

## Defining the optimal distance between technological sequences during tunnel excavation in poor rock mass

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**Abstract:** When excavating tunnels in urban areas with shallow overburden in poor rock mass, the deformations are very pronounced, which can result in serious potential risks to the safety, costs and time of tunnel construction. In the Kobilja Glava tunnel, which will be part of the project connecting Vogošća with Sarajevo and connecting the city center of Sarajevo with the A1 motorway on Corridor Vc, monitoring of displacements was conducted in a specific section of the left tunnel tube over a length of 80 m, in terms of various distances between the top heading excavation and the primary invert in poorer rock mass with a defined RMR ranging from 27 to 32. The results indicate that displacements can be effectively controlled by defining the optimal distance between the excavation phases of the top heading and the primary invert. A detailed analysis of the collected data yielded a mathematical function relating displacement to the distance between the excavation of the top heading and the primary invert, which can serve as a tool for quick and straightforward correlation of displacements during tunnel excavation, considering the geological conditions present in the Kobilja Glava tunnel.

**Key words:** tunnel, excavation, deformation, top heading, primary invert

## Definiranje optimalnog razmaka između tehnoloških sekvenci pri iskopu tunela u lošijoj stijenskoj masi

**Sažetak:** Deformacije su vrlo izražene kod iskopa tunela u urbanim dijelovima s malim nadslojem u lošijoj stijenskoj masi što za posljedicu može imati ozbiljne potencijalne opasnosti na sigurnost, troškove i vrijeme izgradnje tunela. Na tunelu Kobilja Glava koji će predstavljati dio projekta povezivanja Vogošće sa Sarajevom i ujedno vezu najužeg gradskog centra grada Sarajeva sa autocestom A1 na koridoru Vc, izvršena su praćenja pomaka u tunelu na određenoj sekciji lijeve tunnelske cijevi u dužini 80 m' u odnosu na različite razmake između iskopa kalote i trajnog podnožnog svoda u lošijoj stijenskoj masi sa definiranim RMR od 27 bodova do 32 boda. Dobiveni rezultati pokazuju kako se pomaci mogu efikasno kontrolirati definiranjem optimalnog razmaka između faza iskopavanja kalote i trajnog podnožnog svoda. Detaljnom analizom prikupljenih podataka dobivena je matematička funkcija ovisnosti pomaka u odnosu na razmak između iskopavanja kalote i trajnog podnožnog svoda i ista se može koristiti kao alat za brzu i jednostavnu korelaciju pomaka prilikom iskopa tunela u odnosu na geološke uvjete kakvi vladaju u tunelu Kobilja Glava.

**Ključne riječi:** tunel, iskop, deformacija, kalota, trajni podnožni svod

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### 1. INTRODUCTION

The rapid development of urban areas in recent decades contributes to the increasing need to use underground space. Tunnels are considered an efficient choice for overcoming congestion problems and reducing traffic pressure [1]. Tunnel excavation is an exceptionally demanding and comprehensive work for consideration, based primarily on geotechnical and geophysical investigations, which are inextricably linked to the planned excavation methods and support system, as well as the necessary geotechnical measurements inside the tunnel, permanent field observations of the surrounding terrain surface, which provide a real picture of the potential impact of the excavation on structures in urban areas [2]. Selecting a proper procedure for the excavation of a large-span tunnel in soft soil is a key factor for its successful construction [3].

Observing the Kobilja Glava tunnel, which will be part of the main project connecting Vogošća with Sarajevo and connecting the city center of Sarajevo with the A1 motorway on Corridor Vc, monitoring of total displacements was conducted in terms of various distances between the top heading and the primary invert during the excavation in a specific section of the left tunnel tube in the rock mass with a defined RMR of 27-32. Kobilja Glava is a twin-tube tunnel where each individual tube is reserved for one direction of traffic. The axis-to-axis distance of the tunnel tubes is 25 m. The tunnel passes through the hill of the same name, on which there are approximately 500 residential units. The total length of the right tunnel tube is 635.10 m, of which 587.10 m is the length of the underground excavation. The temporary entrance portal of the right tunnel tube is at chainage 3+550.15, while the temporary exit portal is at chainage 4+137.15 (chainage along the axis of the right tunnel tube). The total length of the left tunnel tube is 638.885 m, while the excavation length is 590.885 m. The temporary entrance portal of the left tunnel tube is at chainage 3+546.952, while the temporary exit portal is at chainage 4+128.09 (chainage along the axis of the left tunnel tube). Due to the large longitudinal gradient in the tunnel, the main design defines two cross-connections between the left and right tunnel tubes [4].



Figure 1. Geographical location of the Kobilja Glava tunnel on the route of the Sarajevo-Vogošća road

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### 2. ENGINEERING GEOLOGICAL CHARACTERISTICS OF THE ROCK MASS IN THE EXCAVATION ZONE OF THE KOBILJA GLAVA TUNNEL

The geological structure of the terrain along the route of the Kobilja Glava tunnel is assessed as simple, since only Neogene sediments and Quaternary formations are present along the designed tunnel route, as well as in the immediate surroundings. The Neogene is represented by the Upper Miocene ( $^1M_3$ ) sediments of the Sarajevo-Zenica basin, better known as the "Koševo series".

During the excavation of the left tunnel tube from chainage km 3+744.00 to km 3+824.00, engineering geological mapping established that two different lithologies, pelitic and fine clastic, are present in the lithological structure of the open face profile and in both side profiles. Pelitic lithology is represented by marls, while fine clastic lithology is represented by normally graded centimeter layers of fine-grained, well-sorted sandstone. The deposits are dark gray to light gray in color. A darker color indicates an increased proportion of clayey and organic components, while a lighter color indicates an increased proportion of carbonate components and siliciclastic detritus. The aforementioned Upper Miocene complex is characterized by a laminated to thinly stratified texture and pelitic-clastic structure. Marls are sensitive to the presence of water, and in contact with water, their physical and mechanical parameters weaken.

The strata (primary discontinuity) strike perpendicularly to the tunnel axis with a dip of 8 to 10° opposite to the direction of progress of tunnel excavation. In addition to the primary discontinuity at the head of the excavation there is also a secondary discontinuity, or shear cracks that are parallel to subparallel to the fault zone. The fault zone is located at chainage km 3+819.20 in the left part of the top heading. The fault zone has a northwest-southeast (NW-SE) strike in azimuth from 282 to 102°. This rupture has a steeply inclined position with a dip to the southwest (SW) at an angle of 64°. Thus, the fault zone extends diagonally to subparallel to the tunnel axis. The infilling of the fault zone consists of crushed rock material (sandstone and marl debris) mixed with marly clays, which is formed by attenuating the rock mass along the fault. The width of the fault zone is up to 1.0 m, and the fault has a reverse character. Based on the results of mapping the open face of the excavation on the analyzed tunnel section, it can be concluded that the condition of the rock mass according to the RMR (Rock Mass Rating) classification has a value of 27 to 32, and the rock mass is classified as class IV. Figure 2 presents a view of the open face and the geological report from the beginning of the considered section of the left tunnel tube, while Figure 3 presents a view of the open face and the geological report for chainage km 3+821.60.

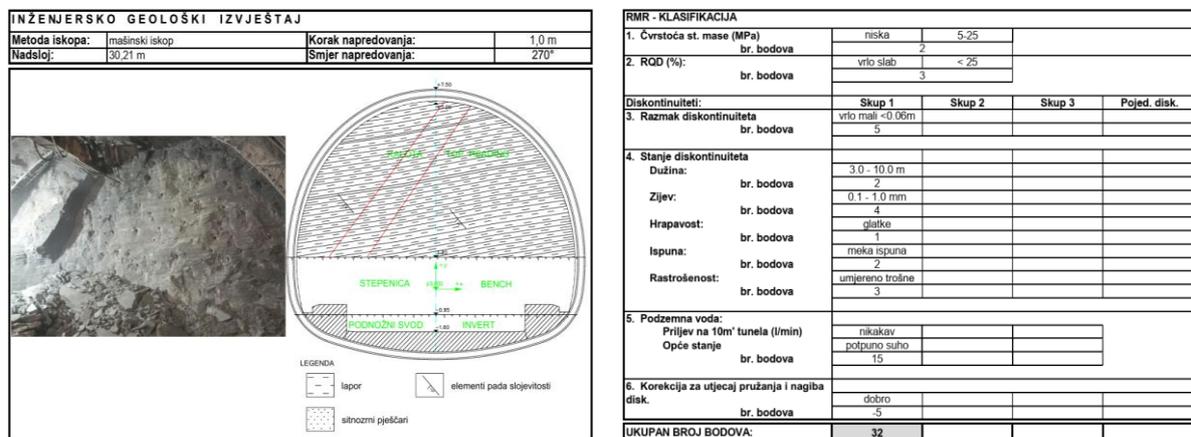


Figure 2. View of the face in LTT and geological report at chainage km: 3+746.85

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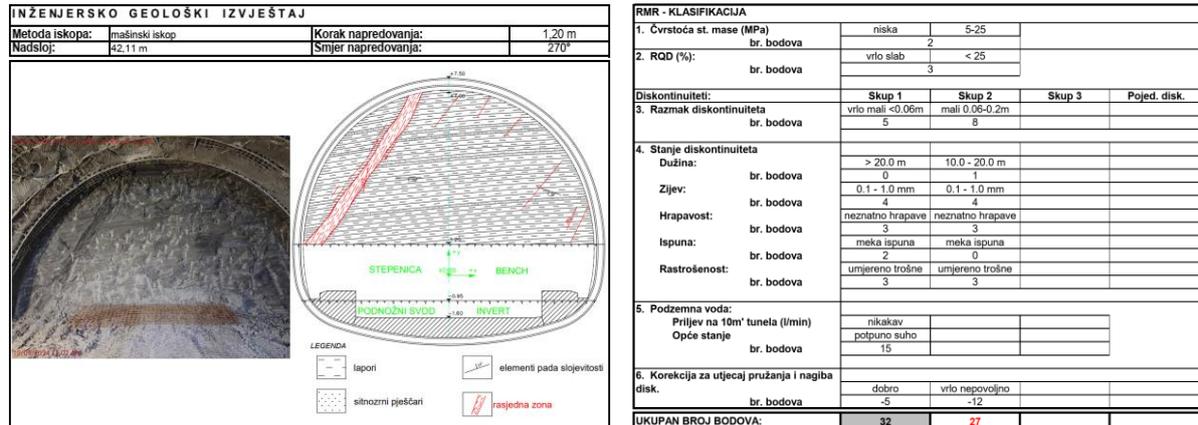


Figure 3. View of the face in LTT and geological report at chainage km: 3+821.60

### 3. ANALYSIS OF DEFORMATIONS OF THE SURROUNDING ROCK MASS USING THE NATM METHOD WHEN EXCAVATING THE TUNNEL

Selection of the construction method of a tunnel with a larger cross-section is mainly based on the conditions of the rock in which the tunnel is constructed [5]. In modern tunneling, there are increasingly pronounced efforts to apply new methods to strengthen the rock mass so that it takes over a large part of the loads by itself. There are no special rules that would facilitate decision-making when choosing an adequate method of tunnel excavation in complex geological conditions. This decision is mainly influenced by engineering experience rather than theoretical calculations [3]. The New Austrian Tunneling Method (NATM) has shown the best results of this adaptation. This method was selected when designing the Kobilja Glava tunnel, and the work on excavation and installation of primary support was carried out according to the same method. The technological and technical concept of the NATM method is based on the fact that the support system is not only a structure but also a time process. The main task of the support system structure is to transform the rock mass around the completed tunnel excavation into a self-supporting structure that enables the formation of safe underground space [6]. According to [7], Müller states in his research that the ring closure time is of crucial importance, especially emphasizing the need to do it in the shortest possible time interval in relation to the excavation.

Determining the relationship between the disturbed part of the rock mass around the tunnel excavation and the bearing capacity of the primary support is shown in Figure 4. In Figure 4, the ground response curve shows the interaction of the rocks, or of the primary support, and the deformations in time. This diagram provides a tool for idealizing the stiffness of primary support and installation time. When choosing to install a stiffer primary support (shown as 2 in Figure 4) it will bear a greater load because the rock mass around the opening has not sufficiently deformed to bring the stresses into a state of equilibrium. Therefore, the safety factor will decrease quickly. After point C, the behavior of the material in which the excavation is performed becomes non-linear. If the primary support (1) is installed after a certain displacement (point A), then the system reaches a state of equilibrium with less load on the primary support. A special characteristic of NATM is that the intersections always take place on the descending branch of the curve [8]. This implies a less stiff support that causes the necessary deformation as in the case of a NATM application. Moreover, the rock support must be neither too stiff nor too flexible. After point B, "detrimental loosening" begins and the required support pressure to stop loosening increases greatly. However, if the primary support

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is applied at the right time for the correct deformation, the support pressure at this point takes the minimum value.

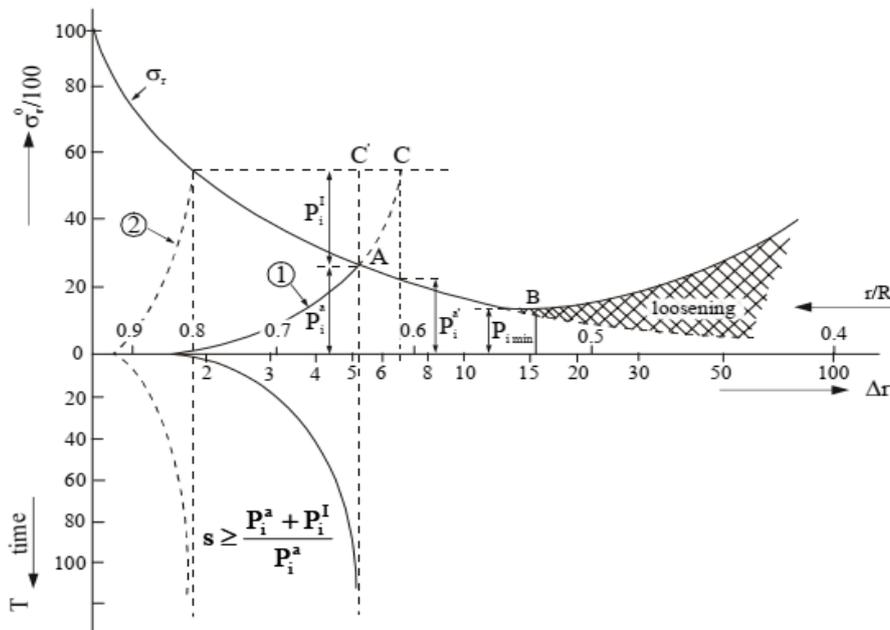


Figure 4. Ground-primary support interaction curves

The tunnel excavation causes a disturbance of the initial stress state in the ground and creates a three-dimensional arc-shaped stress regime around the advancing tunnel face [9]. Such a stress state is indicatively shown in Figure 5.

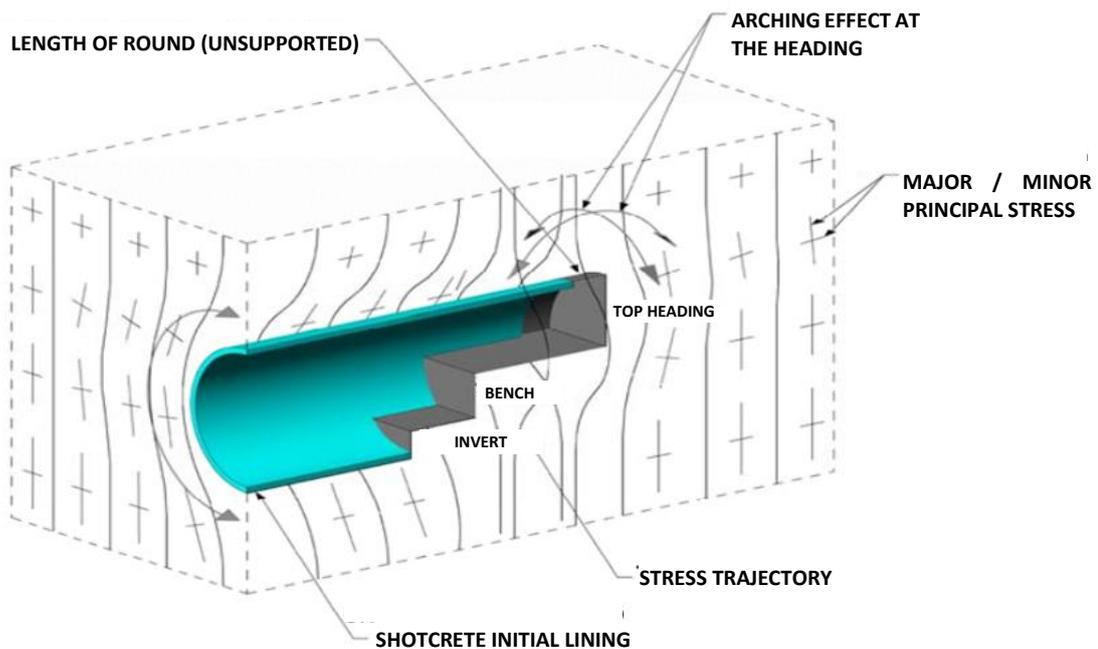


Figure 5. Stress flow around tunnel opening

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Far ahead of the advancing tunnel face, the initial state of stress is represented by vertical and horizontal stress trajectories indicating major and minor principal stresses. At the tunnel face, the stresses flow around the tunnel opening arching ahead of the tunnel excavation and behind it on the newly constructed primary lining in the longitudinal direction. The stresses also act on the sides of the excavated section perpendicular to the tunneling direction (tunnel excavation progress) [10].

The extent of stress disturbance around the active direction depends mainly on the conditions of the environment through which the tunnel is constructed, the volume of excavation and the progress step. This disturbance starts at some distance ahead of the underground excavation face, about  $0.5$  to  $2.5 d$  ( $d$  - the diameter of the underground excavation), reaches about a third of the final value at the face of the excavation, and it reaches its maximum at a distance of  $4.5 d$  behind the face of the excavation, which is indicatively shown in Figure 6.

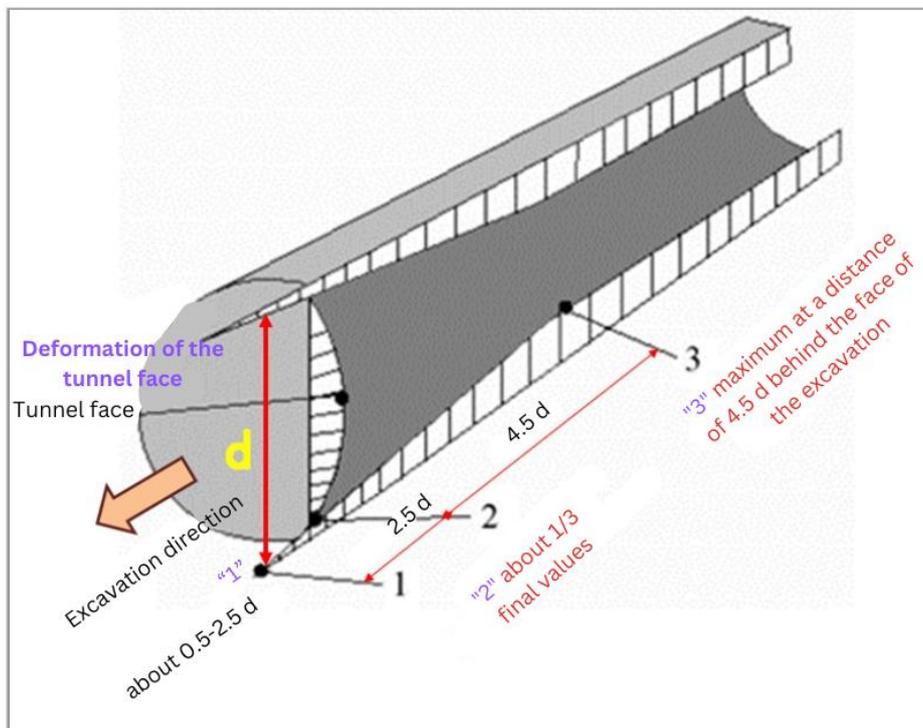


Figure 6. Deformations in the rock mass surrounding the advancing tunnel

Experimental and numerical investigation of ground deformation response shows that the real cause of the entire stress-deformation process that is activated during tunnel excavation lies in the regulation of stiffness of the advancing core using appropriate overlapping techniques, a controlled excavation method as well as in the ring closure time [11]. A graphic representation (Fig. 7) of the effect of the tunnel invert on the limit deformation depending on the distance of the excavation face and the installed primary invert, which was reached by Lunardi, P. in his research [11], is given below.

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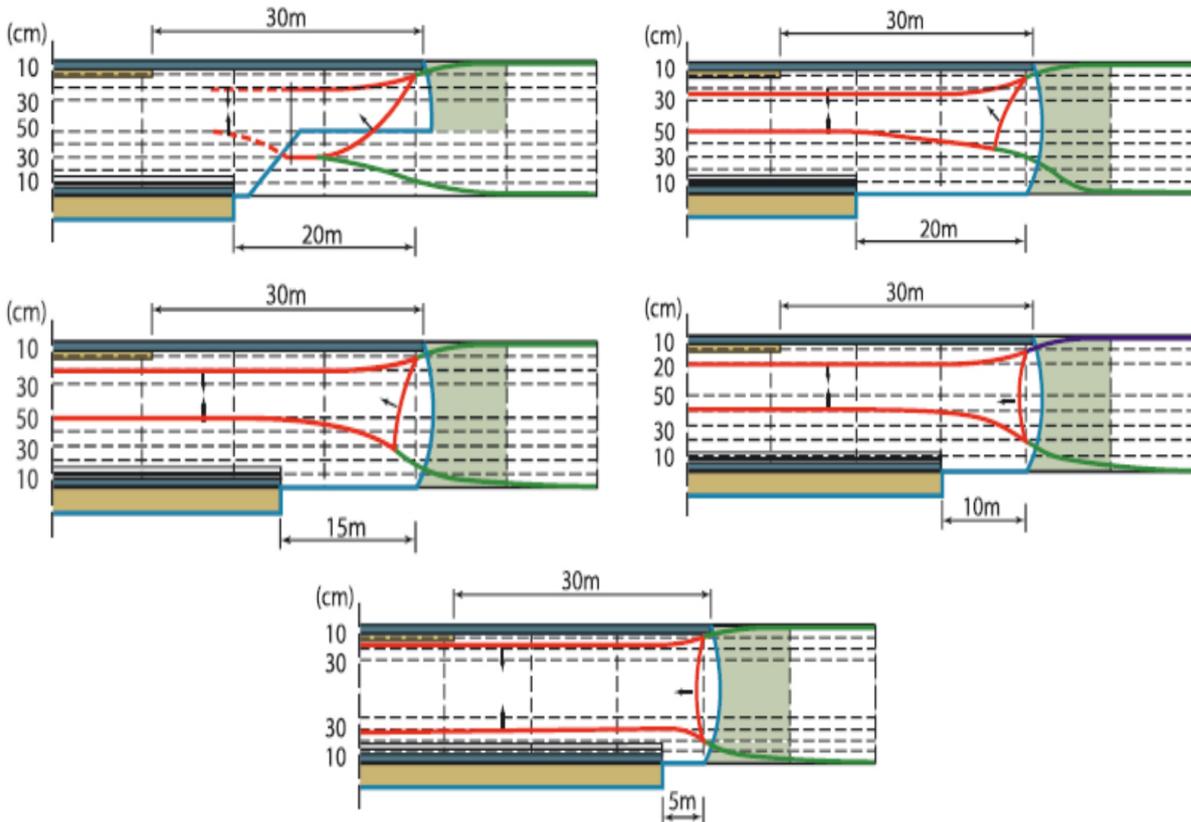


Figure 7. The effect of the distance of invert from the excavation face on the total deformations

The first and most important task of the designer is to determine how the arching effect can be created after the excavation is done, while ensuring that this effect is properly formed by stabilization procedures in complex geological conditions [12].

#### 4. ANALYSIS OF DEFORMATIONS OF THE SURROUNDING ROCK MASS IN TERMS OF DIFFERENT DISTANCES DURING THE EXCAVATION OF INDIVIDUAL PHASES OF THE KOBILJA GLAVA TUNNEL

During excavation of the Kobilja Glava tunnel, on a specific section of the left tunnel tube from chainage km 3+744.00 to km 3+824.00 (tunnel section of 80 m'), total displacements were monitored in terms of various distances between the top heading excavation and the primary invert, i.e., formation of a load-bearing ring around the tunnel and preventing the loss of strength of the rock mass in the rock mass with a defined RMR from 27 to 32. On the analyzed section during tunnel excavation, mainly uniform engineering geological conditions were determined, which can be seen on the longitudinal geological profile (Fig. 8).

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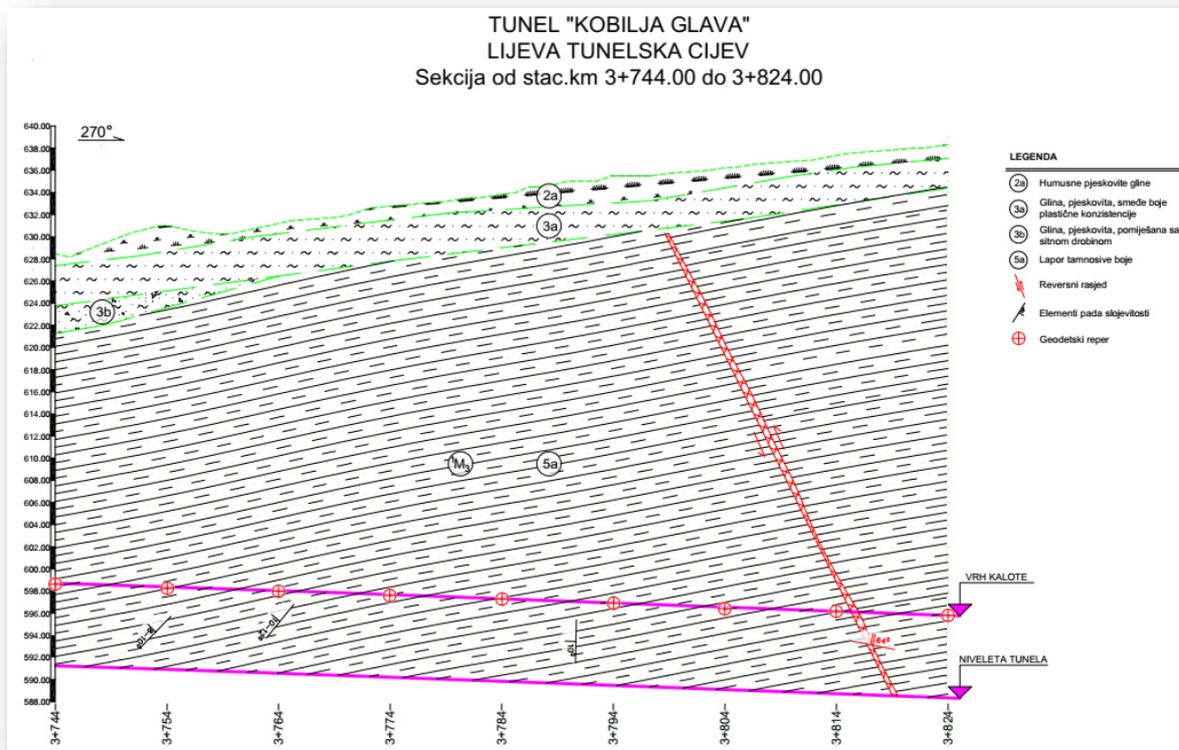


Figure 8. Longitudinal geological profile from chainage km: 3+744.00 to km: 3+824.00

During analysis of the total deformations of the left tunnel tube on the mentioned section, the right tunnel tube had been completely excavated with the primary support installed, and based on measurement of the total deformations in the right tunnel tube, its stability was confirmed. With this it was determined that the right tunnel tube could not affect the excavation of the left tunnel tube. Based on the data of geodetic monitoring of displacements in the excavated part of the left tunnel tube and the results of geological mapping of the open face of the excavation on the observed section of the left tunnel tube, a stability back analysis was performed and the primary support measures were defined as follows:

1. excavation step 1.2 m,
2. anchors IBO R32 ( $\varnothing 32\text{mm}$ ) or SN ( $\varnothing 28\text{mm}$ ), with a bearing capacity of 250 kN in the following layout:

- a) top heading  $l=4.0$  m 12/11 pcs;
- b) bench  $l=4.0$  m 2/4 pcs;

3. use of lattice centerings PS 70/20/30,
4. the thickness of shotcrete in top heading, bench and invert (C25/30) is 25 cm,
5. the thickness of shotcrete (C25/30) of 5 cm for spraying the face. In agreement with the engineer's geologist, the contractor's geologist will determine when and to what extent protection of the excavation face is performed,
6. two layers of reinforcement meshes Q257,
7. protection of the crown is carried out with one row of steel bars ( $\varnothing 28\text{mm}$ ,  $L=4.0$  m,  $e=25$  cm, 1.6 m overlap, 33 pieces). Installation is performed as necessary with the consent of the supervising engineer.

Profiles for measuring convergences in the left tunnel tube were installed along the tunnel contour from chainage km 3+744.00 and thereafter every 10 m of the analyzed tunnel tube

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sequence. The measurement profile consisted of 5 points, three in the top heading part and two in the bench, as shown in Figure 9.

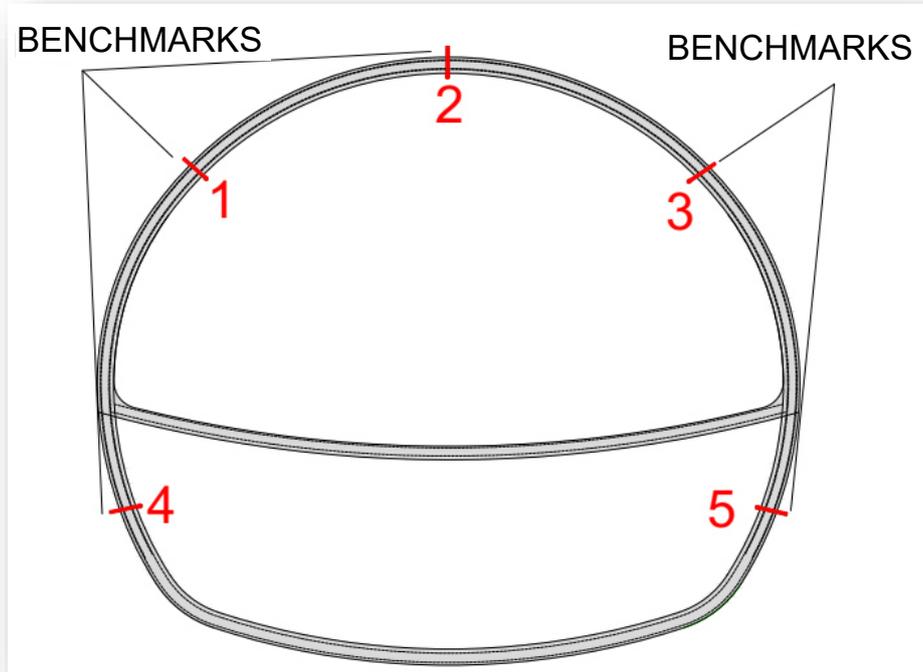


Figure 9. Control measurement profile

In order to reduce deformations of the surrounding material and the primary support in the tunnel, it is necessary to define the optimal distance between the technological sequences of the excavation top heading - primary invert. Figure 10 shows the longitudinal section of the excavation scheme of the left tunnel tube on the observed tunnel section.

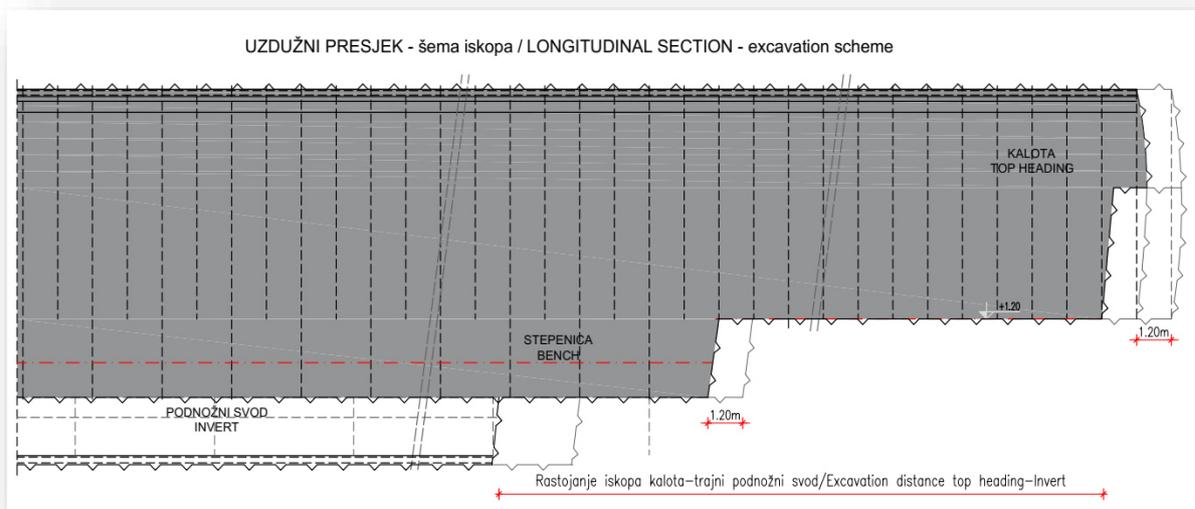


Figure 10. Longitudinal section – excavation scheme

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The distance between the top heading excavation and the primary invert on the analyzed sequence of the left tunnel tube ranged from 15 to 50 m with daily monitoring (measurement) of convergences. By analyzing all the collected data and processing them in detail, a graphic correlation (Figure 11) was established relating the expected total convergences and the distance between the excavation face of the top heading and the primary invert during tunnel excavation in the same or similar geological conditions as those prevailing in the Kobilja Glava tunnel excavation zone.

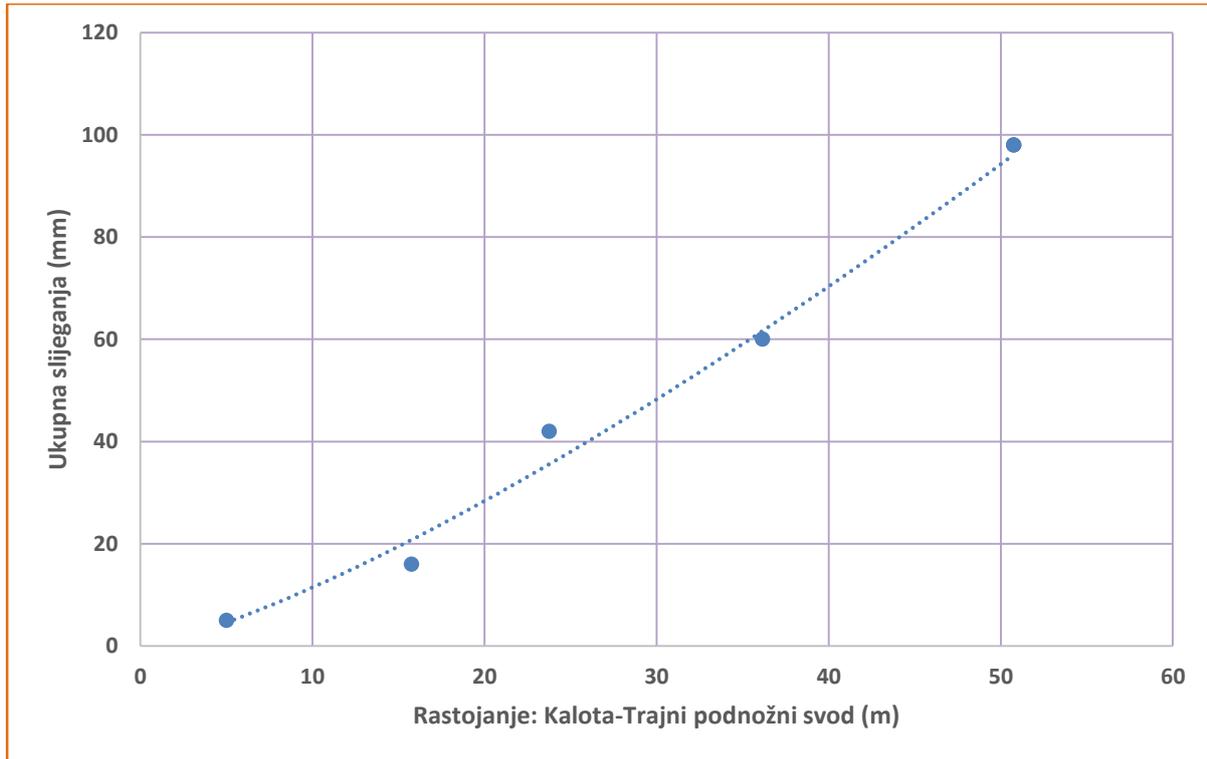


Figure 11. Plot of deformations versus excavation distance top heading - primary invert

From the plot (Figure 11), it can be clearly concluded that the convergences begin to grow significantly when the distance between the bench and performed primary invert increases, and that the registered convergences are the least if the primary invert is made behind the face on the length of  $2D$  of the excavation space ( $D$  - diameter of the excavation space).

Using the Mathematica software, a mathematical function was obtained that, depending on the expected convergence and the distance between the face of the top heading excavation and the primary invert, can be presented in the following form:

$$y = 0.5601 \cdot x^{1.3102} \quad (1)$$

where:

$y$  - is the expected total convergence in the tunnel (mm),

$x$  - is the distance of the excavation top heading-primary invert (m).

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### 5. CONCLUSION

Construction of any tunnel requires a unique approach to investigation and design during tunnel excavation, as well as adaptation to the actual conditions of the rock mass through which the tunnel passes, as well as the structures in the immediate vicinity. The bearing capacity effects of the surrounding rock and the primary support show different characteristics depending on the geological conditions through which the tunneling is performed.

This paper has shown the displacement control on the contour of the excavation, or of the primary support by defining the optimum distance between the excavation phases of the face of the top heading and the primary invert in various geological conditions through which the tunnel passes. A detailed analysis of the data collected during excavation of similar sections in the Kobilja Glava tunnel yielded a mathematical function relating displacement to the distance between the technological sequences of the excavation of the top heading and the primary invert, and it can be used as a tool for quick and straightforward stability analysis in the rock mass based on RMR 27-32.

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