ACCURACY OF CUTTING THE TUNNEL "MALA KAPELA" IN CROATIA

Mladen Zrinjski [1]
Đuro Barković [2]
Tomislav Majcan [3]

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Summary: *The tunnel "Mala Kapela", 5760 m long, is the longest tunnel in the Republic of Croatia. The transverse deviation for the cutting point in the right tunnel tube was* s_Q*=0.8 cm and the longitudinal deviation* s_L*=2.1 cm. The transverse deviation for the cutting point in the left tunnel tube was* s_Q*=1.0 cm and the longitudinal deviation* s_L*=2.2 cm. The vertical deviation for the cutting point in the right tunnel tube was* s_H*=1.9 cm, and for the cutting point in the left tunnel tube* s_H*=2.1 cm.*

Keywords: *Overhead geodetic basis, underground geodetic basis, transverse deviation, longitudinal deviation, vertical deviation*

1. INTRODUCTION

A tunnel is an underground construction object in the form of a tube open at its both ends that is laid out horizontally or slightly inclined, with a traffic route built through it – railway, road, channel or water way [1]. Tunnels are construction objects the building of which requires the greatest possible accuracy from the geodetic experts in their work on surveying. Since tunnels are an ingredient part of traffic routes, and their building is four to five times more expensive than the building of the open part of a traffic route, geodetic works demand special attention.

2. ACCURACY OF TUNNEL CUTTING

Underground geodetic basis should provide the transfer of a mathematically defined tunnel axis with a certain number of points having adequate coordinates below the physical surface of the Earth. In order to ensure the transfer of these points, the quality of

[1] Assist. Prof. Dr. Mladen Zrinjski, Faculty of Geodesy, University of Zagreb, Kačićeva 26, HR-10000 Zagreb, Croatia, tel: ++385 (0)1 4639 337, e – mail: mladen.zrinjski@geof.hr
[2] Prof. Dr. Đuro Barković, Faculty of Geodesy, University of Zagreb, Kačićeva 26, HR-10000 Zagreb, Croatia, tel: ++385 (0)1 4639 226, e – mail: djuro.barkovic@geof.hr
[3] Tomislav Majcan, Faculty of Geodesy, University of Zagreb, Kačićeva 26, HR-10000 Zagreb, Croatia, e – mail: tomajcan@geof.hr.

the established geodetic basis has to enable the staking out of tunnel axis within the limits of tolerances prescribed in advance. The form of the tunnel basis and its accuracy are stipulated by construction and technical requirements related to the accuracy of tunnel cutting, which depends on its length. The accuracy of tunnel cutting is usually defined by the value σ per kilometre (mm/km), so it can be expressed in the following way [2]:

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

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

Since the accuracy of tunnel cutting depends on the quality of geodetic basis and measuring method, it is necessary to make an assessment of accuracy with regard to the approved criteria. It is presented by a relative error ellipse containing information on transverse (s_Q) and longitudinal (s_L) deviation of the tunnel cutting point. The relative error ellipse is computed from the co-factor of coordinate differences of points which define the cutting, and its elements are a big semi axis A, a small semi axis B and a grid bearing of the big semi axis Θ. Relative error ellipse does not depend on the distance between the two points if these were determined independently. If it is applied to the tunnel cutting point, transverse and longitudinal deviation of tunnel cutting will be obtained from the expression [3]:

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

where: t – grid bearing of tunnel axis.
Network quality is defined not only by its precision but also by its reliability. The reliability of the network is tested using methods of mathematical statistics.

3. THE TUNNEL "MALA KAPELA"

The tunnel "Mala Kapela" is placed on the highway Zagreb – Split in the Republic of Croatia. It consists of two parallel tunnel tubes with 25 m of distance between the axes. The right tunnel tube (N–S) is 5760.00 m long, and the left tube (N–S) 5761.76 m. The tunnel "Mala Kapela" is the longest tunnel in the Republic of Croatia. The accuracy of tunnel cutting depends primarily on the accuracy of the overhead and underground geodetic basis, on the precision of instruments and measuring methods, on the manner of transferring of the initial grid bearing into the tunnel, on the shape of the tunnel and the building method (full profile or undermining), on errors in construction, and deformation of a construction object. Therefore, the error in cutting a tunnel is the result of total impact of the above-stated error sources. The largest part of the error in cutting a tunnel originates from the underground geodetic basis, the quality of which depends on the accuracy of measuring directions and distances, and on the geometric form of a network and/or traverses. The geodetic basis of the tunnel "Mala Kapela" consists of an overhead and of an underground basis. Overhead geodetic basis can be divided into the positional and vertical. The positional overhead geodetic basis consists:

- two geodetic rectangles (one in the vicinity of the northern, and the other in the vicinity of the southern portal)
- a precise closed traverse that connects positionally these two micro-networks (from the point S3 in the northern micro-network to the point J2 in the southern micro-network).

The homogeneity of micro-networks in the northern and southern tunnel portal has been tested and confirmed with a precise traverse that connects these two networks. This traverse has been determined with the positional relative accuracy of R=1:60 000. The vertical overhead geodetic basis is defined by a precise levelling figure that vertically connects the micro-network of the entrance and exit portals. At the northern portal, the levelling figure is connected to the benchmark on the pillar S1, and on the southern portal to the benchmark on the pillar J1. The underground geodetic basis relies on the overhead geodetic basis. Underground geodetic basis can also be divided into the positional and vertical. The positional underground geodetic basis consists of (Figure 1):

- two networks in the right tunnel tube (N–S) that are 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 (N–S) (one in the northern, the other in the southern part of the tunnel) connecting the underground networks in the right tunnel tube and the overhead geodetic basis on the northern, i.e. southern tunnel portal.

This was the first time that the triangle chain underground basis of a tunnel like the one in "Mala Kapela" was applied in the Republic of Croatia for the purpose of cutting a tunnel. The vertical underground geodetic basis consists of two closed precise levelling figures (the measurements were performed using the method of geometric levelling – order of precise levelling). On the northern side of the tunnel the levelling figure is connected to the benchmark on the pillar S1, and on the south the levelling figure is connected to the benchmark on the pillar J1. The heights of screws stabilized on reinforced concrete pillars in both tunnel tubes were determined. Due to a large amount of data, this paper analyses in detail only the positional underground geodetic basis. According to the rules on Technical Standards and Conditions for Designing and Constructing Tunnel on the Roads of the Republic of Croatia, for the tunnel "Mala Kapela" (L = 5760.00 m) the allowed transverse and longitudinal deviation is [4]:

$$\varDelta = 60\ \mathrm{mm}\sqrt{L_{\mathrm{km}}} = 60\ \mathrm{mm}\sqrt{5.760} = 144\ \mathrm{mm}\ .$$

The underground geodetic basis of the tunnel "Mala Kapela" is made in the form of two triangle chains in the right tube (one in the north, and the other in the south) and two traverses in the left tunnel tube (one in the north and the other in the south). The triangle chains and traverses connect the underground network in the right tunnel tube with the overhead geodetic basis in the north and in the south of the tunnel. This reduced the influence of refraction, the errors of instrument and signal centring, and the errors of initial grid bearing on the accuracy of tunnel cutting. The points in the underground geodetic basis have been placed at a distance of 200 to 300 m and stabilized on reinforced concrete pillars with metal plate with a screw in the middle. All measurements were carried out using the three tripod centring accessories.

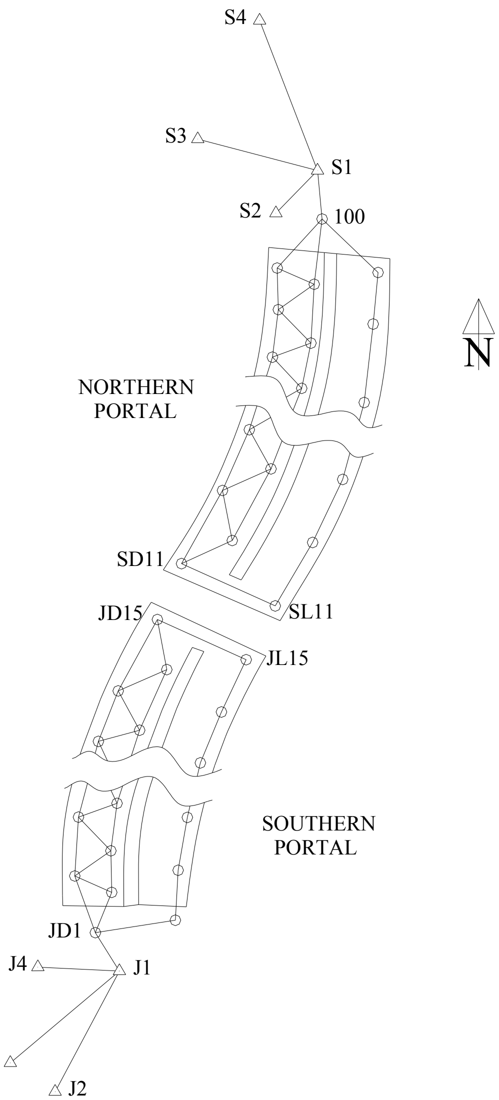

Figure 1. Positional underground geodetic basis in the tunnel "Mala Kapela"

On the basis of the station adjustment, triangle closing and processing other measurement data, the standard deviation of measuring single direction was calculated and runs up to s_p = 1.80", and the standard deviation of measured distance runs up to s_d = 2.1 mm. Considering the unfavourable working conditions in the tunnel and the declared measuring uncertainty of the instrument, the achieved standard measuring deviations are satisfactory. The above-stated measuring deviations were used to calculate the weights in the process of adjustment. Since all points on the tunnel axis refer to the unique coordinate system of Gauss-Krüger projection of meridian zones, the coordinates of geodetic basis points had to be calculated in the same system. Closing of levelling figures was achieved with accuracy: on the northern portal ±2.10 mm (d = 2392 m), and on the southern portal ±3.00 mm (d = 3429 m). Gauss-Markov model was used for the adjustment [5]. The adjustment was carried out in two iterations and has shown that the result converges. The result of the adjustment was the coordinates of points in the underground geodetic basis, their standard deviation (s_y and s_x), the elements of error ellipse (A, B, Θ) and the measurement adjustment with their respective accuracy estimate. Here we present only the standard deviations of coordinates of the last points in the network from which the cutting was done at the northern (SD11 and SL11) and the southern side of the tunnel (JD15 and JL15), (Table 1).

Table 1. Standard deviations of coordinates of last points in the network from which the cutting was done on the northern and southern side of the tunnel

Last point	Standard deviations of coordinates	
	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

After cutting the tunnel, measurements were made in order to calculate the positional uncertainty for the cutting points in the right and the left tunnel tube. This was indicated by transverse and longitudinal deviation. For the cutting point in the right tunnel tube the transverse deviation was s_Q = 0.8 cm and the longitudinal deviation s_L = 2.1 cm (Table 2).

Table 2. Transverse and longitudinal deviation for the cutting point in the right tunnel tube

Cutting point	Transverse deviation s_Q [cm]	Longitudinal deviation s_L [cm]
JD15	0.8	2.1

For the cutting point in the left tunnel tube the transverse deviation was s_Q = 1.0 cm and the longitudinal deviation s_L = 2.2 cm (Table 3).

Table 3. Transverse and longitudinal deviation for the cutting point in the left tunnel tube

Cutting point	Transverse deviation s_Q [cm]	Longitudinal deviation s_L [cm]
JL15	1.0	2.2

For the cutting point in the right tunnel tube (JD15) the obtained vertical deviation was s_H = 1.9 cm, and for the cutting point in the left tunnel tube (JL15) was s_H = 2.1 cm.

4. CONCLUSION

Since the accuracy of tunnel cutting depends primarily on the precision and reliability of underground geodetic basis, its design and implementation should be done after thoroughly made analyses. In addition, great attention should be paid to design and implementation of overhead geodetic basis, because its implementation largely affects the accuracy of the underground geodetic basis, which implies the accuracy of tunnel cutting as well. The underground geodetic basis of the tunnel "Mala Kapela" in the right tunnel tube (at the northern and southern portal) was therefore designed and implemented in the form of a triangle chain. At the beginning it was directly connected to the overhead geodetic basis, and at the end it was connected to the overhead geodetic basis with the traverse through the left tunnel tube (at the northern and southern portal). Thus were obtained two closed polygons (one on the north and the other on the south), along with a large number of redundant measurements in order to increase the accuracy, as well as the possibility to adjust the interior angles in triangles and closed polygons to the theoretical value of $(n-2)\cdot 180°$. When transferring the orientation angle into the underground geodetic basis it is necessary to determine the direction orientation on the initial point with all points of the overhead geodetic basis that are observed. The control measurements in the underground geodetic basis during the tunnel cutting must be made at least after every 500 m of the drilled tunnel.

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ТОЧНОСТ ПРОБОЈА ТУНЕЛА "МАЛА КАПЕЛА" У ХРВАТСКОЈ

Резиме: *Тунел "Мала Капела", дуљине 5760 м, најдуљи је тунел у Републици Хрватској. За точку пробоја у десној тунелској цеви добивено је попречно одступање s_Q=0.8 цм и уздужно одступање s_L=2.1 цм. За точку пробоја у левој тунелској цеви добивено је попречно одступање s_Q=1.0 цм и уздужно одступање s_L=2.2 цм. За точку пробоја у десној тунелској цеви добивено је висинско одступање s_H=1.9 цм, а за точку пробоја у левој тунелској цеви s_H=2.1 цм.*

Кључне речи: *Надземна геодетска основа, подземна геодетска основа, попречно одступање, уздужно одступање, висинско одступање*