Underground Geodetic Basis of the Tunnel "Mala Kapela"

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Key words: tunnel geodetic basis, tunnel building, triangle-chain network, allowed deviations, tunnel cutting accuracy

SUMMARY

The tunnel "Mala Kapela" is the longest tunnel in the Republic of Croatia. This paper present and analyses the geodetic basis of the tunnel "Mala Kapela".
The underground geodetic basis consists of:
- two networks in the right tunnel tube made in the form of a triangle chain (one in the northern, and the other in the southern part of the tunnel)
- two traverses in the left tunnel tube (one in the northern, and the other in the southern part of the tunnel)
- two precise closed traverses (one in the northern, the other in the southern part of the tunnel).

The error sources in direction measurements have been processed with special consideration of the initial bearing angle error. There are the formulas presented for corrections and reduction of lengths measured with electro optical distance meter.
The tunnel geodetic basis in the form of a triangle chain is presented that meets the set criteria in the best way referring to the tunnel cutting accuracy. At the end, there is the positional uncertainty of points presented that the tunnel "Mala Kapela" was cut from.

SAŽETAK

Tunel "Mala Kapela" najdulji je tunel u Republici Hrvatskoj. U ovom radu dan je prikaz i analizirana je podzemna geodetska osnova tunela "Mala Kapela".
Podzemna geodetska osnova sastoji se od:
- dvije mreže u desnoj tunelskoj cijevi koje su izvedene u obliku lanca trokuta (jedna na sjevernom, a druga na južnom dijelu tunela)
- dva poligonska vlaka u lijevoj tunelskoj cijevi (jedan na sjevernom, a drugi na južnom dijelu tunela)
- dva precizna zatvorena nivelmanska vlaka (jedan na sjevernom, a drugi na južnom dijelu tunela).

Obrađeni su izvori pogrešaka pri mjerenju pravaca s posebnim osvrtom na pogrešku početnoga smjernog kuta. Prikazane su formule za korekcije i redukcije duljina izmjerenih elektrooptičkim daljinomjerom.
Izložena je tunelska geodetska osnova u obliku lanca trokuta koja najbolje udovoljava postavljenim kriterijima u pogledu točnosti proboja tunela. Na kraju je prikazana položajna nesigurnost točaka s kojih je izveden proboj tunela "Mala Kapela".

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1. INTRODUCTION

Tunnels are construction objects requiring the highest accuracy in the geodetic measurements. Since they are the ingredient parts of traffic routes, and their construction is 4 to 5 times more expensive than the construction of the open traffic route part, geodetic works require special attention.

The tunnels are objects containing a series of specific characteristics that make them significantly different from other construction objects, which refers especially to the extensive preparation works and the complexity of geodetic works in the process of their cutting and building.

The tunnel construction expenses depend on the geological composition of the soil, the force of underground waters, terrain deformations and a lot of other factors.

However, the complete geodetic works have a significant influence on the tunnel construction expenses, starting with the preparation of project documentation, tunnel cutting, staking out the route axis, control of work performance and surveying the completed situation.

In order to fulfil these tasks a specific geodetic basis is established that is to meet all in advance defined accuracy criteria with its quality.

2. TUNNEL GEODETIC BASIS

The allowed deviation in cutting the tunnel is the basic starting point in designing and optimizing the geodetic basis for the purpose of building a tunnel.

Regarding the demands defined in advance referring to the tunnel cutting accuracy, an optimal selection of network configuration, instruments and measuring method are to be defined.

Geodetic basis for the purpose of building a tunnel consists of three parts:

- overhead geodetic basis (micro networks) in the area of entrance, i.e. exist portal used for the transfer of direction into the underground network
- overhead geodetic basis connecting the micro network of the entrance and exit portal
- underground geodetic basis used for staking out the axis and cutting the tunnel.

The project of the overhead geodetic basis is made on the conceptual project of the tunnel so that it covers the entire area where the future object is to be positioned and meets all its needs till the end of the building process.

Referring to the quality, the basis must be stable, reliable and homogeneous in order to meet the demands defined with regard to the tunnel cutting accuracy.

3. TUNNEL CUTTING ACCURACY

The underground geodetic basis should make it possible to transfer mathematically defined tunnel axis with a certain number of points defined by their coordinates below the physical surface of the Earth.
In order to secure the transfer of these points, a geodetic basis is established that will provide with its quality the staking out of the tunnel within the limits of in advance prescribed tolerances.
The form of the tunnel basis and its accuracy are stipulated by the construction and technical demands of cutting the tunnel that depend on its length.
The accuracy of the tunnel is defined usually with the value σ per each kilometre, and it can be described with the expression (Krüger 1985):

$$s_D = \sigma T_{km} , \tag{1}$$

where: s_D – is standard deviation of tunnel cutting
T_{km} – is the tunnel length in kilometers.

Since the accuracy of tunnel cutting depends on the quality of geodetic basis and measuring method, the accuracy of tunnel cutting must be estimated with the regard to the selected criteria.

3.1 Estimation of network configuration and tunnel cutting

Numerical indicators for a network with defined configuration illustrating whether it meets the defined criteria with regard to the accuracy of tunnel cutting are obtained from simulated adjustment of portal networks and the network in a tunnel.
In the process of adjustment we apply Gauss-Markov model consisting of functional and stochastic part (Kuang 1996).
The functional part of that model is given by the expression:

$$\hat{l} = l + v = A\hat{x} , \tag{2}$$

where: $\hat{l}$ – is adjustment vector of measurement value
l – is a vector of measured values
v – is a vector of measurement correction
A – is a configuration matrix
$\hat{x}$ – is a vector of unknowns.

Stochastic part of Gauss-Markov model is given by the expression:

$$K_{ll} = \sigma_0^2 Q_{ll} = \sigma_0^2 P^{-1} , \tag{3}$$

where: K_{ll} – is the matrix of variance-covariance of measurement

σ_0^2 – *a priori* variance factor

Q_{ll} – matrix of measurement cofactor

P – matrix of measurement weight.

There the matrix of a cofactor of adjusted unknowns is given by the expression:

$$Q_{\hat{x}\hat{x}} = (A^T P A)^{-1}. \tag{4}$$

The basic criterion in estimating the quality of the network configuration and measurement accuracy is the positional uncertainty of points from which the cutting of a tunnel has been made, and it is determined from both directions of tunnel cutting. It is presented with a relative error ellipse containing the information about longitudinal (s_L) and transverse (s_Q) deviation of a tunnel cutting point (Fig. 1).

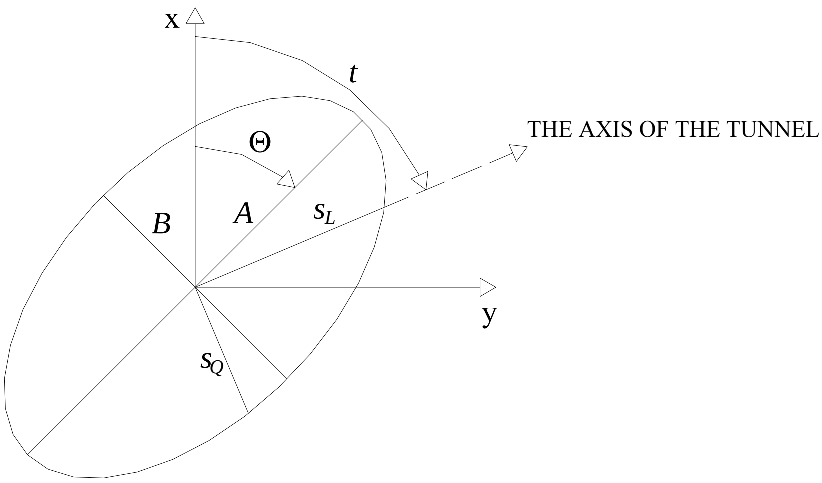


Fig. 1. Longitudinal and transverse deviation of tunnel cutting point.

Relative error ellipse is calculated from the cofactors of coordinate differences of points that define the cutting, and its elements are great semi axis *A*, small semi axis *B* and bearing angle of the great semi axis Θ.
The elements of the relative error ellipse are given with the expressions:

$$\lambda_{1,2} = \frac{1}{2}\left(q_{\Delta x \Delta x} + q_{\Delta y \Delta y} \pm \sqrt{\left(q_{\Delta x \Delta x} - q_{\Delta y \Delta y}\right)^2 + 4 q_{\Delta x \Delta y}^2} \right) \tag{5}$$

$$\Theta = \frac{1}{2} arc\,tg \left[\frac{2q_{\Delta x \Delta y}}{q_{\Delta x \Delta x} - q_{\Delta y \Delta y}} \right] \tag{6}$$

$$A = s_0 \sqrt{\lambda_1} \qquad B = s_0 \sqrt{\lambda_2}\,, \tag{7}$$

where: $\lambda_{1,2}$ – are typical values of cofactor matrix of coordinate differences $Q_{\Delta\hat{x}\Delta\hat{x}}$

$q_{\Delta x \Delta x}, q_{\Delta y \Delta y}, q_{\Delta x \Delta y}$ – elements of cofactor matrix of coordinate differences

s_0 – reference standard deviation *a posteriori*.

Relative error ellipse does not depend on the distance of two points if they have been determined independently.
If it is applied for the point of tunnel cutting, transverse and longitudinal deviation of the cutting will be obtained from the expression:

$$\begin{aligned} s_Q^2 &= A^2 \sin^2(t-\Theta) + B^2 \cos^2(t-\Theta) \\ s_L^2 &= A^2 \cos^2(t-\Theta) + B^2 \sin^2(t-\Theta), \end{aligned} \tag{8}$$

where: t – is a bearing angle of the tunnel axis.
Apart from the precision, the network quality is defined by the reliability as well. The reliability of network is tested with the methods of mathematical statistics.

4. THE TUNNEL "MALA KAPELA"

The tunnel "Mala Kapela" is placed in the Republic of Croatia on the highway Zagreb – Split. It consists of two parallel tunnel tubes with the axes distance of 25 m.
The right tunnel tube is 5760,00 m long, and the left tunnel tube 5761,76 m.
The tunnel "Mala Kapela" is the longest tunnel in the Republic of Croatia.
Out of the project documentation is can be seen that all allowed deviations between the designed and performed situation are within the limits of 0,5 to 3 cm, which encouraged the surveying experts to make thorough analyses before establishing the geodetic basis that would meet the defined criteria.
Since the tunnel cutting depends primarily on the accuracy of overhead and underground geodetic basis, the precision of instruments, measuring methods, the manner of transferring the elements into the tunnel, the shape of the tunnel, construction method, (full profile or drift), error in building and deformation of the structure, the error in cutting the tunnel is the results of total activity of all mentioned error sources.
The largest part of the error in tunnel cutting comes from the underground geodetic basis, the quality depends on the direction and distance measurement accuracy and on the geometric figure of the network and/or traverses.
Overhead geodetic basis needed for the construction of the tunnel "Mala Kapela" consists of:

- two geodetic rectangles (one in the vicinity of the northern and the other in the vicinity of the southern portal)
- precise traverse connecting positionally these two networks
- precise levelling figure connecting vertically these two networks.

The homogeneity of the micro networks has been tested and confirmed with precise traverse connecting these networks. The traverse is determined with the positional accuracy of 1:60000.

The positional underground geodetic network consists of:

- two networks in the right tunnel tube (one on the northern, and the other on the southern part of the tunnel) that are made in the form of triangle chain
- two traverses in the left tunnel tube (one on the northern, the other on the southern part of the tunnel) connecting underground networks in the right tunnel tube and the overhead geodetic basis on the northern, i.e. soothers tunnel portal.

Vertical underground geodetic basis consists of:

- two precise closed levelling figures (on the northern, the other on the southern part of the tunnel).

This paper describes in details only the positional underground geodetic basis.

4.1 Analysis of errors in direction

Direction measurement in the underground geodetic network is a special problem because of a large source of errors that can have significant influence on the tunnel cutting accuracy, since all measurements are made under the ground.
The accuracy of the measured direction is the function of errors connected with instruments, mistakes made in centring the instruments, mistakes made in centring the signal and mistakes in sighting that depends on atmospheric conditions, the light within the tunnel and their influence of lateral refraction. The influence of lateral infraction is especially large because of the relatively small tunnel tube diameter, so the sighting line passes close to the rocks being colder than the air in the tunnel. The orientation error is transferred directly to the tunnel network in its full amount, which is especially inconvenient in open traverses.
The total influence of individual errors should be smaller than the standard angle deviation that is obtained from the transverse deviation of the open traverse (Janković 1981):

$$s_{\beta}^{''} = \frac{0{,}45\Delta\rho''}{L}\sqrt{\frac{6(n-1)}{n(2n-1)}}, \tag{9}$$

where: Δ – is allowed transverse deviation
L – is the length of traverse diagonal

n – is the number of angles of refraction.

The errors of instruments and their influence on the measured angle can be removed to a great extend using a measuring method, apart from the error of the vertical axis that is the result of the system for levelling up an instrument being to sensitive, and it is estimated (Kuang 1996):

$$s_h^{''} = 0{,}2v'', \tag{10}$$

where: v'' – is the value of pars level expressed in seconds.
The sighting errors depends first of all on the properties of an instrument, sighting abilities of an observer, changes of atmospheric conditions, forms and distances of signal, and of its illumination.
Due to the air turbulences, great humidity and bad illumination, with the sighting line length of about 200 m, this error will amount to (Kuang 1996):

$$s_v^{''} = \frac{60''}{M}, \tag{11}$$

where: M – is the telescope enlargement.

4.1.1 Error of the initial bearing angle

External geodetic basis needed in tunnel construction is set in the vicinity of the entrance and exit portal. It consists of a certain number of stabilized points, and their number depends on the terrain configuration as well. These points serve for the transfer of orientation into the tunnel geodetic basis in the entrance, as well as in the exit portal. The accuracy of the orientation or the transfer of the initial bearing angle is very important, because along with the enlargement of the closed traverse length the influence of this error rises linearly (Fig. 2).

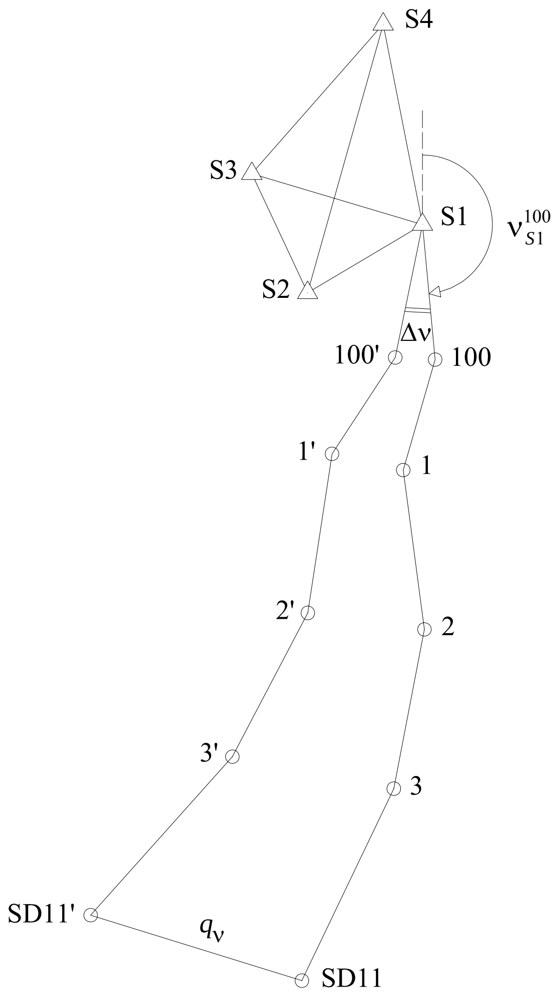


Fig. 2. Influence of the error of the initial bearing angle on transverse deviation in tunnel cutting.

If the initial bearing angle ν_{S1}^{100} is determined with the error $\Delta\nu$, then the influence of this error rises with the increase of the traverse length. The transverse deviation q_ν, caused by the error of the initial bearing angle, in the point SD11 placed at the distance D of the initial point of the traverse S1, is determined using the expression (Cvetković 1970):

$$q_\nu = D\, tg\Delta\nu\,. \tag{12}$$

Therefore, it is necessary to determine the standard deviation of the bearing angle at the initial side of the underground network that will define the configuration of the network and the working method so that the influence of the initial bearing angle error would be as small as possible. Since the control angle is measured at all visible points of the micro network, it is possible to obtain more values for the initial bearing angle. The most probable value of the initial bearing angle will be obtained from the orientation as an ordinary arithmetic mean (Džapo 1992):

$$\nu_{S1}^{100} = \frac{1}{n}\sum_{i=1}^{n}\left(\nu_{S1}^{100}\right)_i , \tag{13}$$

where: n – is the number of measured control angles to the points of the micro network.

4.2 Network configuration and measured values

According to the Book of Rules on Technical standards and conditions for the design and construction of tunnels on the roads of the Republic of Croatia, Art. 53 of the Law on Standardisation, the allowed transverse deviation for the tunnel "Mala Kapela" (L = 5760,00 m) makes:

$$\Delta = 60\ mm\sqrt{L_{km}} = 60\ mm\sqrt{5{,}760} = 144\ mm .$$

The underground geodetic basis in the tunnel "Mala Kapela" is made in the form of 2 triangle chains (1 on the north and 1 on the south) and 2 traverses in the left tunnel tube (1 on the north and 1 on the south) (Fig. 3). In this way the influence of the refraction, of the error in centring the instruments and the signal and the error of initial bearing angle on to the accuracy of tunnel cutting has been reduced. The points are placed at the distance of 200 to 300 m and stabilized with the enforced concrete pillars with the metal plate having the centring screw in the middle. All measurements were made with the equipment for the method of three tripods over the concrete pillars and/or tripods. The points are set away from the side walls of the tunnel as much as possible because of the lateral refraction influence, but at such a distance that the transport of the material dug up can be carried out undisturbed. Since all points of the geodetic basis are set in the subsiding and deforming zone of the Earth surface, check observations have to be done after ever 500 m of dug up material during the building process in order to define their stability.
The measured values are horizontal directions, zenith distances and lengths.
The measurements of these quantities are performed with the following number of repetitions:

- horizontal directions are measured in 2 rounds of horizontal angles
- zenith distances are measured both ways, in 2 series, in two positions of telescope
- slope distances are measures both ways, in 2 series with 2 repeated procedures (altogether 6 measurements in each direction).

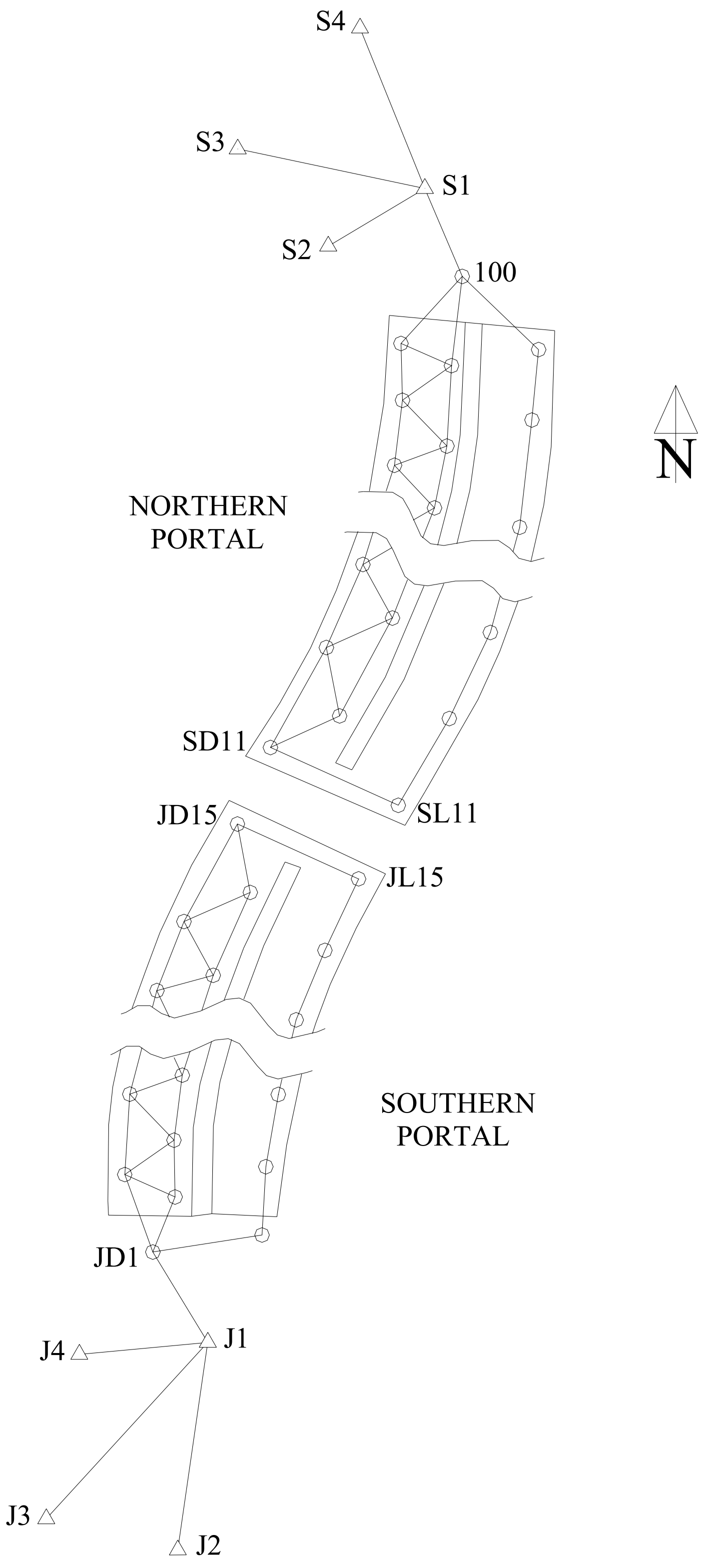


Fig. 3. Sketch of the underground geodetic basis of the tunnel "Mala Kapela".

On the basis of station adjustment and closing the triangle, adequate precisions in measuring the direction with standard deviation of a single direction is s_p = 1,80", and the standard deviation of measured lengths is s_d = 2,1 mm.
With regard to inconvenient working conditions in the tunnel and the declared measuring uncertainty of the electronic instrument Leica TC 1600 with 1" the achieved standard deviation for the directions and 3 mm + 2 ppm for distances is satisfactory.
At the time of performing measurements, the temperature difference in the tunnel and outside of it was maximally 26 °C (south portal), which required additional check measurements at the crossing from one medium into the other. In the process of measurements at the north portal, the temperature in the tunnel and outside of it was approximately the same. Regardless of that, there were also two independent check measurements made at the entrance and exit portal.

4.3 Data processing and adjustment of the positional underground geodetic basis

On the basis of the performed measurements, standard deviations in measurements of single angles and distances have been calculated and used for calculating the weights in adjustment processes.
Since all points on the tunnel axis refer to a unique coordinate system of the Gauss-Krüger projection of meridian zones, the coordinates of the points of the geodetic basis needed to be calculated in the same system.
Therefore, the following corrections and reductions needed to be introduced for all distances measured on the physical surface of the Earth:

- atmospheric correction
- reduction of the measured distance on the horizon
- correction for the reduction of the distance to the reference ellipsoid surface
- correction for the reduction of the distance into the plane of Gauss-Krüger projection.

4.3.1 Atmospheric correction

$$\Delta D_1 = \left(281{,}8 - \frac{0{,}29065\,p}{1 + 0{,}00366t} \right) \cdot 10^{-6}, \qquad (14)$$

where: ΔD_1 – is atmospheric correction
p – is air pressure [hPa]
t – is air temperature [°C].

$$D_{Atm} = D_{mj} + \Delta D_1 D_{mj}, \qquad (15)$$

where: D_{mj} – is the distance measured with electro optical distance meter
D_{Atm} – the distance corrected for the atmospheric correction.

4.3.2 Reduction of the measured distance to the horizon

$$D_{Hz} = D_{Atm} \sin Z \,, \tag{16}$$

where: D_{Hz} – is the distance reduced to the horizon
Z – is the measured zenith distance.

4.3.3 Correction for the reduction of the distance to the reference ellipsoid surface

$$\Delta D_2 = -\frac{h_m}{R} \qquad h_m = \frac{h_1 + h_2}{2} \,, \tag{17}$$

where: ΔD_2 – is the correction for the reduction of the distance to the reference ellipsoid surface
h_m – mean height of end points of the distance above the reference ellipsoid
R – Earth radius (R=6 379 000 m).

$$D_{El} = D_{Hz} + \Delta D_2 D_{Hz} \,, \tag{18}$$

where: D_{El} – is the distance reduced to the reference ellipsoid surface.

4.3.4 Correction for the reduction of the distance into the plane of Gauss-Krüger projection

$$\Delta D_3 = \frac{y_m^2}{2R^2} - 0{,}0001 \qquad y_m = \frac{y_1 + y_2}{2} \,, \tag{19}$$

where: ΔD_3 – is the correction for the reduction of the distance into the plane of Gauss-Krüger projection
y_m – mean distance of end points of the mean meridian length.

$$D_{GK} = D_{El} + \Delta D_3 D_{El} \,, \tag{20}$$

where: D_{GK} – is the distance reduced into the plane of Gauss-Krüger projection.

There were also the measured direction reduced from the physical surface of the Earth to the reference ellipsoid surface, however, these corrections were of a very small amount.
After introducing the corrections, and before the adjustment, it was found out that there are no rough errors in the network measurements.

Before calculating the coordinates of points of the underground geodetic network there was station adjustment of directions made, the angles in the triangle were adjusted to the theoretical value of 180°, and then they were adjusted to the amount of angles in the closed traverse.

Gauss-Markov model was used for the adjustment (see the expressions (2) and (3)).

The adjustment has been carried out in two iterations, and it came out that the solution was converging.

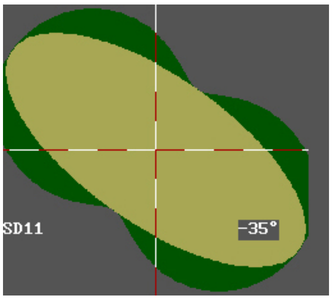
The coordinates of the requested points were obtained as adjustment result, as well as their standard deviations s_y and s_x, the elements of error ellipse (A, B, Θ) and the adjusted measurements with the belonging accuracy estimation.

The coordinates of points in the underground geodetic network and the belonging accuracy estimates were calculated with the program package GPSurvey v. 2.35.

Here, there are only the results for the accuracy estimate of the last network points presented from which the cutting was done on the northern and southern side of the tunnel (table 1), and there are also the error ellipses of these points on the northern (Fig. 4) and southern tunnel portal (Fig. 5) shown.

Table 1. Standard deviation of coordinates of the last network points from the tunnel cutting on the northern and southern side was made.

T_n	Standard deviations	
	s_y [cm]	s_x [cm]
SD11	3,9	2,9
SL11	4,0	2,9
JD15	5,9	4,5
JL15	5,9	4,6



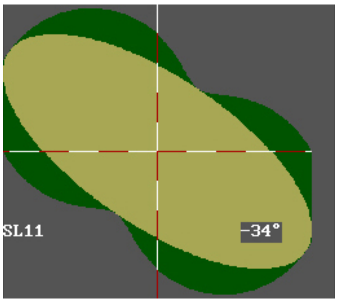


Fig. 4. Error ellipses and foot curves of the last network points from which the cutting was made on the northern tunnel portal (scale unit = 1 cm).

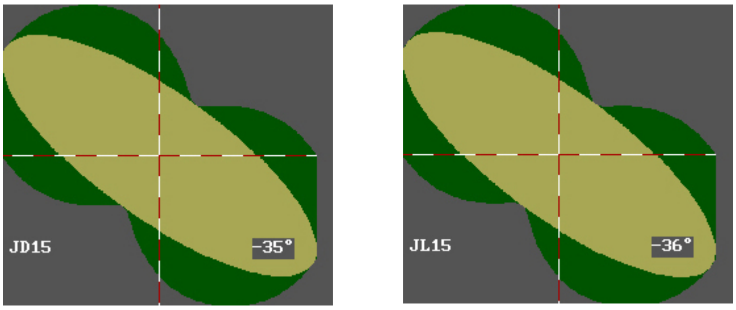


Fig. 5. Error ellipse and foot curves of the last network points from the cutting was made on the southern tunnel portal (scale unit = 1 cm).

4.4 Positional uncertainty of the tunnel cutting points

During the digging works in the tunnel "Mala Kapela" there were two check measurements made, the first one in July 2003 and the second one in January 2004, and there were also two independent adjustments of these measurement series made.

The last measurement was made when there were about 400 m left till the final cutting. The underground geodetic basis is connected to the overhead geodetic basis that has been determined with the adjustment of terrestrial measurements.

On the starting points of the underground geodetic basis (S1 on the north and J1 on the south) there was the orientation of direction from all three points in the northern (S2, S3 and S4) and southern (J2, J3 and J4) micro network calculated, which lead to higher accuracy in transferring the initial bearing angle ν_{S1}^{100} (on the north) and ν_{J1}^{JD1} (on the south) into the underground geodetic basis.

The left tube of the tunnel "Mala Kapela" was cut in February, and the right one in March 2004.

After that there were measurements made in order to have the positional uncertainty of the cutting point calculated in the right and left tunnel tube that was indicated with transverse and longitudinal deviation.

For the cutting point in the right tunnel tube the obtained transverse deviation was s_Q = 0,8 cm and longitudinal deviation s_L = 2,1 cm (table 2).

For the cutting point in the left tunnel tube the obtained transverse deviation was s_Q = 1,0 cm and longitudinal deviation was s_L = 2,2 cm (table 3).

Table 2. Positional uncertainty of cutting point in the right tunnel tube.

Cutting point	Coordinate	Northern portal (1)	Southern portal (2)	Difference (1) – (2) [cm]	Transverse deviation s_Q [cm]	Longitudinal deviation s_L [cm]
A	y	5 518 063,287	5 518 063,267	2,0	0,8	2,1
	x	4 994 441,017	4 994 441,006	1,1		

Table 3. Positional uncertainty of cutting points in the left tunnel tube.

Cutting points	Coordinate	Northern portal (1)	Southern portal (2)	Difference (1) – (2) [cm]	Transverse deviation s_Q [cm]	Longitudinal deviation s_L [cm]
B	y	5 518 096,040	5 518 096,017	2,3	1,0	2,2
	x	4 994 427,541	4 994 427,533	0,8		

5. CONCLUSION

Geodetic basis needed in the construction of tunnels contain a lot of specific characteristics, which refers especially to their shape, measuring method and requested accuracy.

Since the accuracy of tunnel cutting depends in the first place of the precision and the reliability of geodetic basis, its designing, implementation and data processing should be done after thoroughly performed analyses.

This paper presents the performed analysis connected with the errors in angle measurements on the underground geodetic basis, and their influence on the accuracy of tunnel cutting, and on the basis of measurements data obtained on the underground geodetic basis of the tunnel "Mala Kapela".

In straight line open traverses the error in transferring the orientation is transferred in its full amount, as well as the error of centring an instrument and the error of centring a signal, and the influence of refraction cannot be avoided not exactly determined.

Therefore, the geodetic basis in the right tunnel tube (on the northern and southern portal) was designed and perfumed in the form of a triangle chain, and at the beginning it was directly connected to the overhead geodetic basis, and at the end it was connected to the overhead geodetic basis by means of a traverse through the left tunnel tube (on the northern and southern portal).

Thus, two closed traverses were obtained (1 on the north and 1 on the south), a large number of redundant measurements and the possibility to adjust the angles in triangles and closed traverses to the theoretical value (n – 2)180°.

Before transferring the orientation angle into the underground geodetic basis it is necessary to determine the direction orientation by means of all points of the overhead geodetic basis that are observed.
The measurements at the entrance and exit of the tunnel should be done at the approximately adjusted temperature in the tunnel and outside of it.
In order to reduce the influence of refraction, the distance of the sighting line from the side walls must be at least 1,5 m.
The underground geodetic basis that is used for tunnel cutting should be checked after every 500 m of cut tunnel.

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