken into account.

In order to obtain the optimal configuration of the network, by which the breakthrough precision of the tunnel will be achieved, the simulation of the underground network has been carried out several times, using different plans for measuring angles and lengths. In this paper, plans of observations and analysis of obtained results will be presented, as well as the adopted plan of observations, which provides for the required precision of the tunnel breakthrough. According to the equation (6), the transverse tolerance of a tunnel breakthrough for the tunnel length of $L = 3430$ m is:

$$\Delta_Q = \pm 60 \text{ mm} \sqrt{L_{[\text{km}]}} = 111 \text{ mm}$$

In practical applications, the required breakthrough precision, for 95% probability is:

$$\sigma_{RBA} = \frac{\Delta_Q}{2.447} = 4.5 \text{ cm}$$

which means that the transverse breakthrough error must not exceed 4.5 cm.

a) Preanalysis – the zero-order plan of observations

The underground network would consist of two zigzag traverses, composed of 70 points in total (Figure 4). Such a large number of points is conditioned by the shape and the longitudinal profile of the designed alignment, as well as the width of the excavation. Traverses would end at the breakthrough point BT. The breakthrough point BT is represented by two points: BT1 and BT2 (Figure 4), the coordinates of which slightly differ. For the purpose of the preanalysis, approximate coordinates of these points were determined.

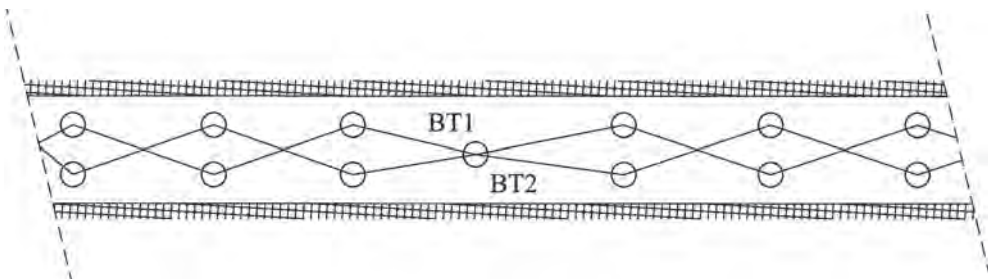


Figure 4: Design of the underground network with breakthrough point – the zero-order plan of observations.

A designer starts the preanalysis by choosing the number and type of observations for the adopted network design, that is which directions will be observed and which distances will be measured.

The assumed observation standard deviation is 1.0“ for the measured directions at the station and (1 mm; 1 ppm) for measured distances. Basic information about the underground network designed for the zero-order plan of observations includes:

- The total number of points covered by the plan of observations: 83;
- Types of observations to be measured: directions and distances;
- The number of directions to be measured: 192;
- The number of distances to be measured: 98.

Observations are planned to involve adjacent diagonal points of traverses. As a result of the preanalysis, the relative error ellipse, shown in Table 1, was obtained, based on which the transverse breakthrough error was calculated according to the equation (12). The direction of the tunnel axis t is determined by the axis azimuth at the breakthrough point and its value is $131^{\circ} 37' 44''$.

Table 1: Elements of the relative error ellipse and breakthrough error – the zero-order plan.

| From - To | A [cm] | B [cm] | Θ | s_0 [cm] |
|-----------|----------|----------|------------------|------------|
| BT1 – BT2 | 25.4 | 5.2 | $40^{\circ} 30'$ | 25.4 |

Based on the results obtained from the preanalysis of the underground network for the zero-order plan of observations, it was concluded that the required criterion, according to which transverse breakthrough error must not exceed 4.5 cm, is not satisfied. Because of that, this plan of observations cannot be accepted as the final plan, that is corrections should be made and a new plan of observations should be assumed.

b) *Preanalysis – the first-order plan of observations*

In the first-order plan of observations, the zero-order plan of observations was expanded by adding measurements of transverse directions and distances. In addition, eight gyroscopic measurements, specifically four measurements at connection points of both portal networks, were planned. In order to nullify the influence of the lateral refraction, planned gyroscopic measurements should be performed as reciprocal measurements, i.e. azimuths should be measured at both points of same traverse line (Figure 5). The assumed observation standard deviation is $3.2''$ for the measured azimuths. The assumed observation standard deviations for the measured directions and distances remain unchanged. Basic information about the underground network designed for the first-order plan of observations includes:

- The total number of points covered by the plan of observations: 83;
- Types of observations to be measured: directions, azimuths and distances;
- The number of directions to be measured: 262;
- The number of azimuths to be measured: 8;
- The number of distances to be measured: 133.

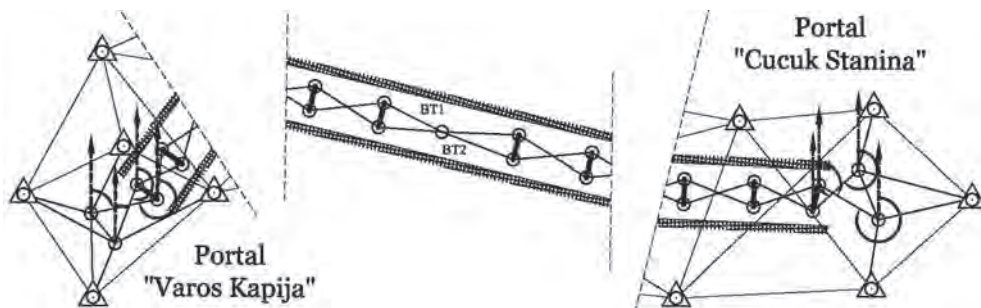


Figure 5: Design of the underground network with breakthrough point – the first-order plan of observations.

The following parameters of the relative error ellipse and breakthrough error that were obtained, as the results of the preanalysis for the first-order plan of observations, are shown in Table 2.

Table 2: Elements of the relative error ellipse and breakthrough error – the first-order plan.

| From - To | A [cm] | B [cm] | Θ | ϵ_0 [cm] |
|-----------|----------|----------|----------|-------------------|
| BT1 – BT2 | 24.5 | 5.0 | 41° 20' | 24.5 |

Based on the results obtained from the preanalysis of the underground network for the first-order plan of observations, it was concluded that there have been no significant changes in the results of the preanalysis. As the breakthrough error still exceeds 4.5 cm, it is necessary to assume a new plan of observations.

c) Preanalysis – the second-order plan of observations

In the second-order plan of observations, the first-order plan of observations was expanded by measurements of diagonal directions and distances to every second point of both traverses (Figure 6). Beside eight reciprocal gyroscopic measurements at connection points of portal networks, eight more reciprocal gyroscopic measurements were added: four of them at two points on the same profile, in the middle of the part of the alignment from the portal “Varos Kapija” to the breakthrough point and, by the same principle, another four reciprocal measurements in the middle of the part of the alignment from the portal “Cucuk Stanina” to the breakthrough point (Figure 6). The assumed observation standard deviations were taken over from a previous plan of observations. Basic information about the underground network designed for the second-order plan of observations includes:

- The total number of points covered by the plan of observations: 83;
- Types of observations to be measured: directions, azimuths and distances;
- The number of directions to be measured: 302;
- The number of azimuths to be measured: 16;
- The number of distances to be measured: 153.

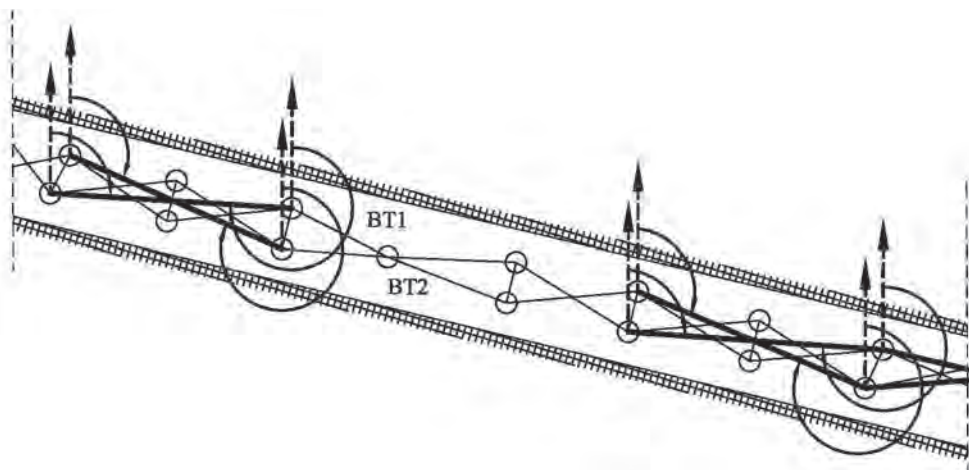


Figure 6: Design of the underground network with breakthrough point – the second-order plan of observations.

The following parameters of the relative error ellipse and breakthrough error that were obtained, as the results of the preanalysis for the second-order plan of observations, are shown in Table 3.

Table 3: Elements of the relative error ellipse and breakthrough error – the second-order plan

| From - To | A [cm] | B [cm] | Θ | s_0 [cm] |
|-----------|--------|--------|----------|------------|
| BT1 – BT2 | 12.9 | 3.2 | 54° 12' | 12.9 |

The results obtained from the preanalysis of the underground network for the second-order plan of observations show that the breakthrough error is significantly reduced compared to the first-order plan of observations. Since it still exceeds the required criterion, it is necessary to assume a new plan of observations.

d) *Preanalysis – the third-order plan of observations*

In the third-order plan of observations, the second-order plan of observations was expanded by additional gyroscopic measurements. Beside sixteen gyroscopic measurements from the previous plan, twelve reciprocal measurements more were added:

- On the part of the alignment from the portal „Varos Kapija“ to the breakthrough point, eight additional gyroscopic measurements are planned. Azimuth measurements on this part of the alignment are planned on the points, which are placed right after every horizontal bent section, as well as right before the breakthrough point. This created a more balanced distribution of gyroscopic measurements at distances from 400 m to 500 m.
- On the part of the alignment from the portal „Cucuk Stanina“ to the breakthrough point, four gyroscopic measurements were added. On this part of the alignment, the distribution of the azimuth observations is also corrected in same way as it was done on the previous part of the alignment. The uniform distribution of these measurements was achieved, at the mutual distance of 750 m. Such a long distance between the gyroscopic measurements is allowed by predominantly rectilinear shape of this part of the alignment with only one vertical bend.

The assumed observation standard deviation is 1.0 “ for the measured directions at the station, 3.2 “ for measured azimuths and (1 mm; 1 ppm) for measured distances. Basic information about the underground network designed for the third-order plan of observations includes:

- The total number of points covered by the plan of observations: 83;
- Types of observations to be measured: directions, azimuths and distances;
- The number of directions to be measured: 302;
- The number of azimuths to be measured: 28;
- The number of distances to be measured: 153.

The assumed observation standard deviations remain unchanged compared to the previous plans of observations.

The following parameters of the relative error ellipse and breakthrough error that were obtained, as the results of the preanalysis for the third-order plan of observations, are shown in Table 4.

Table 4: Elements of the relative error ellipse and breakthrough error – the third-order plan.

| From - To | A [cm] | B [cm] | Θ | s_0 [cm] |
|-----------|--------|--------|-----------|------------|
| BT1 – BT2 | 3.5 | 2.1 | 18 ° 54 ′ | 3.5 |

By analyzing the obtained results, it is concluded that the breakthrough error of less than 4.5 cm was achieved. Because of that, the third-order plan is adopted as the final plan of observations.

4 CONCLUSION

Optimization of a breakthrough precision primarily depends on the optimization and design improvements of the tunnel underground network, which usually consists of zigzag traverses. The tunnel breakthrough error, when gyroscopic measurements are not used, depends only on geometry of the surface and the underground network, precision of conducted measurements in those networks, and the status of point coordinates of the surface network. In this paper, the surface network points are treated as known points with fixed coordinates. In every plan of observations, the assumed observation standard deviations remained unchanged. Also, the number of points in the traverses remained unchanged because of the designed alignment characterized by sharp horizontal and vertical bends. It can be seen from the results of the preanalysis that, with unchanged observation standard deviations and a constant number of points in the traverses, the increase of the number of underground network observations itself has almost an insignificant influence on the tunnel breakthrough error. But, when gyroscopic measurements are incorporated in the observation plan, the breakthrough precision is significantly increased. To undo the influence of lateral refraction, it is necessary to perform reciprocal gyroscopic measurements. Comparing the results from the preanalysis obtained for the second-order plan and the adopted plan of observations, it can be concluded that the determination of the initial orientation of the tunnel axis using gyrotheodolit is not enough, but that the gyroscopic measurements are necessary in the tunnel itself. The results of the adopted plan of observations have shown that the uniform distribution and a sufficient number of measured azimuths, in this case at every fifth or sixth point of the traverse, both also significantly contribute to achieving the required criterion.

References:

- Cross, P. A. (1985). Numerical methods in network design. In E. W. Grafarend and F. Sanso (Eds.), *Optimization and design of geodetic networks* (pp. 132–168). Berlin: Springer. DOI: http://dx.doi.org/10.1007/978-3-642-70659-2_7
- Cvetković, C. (1970). *Primena geodezije u inženjerstvu*. Belgrade: Građevinska knjiga.
- EGIS (2012). *Studija opšteg koncepta metro sistema grada Beograda*.
- Grafarend, E. W. (1974). Optimization of geodetic networks. *Bolletino di Geodesia e Science Affini*, 33 (4), 351–406.
- Ingsand, H., Ryf, A., Stengele, R. (1998). The Gotthard Base Tunnel - a challenge for geodesy and geotechnics. In H. Kahmen, E. Brückl, T. Wunderlich (Eds.), *Proceedings of the Symposium on Geodesy for Geotechnical and Structural Engineering*, Eisenstadt, Austria, 20–22 April 1998, Zürich: Institute of Geodesy and Photogrammetry, Swiss Federal Institute of Technology.
- Koch, K. R. (1980). *Parameterschätzung und hypothesentests in linearen modellen*. Bonn: Dümmler Verlag.
- Krüger, J. (1985). Geodätische Netze in Landes- und Ingenieurvermessung II, Absteckung netze, speziell für Tunnel absteckungen, In: *Vorträge des Kontaktstudiums*, Hannover, Germany, February 1985, Stuttgart: Konrad Wittwer Verlag.
- Kuang, S. (1991). *Optimization and design of deformation monitoring schemes*. Doctoral Dissertation. New Brunswick: University of New Brunswick.
- Kuang, S. (1996). *Geodetic Network Analysis and Optimal design: Concept and Applications*. Michigan: Ann Arbor Press, Inc.
- Lewen, I. (2006). *Use of gyrotheodolite in underground control network*. Master's of Science Thesis. Stockholm: Royal Institute of Technology.
- Ninkov, T. (1989). *Optimizacija projektovanja geodetskih mreža*. Belgrade: Naučna knjiga.
- Paar, R. (2006). *Uspostava geodetske osnove za posebne namjene*. Master's of Science Thesis. Zagreb: University of Zagreb.
- Pelzer, P.H. (1979). *Some Criteria for the Accuracy and the Reliability of Networks*. IUGG (The International Union of Geodesy and Geophysics), XVII General Assembly of the International Union of Geodesy and Geophysics. Canberra, Australia, 2–15 December 1979, Potsdam: The International Union of Geodesy and Geophysics.
- Rao, C. R. (1973). *Linear statistical inference and its application*. New York: John Wiley & Sons.
- Redovniković, L. Džapo, M., Kapović, Z. (2011). Ispitivanje utjecaja bočne refrakcije na mjerenja horizontalnih pravaca u tunelu. *Geodetski list*, 65 (3), 241–259.
- Schaffrin, B. (1985). Aspects of network design. In E. W. Grafarend and F. Sanso (Eds.), *Optimization and design of geodetic networks* (pp. 548–597). Berlin: Springer. DOI: http://dx.doi.org/10.1007/978-3-642-70659-2_19
- Schmitt, G. (1985). A review of network designs: criteria, risk functions, design ordering. In E. W. Grafarend and F. Sanso (Eds.), *Optimization and design of geodetic networks* (pp. 6–10). Berlin: Springer. DOI: http://dx.doi.org/10.1007/978-3-642-70659-2_2
- Searle, S. R. (1971). *Linear models*. New York: John Wiley & Sons.
- Seemkoei, A. A. (2001a). Comparison of reliability and geometrical strength criteria in geodetic networks. *Journal of Geodesy*, 75 (4), 227–233. DOI: <http://dx.doi.org/10.1007/s001900100170>
- Seemkoei, A. A. (2001b). Strategy for designing geodetic network with high reliability and geometrical strength criteria. *Journal of Surveying Engineering*, 127 (3), 104–117. DOI: [http://dx.doi.org/10.1061/\(asce\)0733-9453\(2001\)127:3\(104\)](http://dx.doi.org/10.1061/(asce)0733-9453(2001)127:3(104))
- Zrinjski, M., Džapo, M., Redovniković, L. (2006). *Underground Geodetic Basis of the Tunnel "Mala Kapela"*. FIG (The International Federation of Surveyors), XXIII FIG Congress: Shaping the Change, Munich, Germany, 8–13 October 2006, Copenhagen: The International Federation of Surveyors.

Savanović M., Savanović R., Ninkov T., Sabados I.. (2015). Proposed design of local 2D geodetic network for the construction of the tunnel part of the Belgrade metro. *Geodetski vestnik*, 59 (3): 567–579. DOI: [10.15292/geodetski-vestnik.2015.03.564-576](https://doi.org/10.15292/geodetski-vestnik.2015.03.564-576)

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