submitted: 18.11.2024. *Scientific research paper*
corrected: 24.12.2024. *UDC: 624.19*
accepted: 25.12.2024. *https://doi.org/10.62683/ZRGAF40.3*

ANALYSIS OF SURFACE DEFORMATIONS DURING EXCAVATION OF A SMALL OVERBURDEN TUNNEL IN WEAK ROCK MASSES

Ekrem Bektašević[1]
Satko Filipović[2]
Kemal Gutić[3]
Džemal Hodžić[4]
Namik Musa[5]

Abstract

Excavation of tunnels with a small overburden inevitably implies surface settlements, especially when they are carried out in soft soil or weak rock masses. Subsidence becomes a critical aspect when the construction of tunnels is realized in narrower urban areas, directly below occupied residential buildings. Taking as an example the Kobilja Glava tunnel, which will represent part of the main project connecting Vogošća with Sarajevo and at the same time the connection of the narrowest city center of Sarajevo with the A1 motorway on the Vc corridor, surface deformations were monitored during the excavation and installation of the primary support of the left tunnel tube. Special attention was dedicated to excavation from the entrance side on a certain section of the tunnel where the height of the overburden was less than 2D. During the excavation of the left tunnel tube of the Kobilja Glava tunnel, which was carried out from the entrance portal at chainage km 3+543,202 in the direction of Vogošće, multiple surface settlements were measured from the very entrance to the place where the excavation was stopped (chainage km 3+615,56) compared to the predicted values obtained by assessment. The main reason for stopping the further progress of the excavation of the left tunnel tube from the chainage km 3+615.56 lies in the fact that the direction of the geological layers coincided with the direction of the progress of the excavation, which had a significant negative impact on the movement of the soil itself, and therefore on the increase surface deformations. After a comprehensive analysis of the above, as well as consideration of optional possibilities, it was decided to approach the excavation of the left tunnel tube from another attack point, i.e. to start the excavation from cross passage No. 1 in the direction towards the entrance. In this way, it was possible that the direction of the geological layers under these cirrcustamces positively contributes to the reduction of surface subsidence caused by the progress of the tunnel excavation by over 50%.

Key words: *Tunnel, Excavation, Deformation, Overburden, Settlement, Weak rock*

[1] Dr.sc., “PPG” d.o.o. Sarajevo, BiH, bektasevic.ekrem@gmail.com, ORCID.ORG/0000-0001-6742-966X
[2] BSc Civ. Eng., Road Directorate of Canton Sarajevo, BiH, satko.filipovic.dpks@gmail.com, ORCID.ORG/0009-0003-7456-4773
[3] Prof.Dr.sc., FMGCE, University of Tuzla, BiH, kemal.gutic@untz.ba, ORCID.ORG/0009-0008-9107-4641
[4] MSc. Geol. Eng., “Euro-Asfalt” d.o.o. Sarajevo, BiH, dzemal.hodzic@euro-asfalt.ba, ORCID N/A
[5] BSc Min. Eng., “PPG” d.o.o. Sarajevo, BiH, Namikmusa18@gmail.com, ORCID N/A

1. INTRODUCTION

The rapid development of urban areas in recent decades contributes to the increasing need to use underground space [1]. Tunnels are considered an efficient choice for overcoming congestion problems and reducing traffic pressure. Tunnels are often built in urban areas, where a small overburden is not uncommon, which further increases the complexity of the construction itself [2].

During the construction of tunnels in urban areas, soil deformations on the surface cannot be ignored under any circumstances, because they inevitably lead to damage to a large number of infrastructure and residential buildings, which implies significant material and financial damage, and ultimately can lead to the loss of human life. In other words, the construction of tunnels in urban areas is many times more complex than in areas where there are no infrastructure buildings [3]. Choosing a suitable procedure for the excavation of a long-span tunnel in soft soil is a key factor for its successful construction [4].

The height of the overburden represents the height from the upper edge of the primary support to the elevation of the terrain and is most often marked with H. The classification of the tunnel in terms of the thickness of this layer is closely related to the diameter (D) of the tunnel. If we are talking about a tunnel with a small (low) overburden, the New Austrian Tunnel Method (NATM) defines those tunnels where the limit value is given by the expression H=2D, so this represents a generally accepted approach in construction practice. Excavation of tunnels where the height of the overburden is less than 2D represents a special challenge and requires special attention, including the selection and application of different technologies, based on previous experiences [2].

Surface deformations caused by tunneling primarily depend on: the properties of the soil or rock mass through which the tunnel is constructed, the geometry of the tunnel, as well as the method of excavation and application of the primary support [5, 6]. Taking the Kobilja Glava tunnel, which will be part of the main project connecting Vogošće with Sarajevo and at the same time the connection of the narrowest city center of the city of Sarajevo with the A1 motorway on the Vc corridor, surface deformations were monitored during the excavation and installation of the primary support the left tunnel tube from the entrance side on a certain section of the tunnel where the height of the overburden was less than 2D.

The Kobilja Glava tunnel is a two-tube tunnel that passes through the hill of the same name, on which there are approximately 500 residential buildings. 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 located at chainage 3+550.15, while the temporary exit portal is located 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 located at chainage 3+546,952, while the temporary exit portal is located at chainage 4+128,09 (chainage along the axis of the left tunnel tube). The position of the tunnel is presented in Figure 1.

Due to the large longitudinal slope in the tunnel, the Main Project defined two cross passages between the left and right tunnel tubes. The designed method for construction is the New Austrian Tunneling Method [7].

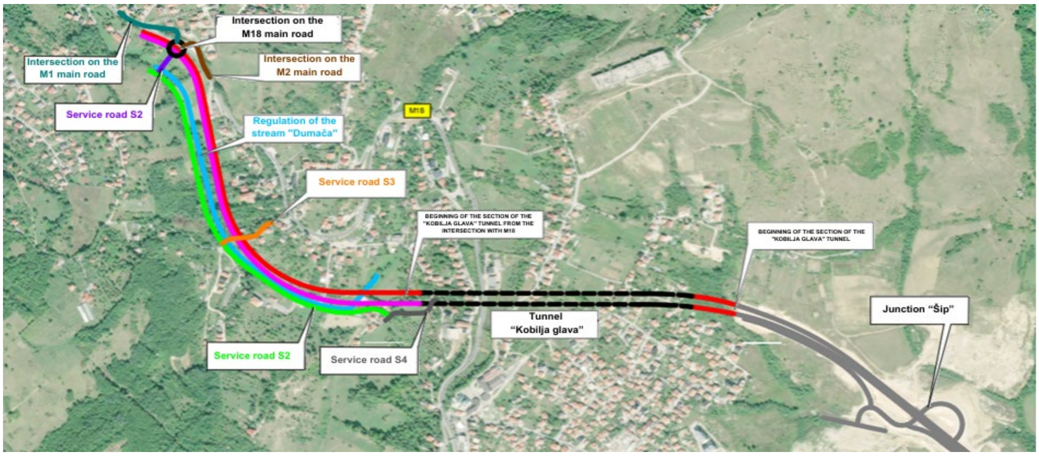

Figure 1. Geographical location of the Kobilja Glava tunnel on the route of the Sarajevo-Vogošća road

Most theoretical studies on the excavation of small overburden tunnels have focused on excavation in urban areas using tunnel boring machines (TBM). However, when excavating shorter tunnels, the application of TBM is still significantly more expensive than excavation with standard NATM, which is why this method is used in practice.

The greatest risk of excavation in weak rock masses with small overburden is associated with large surface deformations, because the consequences can sometimes be very dangerous (Figure 2), even catastrophic, causing human casualties [8].

London (2002.) München (1994.)

Figure 2. Consequences of large ground settlements during tunnel excavation in urban areas [8]

2. WORKING METHODOLOGY

For a successful analysis of surface deformations when excavating a small overburden tunnel in weak rock masses, it is necessary to study carefully all the parameters of the environment in which the construction of the tunnel is planned, which can affect the total height of the surface settlements, and take them into account when assessing the settlement and defining the excavation methodology.

2.1. Engineering-geological characteristics of the rock mass in the "Kobilja Glava" tunnel excavation zone

The geological basis of the wider area of the "Kobilja Glava" tunnel is built by clasts of the Neogene, i.e. Upper Miocene and Quaternary formations (Q) represented by eluvial-deluvial sediments. As part of the Miocene complex, that is, the so-called the Koševo series of geological substrate consists mainly of marls, marly clays, siltstones, weakly bound clayey sandstones, gravels, weakly bound conglomerates and very rarely carbonaceous clays with thin carbonaceous interlayers. Miocene clasts have pelitic-psamitic structures and thin-layered to laminated texture.

As a whole, the rock complex of the geological base of the terrain is "covered" with a Quaternary eluvial-deluvial cover. The eluvial-deluvial cover is isolated on the slope part of the terrain. The structure of this cover includes yellow-brown clays, difficult to putty with the presence of small particles of different diameters.

In the surface zone, there are humus-dusty-sandy clays with the presence of dark brown organic matter. Excavation of the left tunnel tube from the entrance portal of the "Kobilja Glava" tunnel was completely carried out within upper Miocene clastites, i.e. within marl and fine-grained sandstones. During the engineering geological mapping of the initial step of the left tunnel tube, two zones were distinguished that differ in lithological composition, physical-mechanical characteristics and color.

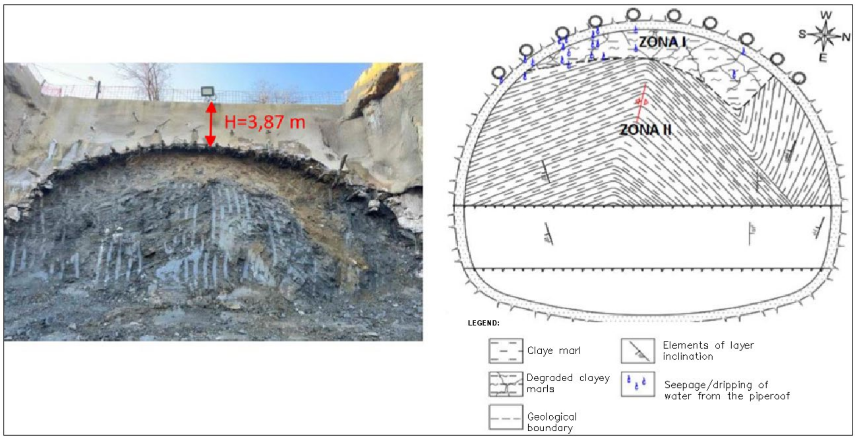

Figure 3. Geological mapping of the initial step of excavation of the left tunnel tube – km. 3+546.20

In the lithological zone I, which was positioned in the upper part of the top heading, there were marly clays with a transition to clayey marl and degraded yellow-brown clayey marls. The feature of the mentioned lithological complex within zone I is the vertical and lateral alternation of the mentioned lithological members without any regularity. The lithological structure of zone II was represented by clayey marls - gray marls. The mentioned materials are characterized by highly variable and uneven physical-mechanical properties that are very prone to change under the influence of tunneling works. Figure 3 shows the appearance of the open face with geological characteristics at the very beginning of the left tunnel tube excavation from the entrance side.

Dip amount of layers measured at the temporary entrance portal of the left tunnel tube were 160/220 (left wing of the anticline); 357/510 (right wing of the anticline) and 195/710 (fall elements in the right side of the top heading).

Regarding the above, a wide range of measured values of the spatial orientation of the layering is visible, which is a consequence of the tectonic activity of a plicative character. Therefore, by measuring the spatial orientation of the deposit, it was established that there was a slanted asymmetrical anticline at the head of the temporary entrance portal of the left tube.

On the analyzed section during the excavation of the tunnel, more or less uniform engineering-geological conditions were established, which can be seen on the longitudinal geological profile, Figure 4.

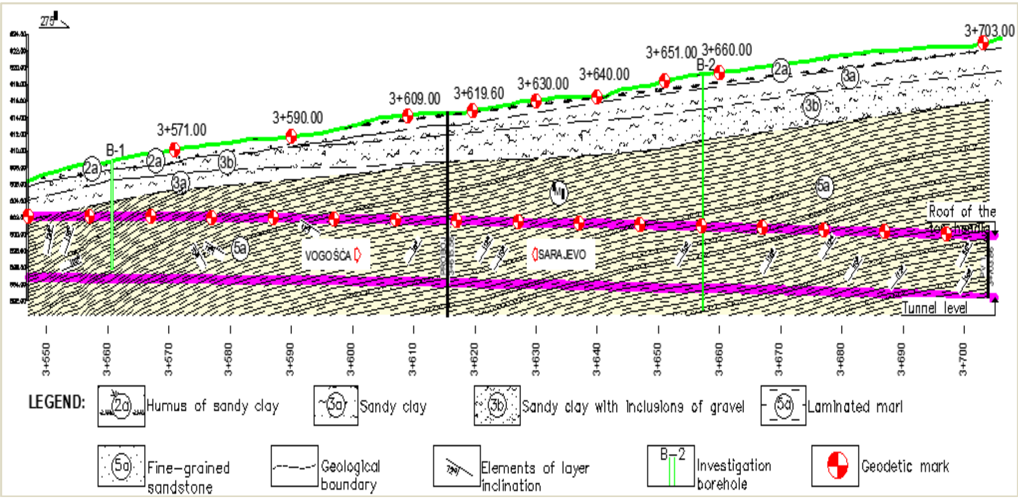

Figure 4. Longitudinal geological profile from the entrance into the left tunnel tube to the first cross passage

2.2. Methods of predicting surface deformations

In the past period, many studies have been dedicated to better predicting the response of the soil to stress changes resulting from the construction of tunnels and defining demanding solutions for these problems [9]. Due to the nature of the tunnel excavation process, the excavated shape of the tunnel will always be larger than the designed shape resulting in a real series of displacements towards the cavity.

This phenomenon is described by the term "soil loss" or, more commonly used, "volume loss" (Peck, 1969). Peck (1969) defines surface settlement as radial in the direction of the cross-section and longitudinal deformation on the axis of the tunnel (Figure 5).

These two settlements proved difficult to separate, and therefore, estimates of volume loss were determined by considering plane strain. In other words, tunneling is a three-dimensional problem. For purposes of analysis, some studies have split this into two, two-dimensional problems (Figure 5). These are transverse settlements (plane x-z, which is called the stress plane) and longitudinal settlements (plane y-z).

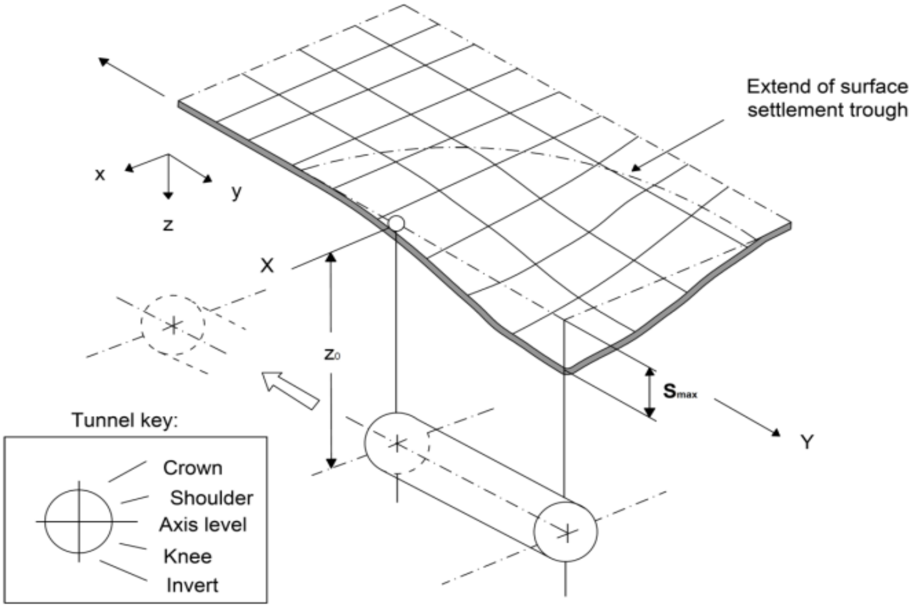

Figure 5. Settlement above the advancing tunnel direction [10]

There are various methodologies for accurate prediction and management of maximum surface settlement, including empirical, analytical, numerical and artificial intelligence methods [11].

Traditional approaches often rely on empirical or analytical equations, which are developed through engineering experience and theoretical assumptions. Empirical methods for estimating surface settlement caused by tunneling are generally consistent with engineering practice and measured field data. They provide a rough estimate of soil settlement with permissible precision. In other words, empirical methods are proposed simple mathematical equations based on measurements collected in the field. These formulas can be used to approximately determine the surface subsidence and calculate the ground displacement at any point in a certain area. The first form of surface settlement above the underground tunnel construction was analyzed by Martos (1958) [3]. Morts suggested that a normal distribution curve can well represent the shape of the surface settlement as shown in Figure 5. Peck (1969) extended the research and showed that the Gaussian curve is suitable for fitting tunneling-induced ground settlement. He analyzed settlement data from many tunnels as well as mining projects and found that the settlement curve was roughly symmetrical above the tunnel's vertical axis. A semi-empirical approach is adopted to calculate soil deformation based on Eq:

$$S_V = S_{max} \exp\left(-\frac{x^2}{2i^2}\right) \quad (1)$$

Where:

- S_v - settlement value,
- S_{max} - theoretical maximum settlement on the center line of the tunnel,
- x - lateral distance from the center line of the tunnel,

- i - lateral distance from the center line of the tunnel to the point of inflection in the Gaussian distribution curve.

Empirical formulas in predicting tunneling-induced surface settlement can still be used for preliminary estimation [12]. However, in a more complex situation, it is suggested to perform a finite element analysis and soil structure interaction study [13]. Numerical simulations such as the finite element method (FEM) and the finite difference method (FDM) provide a more sophisticated approach. These simulation techniques can be adapted to a wide range of soil parameters and capture the complex interaction between soil layers and tunnel walls.

Tunnel construction is three-dimensional in nature and time-dependent. Compared with 3D analysis, the application of 2D simulation can simplify the constitutive model and save calculation time. However, 2D analysis requires that the effect of 3D tunneling as a result of volume loss be taken into account [14].

Numerical methods are widely used in geotechnical engineering. It is a theoretically more realistic and rigorous method for estimating surface subsidence [15].

With the possibility of considering various relevant parameters, such as nonlinear soil behavior, soil heterogeneity, groundwater level, and soil-tunnel interaction, the numerical method has proven to be an effective approach to tunnel analysis. However, the numerical method has been criticized for its effectiveness because the simulation models are time-consuming and sensitive to boundary conditions [16].

The accuracy of numerical methods depends on the grid size and the choice of failure criteria model. In addition, the excavation process is difficult to simulate, and the results obtained sometimes differ from those obtained by field measurement [17].

2.3. Excavation of the left tunnel tube from the entrance in the low overburden zone

Before the start of the excavation of the left tunnel tube, the right tunnel tube was excavated with an embedded primary support over 300 meters, and based on the measurement of total deformations in the right tunnel tube, its stability was confirmed, which established that the right tunnel tube could not affect the excavation of the left tunnel tube.

On the basis of all available data collected by geodetic monitoring of movement during the excavation of the right tunnel tube and the results of geological mapping of the frontal slope, the following supporting measures were proposed for the start of the excavation of the left tunnel tube on the entrance side of the Kobilja Glava tunnel [18], namely:

1) Step of excavation 0,5 m;
2) Anchors IBO R51-630 (Ø51mm), 530 kN in following distrubition:
    a) top heading l=6,0m 6/4;
    b) bench l=6,0m 4/6;
3) Thickness of shotcrete layer (C25/30) is 5 cm for excavation face;
4) One layer of the wire mesh of type Q257 for excavation face (if necessary);
5) Protection of the excavation face with 8 pieces of IBO anchors (Ø32mm) l=12.0 m and lap length of 4m, 250 kN.

6) The thickness of the shotcrete in the top heading, bench and primary invert (C25/30) is 30 cm;
7) Two layer of the wire mesh of type Q257;
8) Lattice girder PS 95/20/30;
9) The thickness of the shotcrete (C25/30) for the primary invert in the top heading is 25 cm;
10) Two layer of the wire mesh of type Q257 for the primary invert;
11) For the protection of the excavation face installation of one row of steel pipes (Ø114mm, L=12,0m, e=40cm, with 4,0 m overlap, 29 pieces).
12) Installation of the elephant's foot at the connection of the top heading and the bench for the first 8 meters of the excavation, and further installation will be defined as necessary.

In order to reduce deformations of the surrounding material and the primary support, the following technological sequences must be respected (Figure 6):

- The maximum distance between the top heading and primary invert is 2 m ;
- The maximum distance between the top heading and bench is 10 m;
- The maximum distance between the bench and primary invert is 4 m.

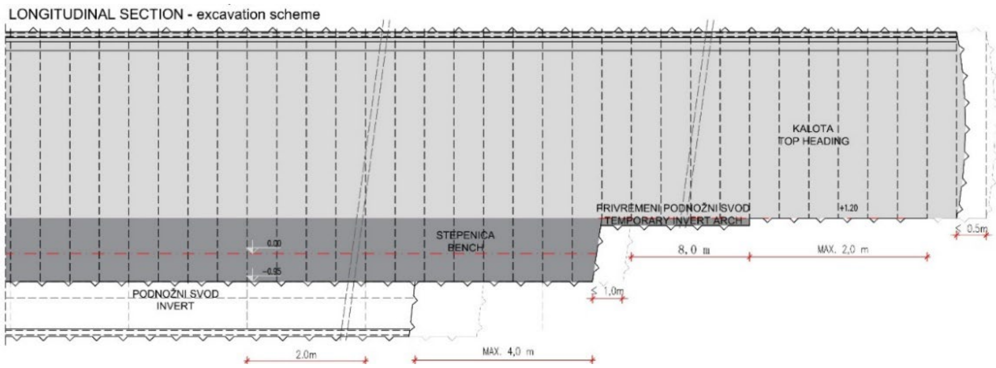

Figure 6. Longitudinal section - excavation scheme

Before the start of the excavation, a profile was installed to monitor the settlement on the surface above the left tunnel tube at distances of approx. 10 m (Figure 7). Three marks were installed on each profile (one along the axis of the tunnel, and the other two at a distance of 10 m from the axis, left and right).

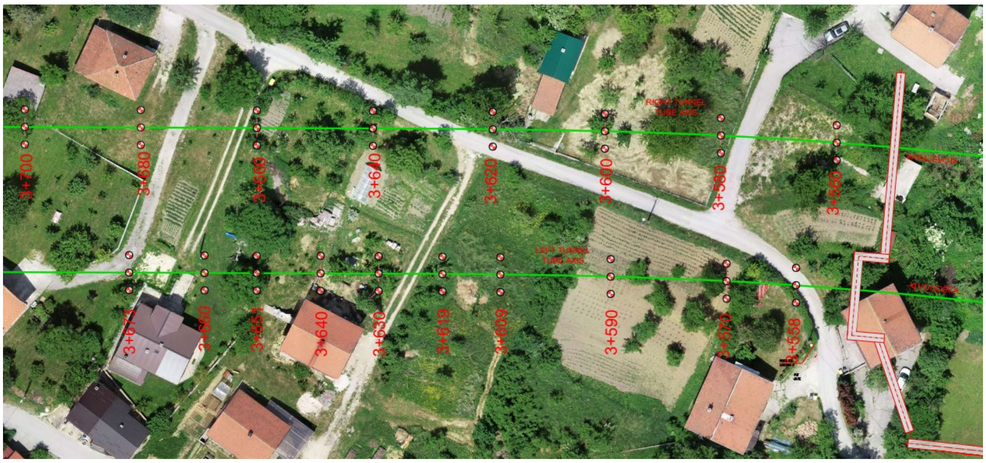

Figure 7. Arrangement of geodetic marks on the surface above the left tunnel tube

Excavation of the left tunnel tube on the entrance side starts from km: 3+543,202 where the height of the overburden was 3.87 m (Figure 3). During the excavation and installation of the primary support, there were no deviations in observing the technological sequences prescribed by the geotechnical mission (Figure 6).

During the excavation, geodetic measurements (observation) of deformations on the surface and in the tunnel were carried out daily. On the entrance side, the excavation was stopped at km: 3+615.56 due to the appearance of large deformations on the surface of the ground above the excavated part of the tunnel, which exceeded the forecasted values several times.

The main reason for stopping the excavation is reflected in the appearance of inevitable deformations on the surface of the ground in front of the excavation face, which can cause damage to residential buildings located at km: 3+630.00 and km 3+660.00. In order to reduce the impact of the tunnel on the surface of the field, it was proposed to excavate out the left tunnel tube from the cross passage number one towards the entrance to the km. 3+615.56 (Figure 8).

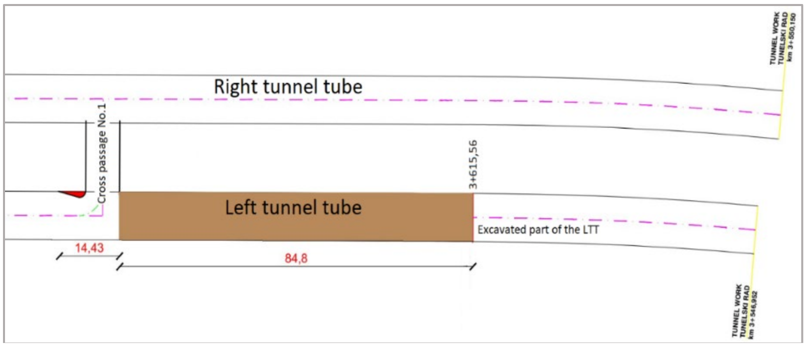

Figure 8. Situation view of the excavation of the left tunnel tube from the cross passage no. 1 to km. 3+615,56

Excavation of the left tunnel tube was carried out technologically after the excavation of cross passage no. 1 and the creation of a curve towards the exit while maintaining the same (smaller) profile as in cross passage no. 1. After reaching the full excavation profile of the left tunnel tube, the excavation was stopped towards the exit.

Given that a technological curve was made when entering the left tube from cross passage no. 1, the curve was reprofiled and the excavation of the left tunnel tube from cross passage no. 1 to km. 3+516.56 (Figure 8) in the length of 84.80 m. During the excavation, geodetic measurements and observation of deformations on the surface above the excavation were carried out daily.

3. THE RESULTS

Before the start of the excavation, an assessment of the surface settlement above the axis of the left tunnel tube was made for the given geological conditions and assumed support elements using the finite element method in the PLAXIS program (2D analysis that takes into account the 3D effects of tunnel excavation) [18]. The obtained results showed that maximum displacements on the surface above the axis of the left tunnel pipe are expected up to 3.2 cm (Figure 9).

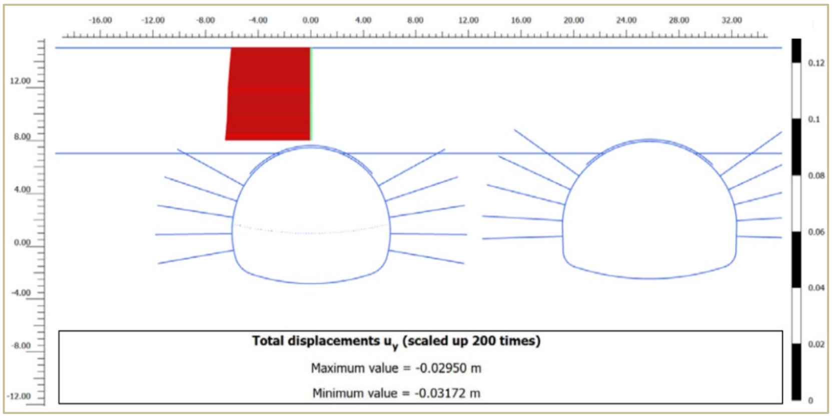

Figure 9. Presentation of the results of the settlement assessment expected above the left tunnel tube from the entrance, using the program PLAXIS [18]

Optical methods were used to observe daily surface settlements during the excavation of the left tunnel tube from the entrance to the stop of the excavation (chainage km: 3+615.56), as well as during the excavation from cross passage no. 1 to the chainage km: 3+615.56. Table 1 shows the total surface settlement recorded by geodetic measurement above the excavated part of the left tunnel tube from the beginning of excavation on the entrance side to the moment when excavation was stopped (chainage 3+615,56).

Table 1. Results of measurement of total surface settlements above the excavated part of the left tunnel tube from the entrance to the km: 3+619,00

Chainage	Tunnel axis (mm)	Overburden height (m)
3+558,00	210,00	6,33
3+570,00	212,00	7,88
3+590,00	207,00	9,80
3+609,00	174,00	12,55
3+619,00	30,00	13,07

Table 2 shows the total surface setllements recorded by geodetic measurement above the excavated part of the left tunnel tube from the cross passage to the previously excavated part (chainage 3+615,56).

Table 2. Results of measurement of total surface settlements during the excavation of the left tunnel tube from the cross passage to km.3+615.56 in the low overburden zone

Chainage	Tunnel axis (mm)	Overburden height (m)
3+673,00	50,00	20,07
3+660,00	55,00	18,46
3+651,00	58,00	17,28
3+640,00	60,00	15,23
3+630,00	62,00	14,62
3+619,00	70,00	13,07

The total settlement of the surface above the left tunnel tube at chainage 3+619.00 is 100.00 mm, of which the recorded settlement of 30.0 mm occurred during the excavation from the entrance to the chainage 3+615.56 and the difference of 70.00 mm is the settlement during excavation from the cross passage to the connection point.

4. DISCUSSION

During the construction of the tunnel, the natural state of stress in rock mass in which the tunnel is being constructed is disturbed, which leads to potential settlements of the surface. Therefore, an appropriate assessment of the surface settlement above shallow tunnels is of great importance in the design of the tunnel, regarding all the essential parameters of the rock mass through which the tunnel is planned to be constructed.

The estimation of settlement that was performed using the finite element method (Figure 9) is many times smaller compared to the values measured on the surface above the left tunnel tube. Multiple measured displacements of surface settlement from the entrance to the stop of excavation at the chainage km: 3+615.56 compared to forecast values is the result of relaxation caused by tunnel excavation. The direction of the longitudinal movements occurring in front of the tunnel excavation face coincides with the direction of the terrain, Figure 10.

At the same time, the layer of water-permeable cover on which the structures are located rests on a layer of impermeable substrate - marl, which creates a suitable environment for the occurrence of sliding, as a result of which the settlements in front of the front were measured and over 50% of the total settlements at individual chainages, Figure 11.

Due to the coincidence of the direction of movement and the terrain, there was an increase in the influence of the excavation of the left tunnel tube on the surface deformations from the entrance to the stop of the excavation at the chainage km: 3+615.56. Changing the direction of the excavation of the left tunnel tube from the entrance side, and continuing the excavation from the cross passage no. 1 towards the entrance, canceled the influence of the deformation that occurs on the surface of the ground because the direction of longitudinal movements (longitudinal) is opposite to the extension of the ground. In this way, multiple surface settlements were reduced (Table 2), which are inevitable on the surface of the terrain due to tunnel excavation in the low overburden zones.

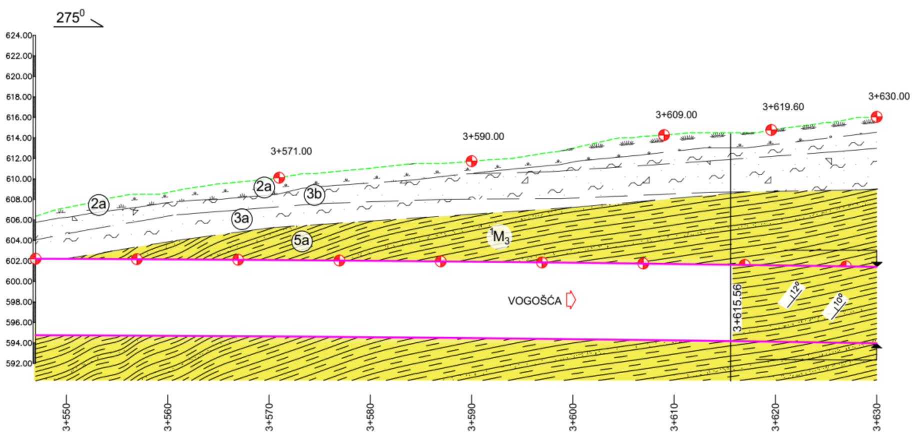

Figure 10. Longitudinal geological profile from the entrance to the stop of excavation on the entrance side

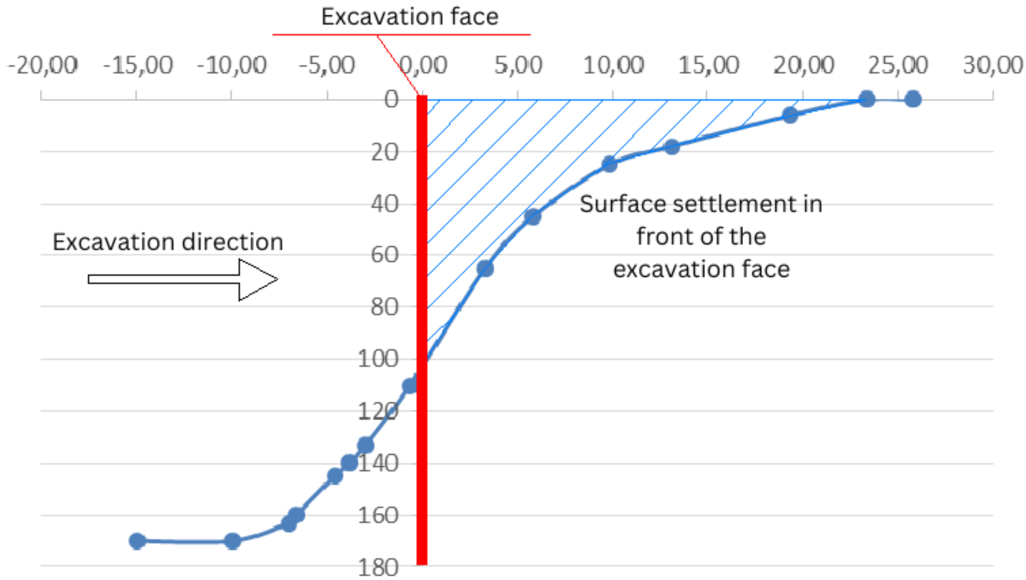

Figure 11. Results of measurement of total settlements on the surface, chainage km: 3+609,00

5. CONCLUSION

In narrower urban areas where significant construction works have been carried out during the construction of infrastructure and residential buildings, the soil is usually characterized by extremely variable and uneven physical and mechanical properties that are a direct consequence of the execution of these works, as well as natural factors with unfavorable physical and mechanical characteristics.

Anyone who carries out underground constructions is faced with solving a particularly complex problem, because compared to above-ground constructions, it is extremely difficult to determine in advance the basic design data for underground works, which is why the appropriate assessment of surface settlements above shallow tunnels is of great importance when designing each underground excavation.

The need for accurate assessment of surface settlements caused by tunnel excavation and potential damage to structures on the surface has led to increased interest in research into this problem.

However, when assessing soil settlement, it is not always easy to take into account all the necessary parameters that can significantly affect the total settlement on the surface above the tunnel excavation. The behavior of the soil when tunneling in incoherent or multi-layered soil is still a big unknown.

Therefore, when choosing an excavation method, care must be taken to ensure that the selected methods ensure a safe working environment and minimal surface settlements that will be in function of the geological and geotechnical properties of the rock mass, cross-section of the tunnel and applied excavation technologies.

REFERENCES

[1] Wang Donglin, Guo Xin, Jia Yusheng: **Analysis of Land Subsidence Deformation Caused by Urban Shallow-buried Tunnel Construction**. *Open Civil Eng J*, 2014; 8:, http://dx.doi.org/10.2174/1874149501408010219

[2] Hrestak Tomislav, Jaguljnjak Lazarević Antonia, Frgić Lidija**: Stress and strain analysis during the Sleme tunnel excavation**. *Technical gazette,* 22 (2015), 3; 703-709. doi: 10.17559/TV-20140530103847

[3] Gang Niu, Xuzhen He, Haoding Xu, Shaoheng Dai, **Tunnelling-induced ground surface settlement: A comprehensive review with particular attention to artificial intelligence technologies**. *Natural Hazards Research*, Volume 4, Issue 1, 2024, Pages 148-168, ISSN 2666-5921, https://doi.org/10.1016/j.nhres.2023.11.002

[4] Sharifzadeh Mostafa, Kolivand Farshad, Ghorbani Masoud, Yasrobi Shahaboddin: **Design of sequential excavation method for large span urban tunnels in soft ground – Niayesh tunnel**. *Tunnelling and Underground Space Technology* 35 (2013), 178–188.

[5] Chen Renpng, Zhang Pin, Wu Huaina, Wang Zhiteng, Zhong Zhiquan: **Prediction of shield tunnelinginduced ground settlement using machine learning techniques.** *Front. Struct. Civ. Eng.* 13 (6), 1363–1378., 2019. https://doi.org/10.1007/s11709-019-0561-3

[6] Terzaghi, K. **Geologic Aspects of SoftGround Tunnelling.** *Chapter 11 in Applied Sedimentation*, *P.D. Trask, ed., John Wiley and Sons,* Inc., New York. 1950, Pp. 193-209.

[7] **Glavni projekt izmjene projekta tunela „Kobilja Glava“ na I transverzali, od km 3+420.00 do km 4+180.00**, *Knjiga D, Mapa D.4 tunelski iskop*, projektant: IRGO Consulting d.o.o. & Lotus d.o.o., Sarajevo, Ljubljana, decembar 2023.

[8] **Civil Engineering and Development Department Catalogue of Notable Tunnel Failure Case Histories.** *Hong Kong Special Administration Region Government*, 2009.

[9] Loganathan N., Poulos G. Harry: **Analytical prediction for tunneling-induced ground movements in clays**. *Journal of Geotechnical & Geoenvironmental Engineering*, 1998, 124(9), 846.

[10] Attewell, P.B. and Yeates, J.B. **Ground movements and their effects on structures.** *In: tunnelling in soil., Surrey University Press, London,*1984, pp 132-215.

[11] Moghaddasi, Mohammad Reza, Noorian-Bidgoli Majid: **ICA-ANN, ANN and multiple regression models for prediction of surface settlement caused by tunneling**. *Tunn. Undergr. Space Technol*. 2018, 79, 197–209., https://doi.org/10.1016/j.tust.2018.04.016.

[12] Taylor, R. N. **Modelling of Tunnel Behaviour**. *Proceedings of the ICEGeotechnical Engineering*, 1998, 131(3), 127-132.

[13] Elmanan, A.M. Atta, Elarabi Hussein: **Analysis of surface settlement due to tunneling in soft ground by using empirical and numerical methods.** *The Fourth African Young Geotechnical Engineer's Conference* (4AyGEC'15), 2015, Casablanca, Morocco.

[14] Karakus Murat: **Appraising the methods accounting for 3D tunnelling effects in 2D plane strain FE analysis**. *Tunn. Undergr. Space Technol*. 22 (1), 2007, 47–56., https:// doi.org/10.1016/j.tust.2006.01.004

[15] Zhang Pin, Wu, Huai-Na, Chen, Ren-Peng, Chan, T.H.Tommy: **Hybrid meta-heuristic and machine learning algorithms for tunneling-induced settlement prediction: a comparative study**. *Tunn. Undergr. Space Technol*. 99. 2020, https://doi.org/10.1016/ j.tust.2020.103383

[16] Zhang Limao, Wu Xianguo, Ji Wenying, AbouRizk M. Simaan: **Intelligent approach to estimation of tunnel-induced ground settlement using wavelet packet and support vector machines**. *J. Comput. Civ. Eng*. 31 (2). 2017, https://doi.org/10.1061/(asce)cp.1943-5487.0000621

[17] Pourtaghi, A., Lotfollahi-Yaghin A. Mohammad: **Wavenet ability assessment in comparison to ANN for predicting the maximum surface settlement caused by tunneling**. *Tunn. Undergr. Space Technol*. 28 (1), 257–271. 2012, https://doi.org/10.1016/ j.tust.2011.11.008

[18] Hekić B. **Geotechnical mission G32, Proposal No. 2_rev., Proposal of supporting measures for the start of excavation of the left tunnel tube of the Kobilja Glava tunnel from the chainage km 3+543,202.** *IRGO Colsulting & LOTUS,* Sarajevo-Ljubljana, 2024.