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Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society

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Conditions géotechniques de la construction du tunnel “Debelo brdo” sur l'autoroute E-80: Nis-Merdare-Pristina (“Autoroute de la Paix”)

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ABSTRACT: The construction of the highway E-80 has begun in Serbia, which will represent the traffic hub of the Western Balkans and will be part of the main regional transport network of Southeast Europe. Its total length through Serbia is 77 km, and one part of the route is designed through a typical plain terrain, while a larger part of the route passes through hilly terrain. The construction of the tunnel “Debelo brdo” is planned partly in an open cut excavation with a length of 240 m, and partly with an underground excavation with a length of 190 m. The geotechnical conditions of tunnel construction in open cut excavation, and especially the geotechnical conditions of tunnel excavation, will be presented in the paper.

RÉSUMÉ: La construction de l'autoroute E-80 a commencé en Serbie, qui constituera la plaque tournante du trafic des Balkans occidentaux et fera partie du principal réseau de transport régional de l'Europe du Sud-Est. Sa longueur totale à travers la Serbie est de 77 km, et une partie de l'itinéraire est conçue sur un terrain plat typique, tandis qu'une plus grande partie de l'itinéraire traverse un terrain vallonné. La construction du tunnel „Debelo brdo“ est prévue en partie avec une excavation à ciel ouvert d'une longueur de 240 m et en partie avec une excavation souterraine d'une longueur de 190 m. Les conditions géotechniques de construction de tunnels en fouille à ciel ouvert, et notamment les conditions géotechniques de creusement de tunnels, seront présentées dans l'ouvrage.

Keywords: „Debelo brdo“ tunnel; temporary slopes; open cut excavation; tunnel excavation; piles.

1 INTRODUCTION

The construction of the E-80 Nis-Merdare-Pristina highway is of special economic and social interest for the Republic of Serbia. It represents the traffic hub of the Western Balkans and will be part of the main regional transport network of Southeast Europe (that's why it was called the "Peace Highway"). The total length of the highway is 77 km. The "Debelo Brdo" tunnel is located on the first 36.3 km long highway section. The construction of one tunnel tube with an approximate cross-section of about 85 m^2 is planned by the project. The height of the open part of the tunnel in relation to the pavement is about 8.3 m, while the structural height ranges from 10.9 - 11.9 m, not counting the protective support structure.

2 GENERAL GEOTECHNICAL CHARACTERISTICS OF THE TERRAIN

The geological structure at the location of the "Debelo brdo" tunnel consists of younger Neogene hilly terrains. The complex corresponds to the upper Miocene and lower Pliocene, so it is separated as a Mio-Pliocene complex of heterogeneous lithological composition. In the surface part, marly clays of the weathered zone dominate (in the tunnel zone, the thickness of the weathering crust is over 10 m), and the base consists of marls with rare layers of silt and fine-grained sand, while thinner layers of sandstone also occur occasionally. In the zone of the entrance portal of the tunnel, the occurrences of active sliding as well as conditionally unstable terrains, whose relief forms are characteristic of calmed landslides, have been determined, so that inadequate cutting could cause new instabilities (Rakic et al., 2019).

Along the route of the tunnel with a total length of 430 m, two geotechnical quasi-homogeneous zones were separated: GTZ-1 and GTZ-2. The first geotechnical zone (GTZ-1) represents the weathering crust of marls and sandstones dominated by silty marly clays. This area is in the overburden area above the tunnel, with a thickness of 10-13 m, and its border approximately follows the surface of the terrain. It is a material of hard-plastic to semi-hard consistent state with extremely high plasticity. When it is exposed to atmospheric influence for a long time, it easily disintegrates, crushes and crumbles. Within this geotechnical zone, the tunnel excavation will be carried out in an open cut excavation. The second geotechnical zone (GTZ-2) is built of clayey marl, locally silty-sandy, and represents the basic rock mass in which the complete underground excavation for the tunnel will be carried out.

Piezometer constructions were installed in two exploration boreholes, in which regular observations were made. The piezometric level ranged from 5.5 to 13.5 m, which indicates that water filtration is carried out down the slope, and as the morphology of the terrain is variable, the GWL ranges from 300 to 307 m. At the time of field investigation works, the groundwater level was approximately at the level of the tunnel or just below it.

Geotechnical longitudinal section of the terrain, with separated geotechnical zones, conditionally stable slope, forecast groundwater level, position of tunnel level and proposed method of excavation, is shown in Figure 1.

3 DEFINING PHYSICAL-MECHANICAL PARAMETERS

Laboratory tests have shown that the Mio-Pliocene clay-marly complex is extremely plastic material with a yield strength of over 110% in some samples.

These are materials with $I_c>1.0$, so the uniaxial compressive strength is usually $q_u>250$ kPa. However, occasional occurrences of sandstone laminae and thinner marl laminae (thickness 10-20 cm), as well as zones of slightly weathered marl, had a significant impact on the increase in uniaxial compressive strength. The tests were performed in accordance with the appropriate standard (SRPS EN 1926), but a non-standard method was also applied, which involved several cycles of unloading and reloading at lower values of axial pressure. For these reasons, a significantly wider interval of q_u values was determined, which ranged from q_u= 243–774 kPa (Figure 2).

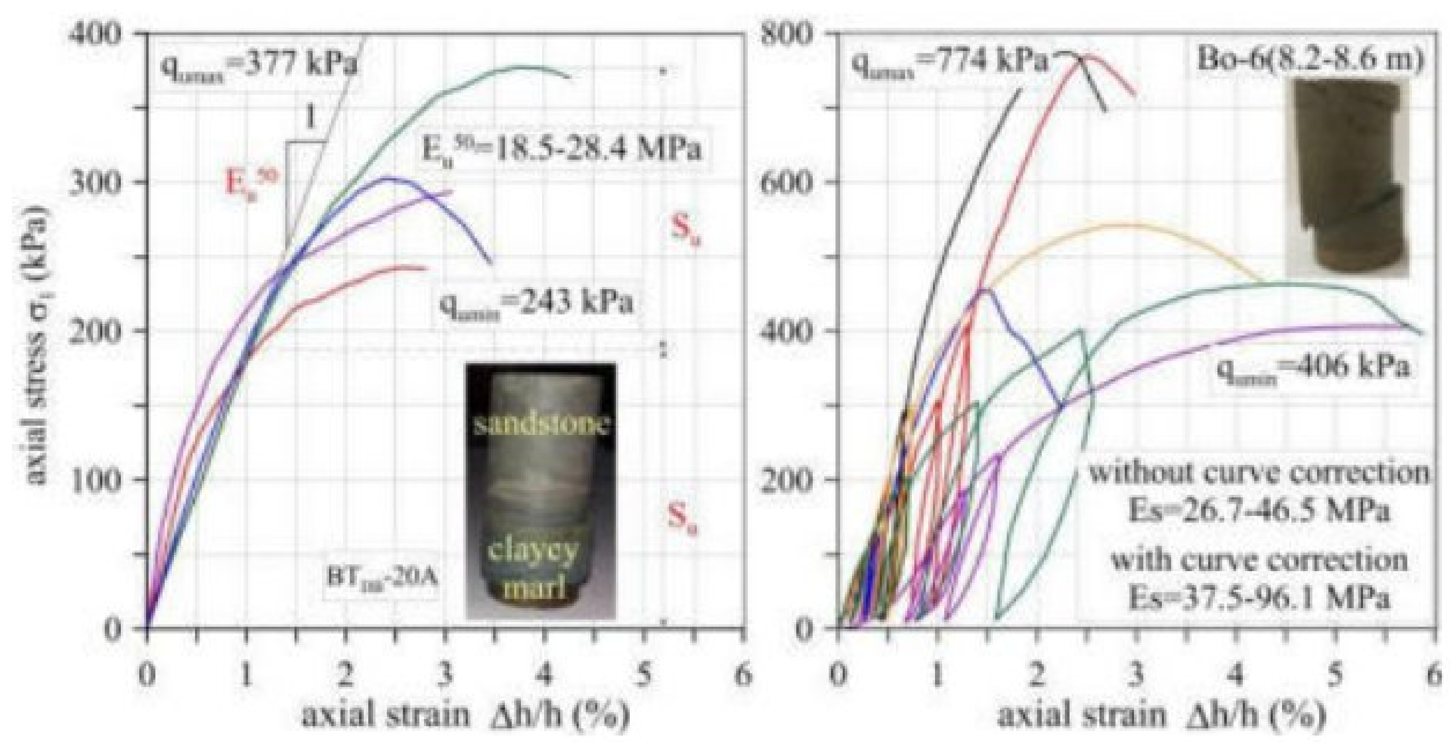

Figure 2. Characteristic diagrams for standard and non-standard uniaxial tests.

Due to significant heterogeneity of the environment, the value of undrained modulus of elasticity ranged in a very wide interval from E_s=26.7-95 MPa. In addition, the values of the undrained modulus of elasticity were also obtained based on correlations with the undrained shear strength (s_u) using the appropriate dependence and amounted to E_s=33.0-89.0MPa (Duncan and Buchignani,1976).

It should be noted that geophysical investigations were also carried out at the location of the tunnel, and that the values of the modulus of elasticity were obtained in the interval of E_s=35-82MPa.

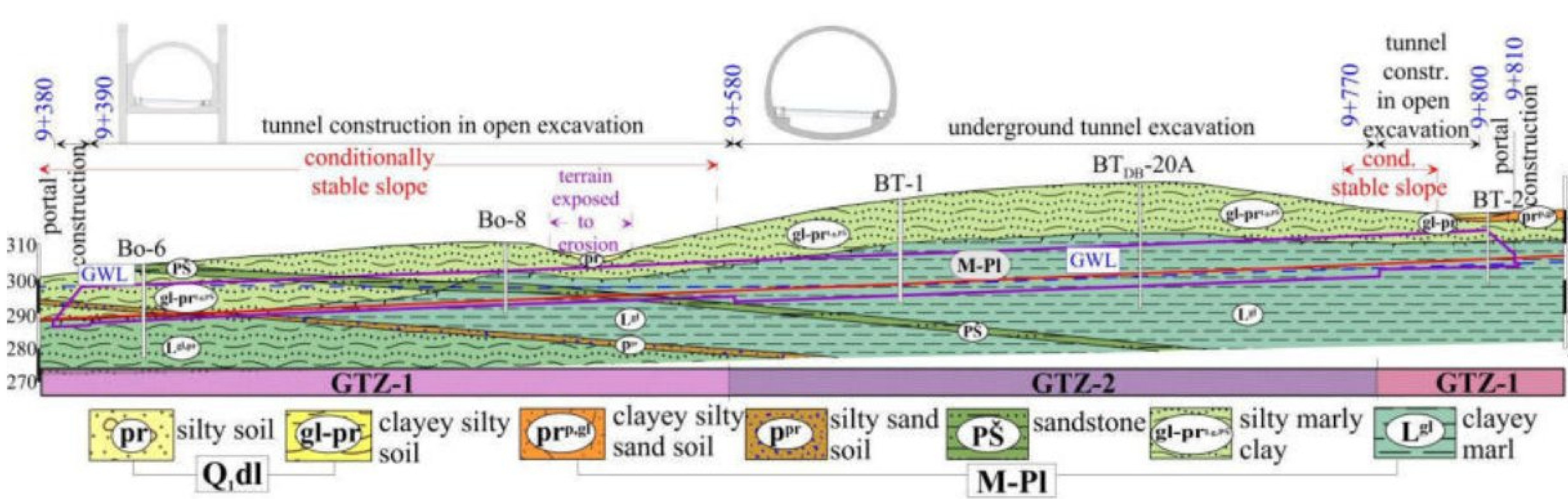

Figure 1. Geotechnical longitudinal section along „Debelo brdo" tunnel.

When it comes to shear strength parameters, geotechnical characteristics have shown that it is necessary to propose parameters for two different excavation systems. The first one refers to the case that underground works and protection of slopes with supporting structures are carried out quickly in a short time interval after excavation. In that case, it is proposed to use "critical" shear strength parameters, which are defined at the appropriate displacement value. In the case that the construction of the tunnel cannot be carried out in a short period of time, the use of residual shear strength parameters is proposed, due to the fact that an active landslide has been identified in the immediate zone of the tunnel.

It is characteristic that on the basis of oedometer tests, all samples showed swelling potential, regardless of the soil from which they were taken (silty marly clays-gl-pr^{Lg} or locally silty clayey marls-$L^{gl,pr}$). In some samples, the swelling stress was higher of σ_{sw}>300 kPa.

Based on the observation of the field conditions and the summary analysis of all laboratory tests, the proper values of the physical-mechanical parameters, which were used during the geotechnical analysis, were adopted (Table 1).

Table 1. Proper values of physical-mechanical parameters.

GT layer	Physical-mechanical parameters						
	γ kN/m³	c' kPa	φ' (°)	c_r kPa	φ_r (°)	E_s MPa	E_r MPa
(gl-pr^{Lg})	18.5	28	18	12	10	20	60
($L^{gl,pr}$)	19	40	20	12	11	25	75

4 GEOTECHNICAL CONDITIONS OF TUNNEL CONSTRUCTION

4.1 Tunnel construction on open excavation part

For the construction of tunnels in an open excavation, securing with piles is provided. Geotechnical analyses were conducted in two phases. In the first phase of the excavation, the top parts of the slope were covered, while in the second phase, the excavation for the construction of the tunnel structure was analysed.

The first phase involves the formation of a temporary slope and a working plateau for the installation of piles. As it is a conditionally stable slope, the analysis was first performed using the residual shear strength parameters, for the designed slope inclination of 1:2, and on that occasion the safety factor Fs<1.0 was obtained. Therefore, it was suggested that the excavation be carried out with one berm 4 m wide at a height of about 5 m in relation to the elevation of the working plateau. However, in the case that earthworks and slope protection with a supporting structure are carried out in a short period of time without the influence of atmospheric changes, the analysis was also performed with "critical" parameters of shear strength, so that a significantly higher factor of safety was obtained (Fs=1.747). Within the second phase of excavation, protective piles will be carried out secured by the brace beam.

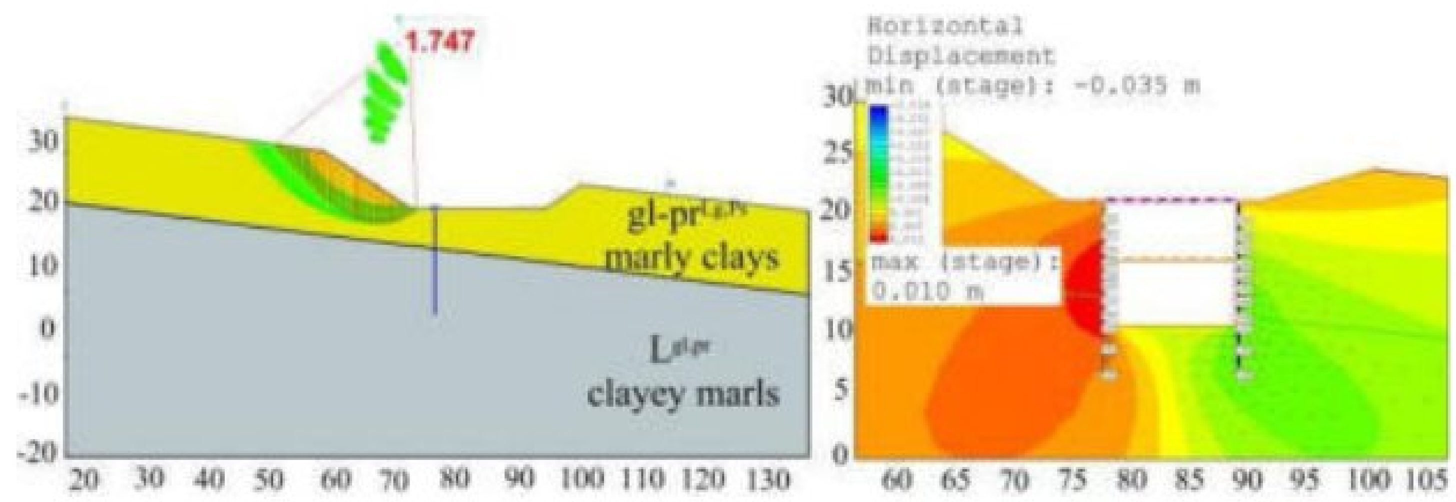

Figure 3. Geotechnical stability analyses (stability of temporal slope and horizontal displacement of piles).

4.2 Tunnel construction on underground excavation part

The underground excavation of the tunnel will be carried out according to the principles of NATM (New Austrian Tunnelling Method). Excavation is planned with phased development of the profile: calotte, abutments, and then the inverted arch. For the protection of the calotte excavation, a primary support is provided: pipe-roof shield, ribs, reinforcement mesh and layers of shotcrete. To prevent excessive settlements, an elephant foot, installation of micro piles and anchors, and construction of a temporary inverted arch are provided. To secure the excavation in the area of abutments and inverted arch, a construction made of ribs, reinforcement mesh, layers of shotcrete and anchors is planned. Also, at the level of the abutments, the construction of the second elephant foot, the installation of the second row of micro piles and the second temporary inverted arch is planned.

For the stress-strain analysis in different phases of construction in the tunnel support and the surrounding rock mass, tunnel stability calculations were performed using a 2D model with the indirect introduction of 3D effects. Simulating tunnel excavation and supporting was carried out in nine steps. By adopting certain assumptions about the properties, condition and behaviour of the rock masses (Coulomb-Moore failure criterion, different values of the modulus of elasticity for loading E_s and unloading E_r, the pipe shield is simulated with a material with equivalent properties, relaxation stress in the excavation phase by λ=0.3, was simulated by progressive softening of the rock, after installing the pipe shield, the stresses in the rock mass were relaxed to λ=0.7), geotechnical analyses were conducted and the values of certain parameters were obtained, which are shown in Table 2.

Table 2. Values of parameters used during the simulation of the impact on the tunnel face excavation.

N_s	λ_{cr}	r_p	λ_0	r_{p0}	K_o
9.8	0.41	24.7	0.7	10.1	0.65

r_p-radius of the plasticization zone for the case of unsupported excavation

r_{p0}-radius of plasticization zone for the case of relaxation λ_o = 0.7

Verification of the tunnel support was performed using the software package *Phase2*. The phases of model creation followed the usual construction practice (excavation and application of security measures). The calculation results indicate that the excavation will cause significant displacements of the rock mass in the zone of the tunnel excavation, and certain displacements will be manifested on the surface of the terrain as well (Figure 4). Also, the plasticization zone of the rock mass occurs up to the surface of the terrain. The biggest stress-strain changes occur in the stage of the calotte excavation, under the pipe shield, in the area of the elephant feet. For these reasons, the possible effects of lowering the pipe shield to the floor of the calotte were considered on a modified model, without the elephant foot and micropiles at the level of the calotte. Calculation models with calculation results, which indicate the effects achieved by modifying the design solution, are shown in Figure 4.

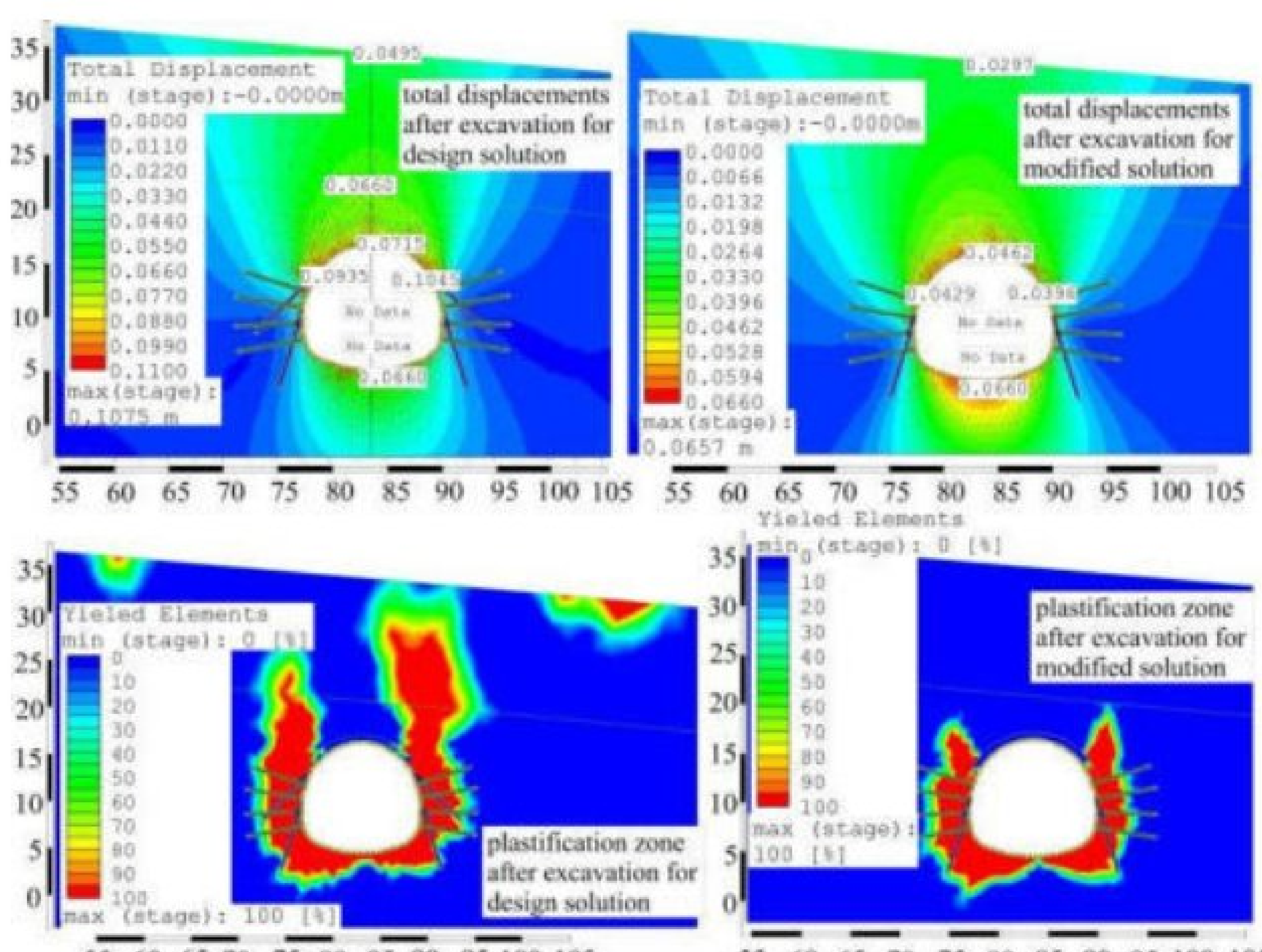

Figure 4. Stress-strain analyses for design and modified solution.

It is proposed that the excavation of the calotte be carried out by phase development of the face side, with the formation of a supporting body.

Summary of all displacements for the proposed design solution, as well as the solution with the proposed modification is shown in Figure 5.

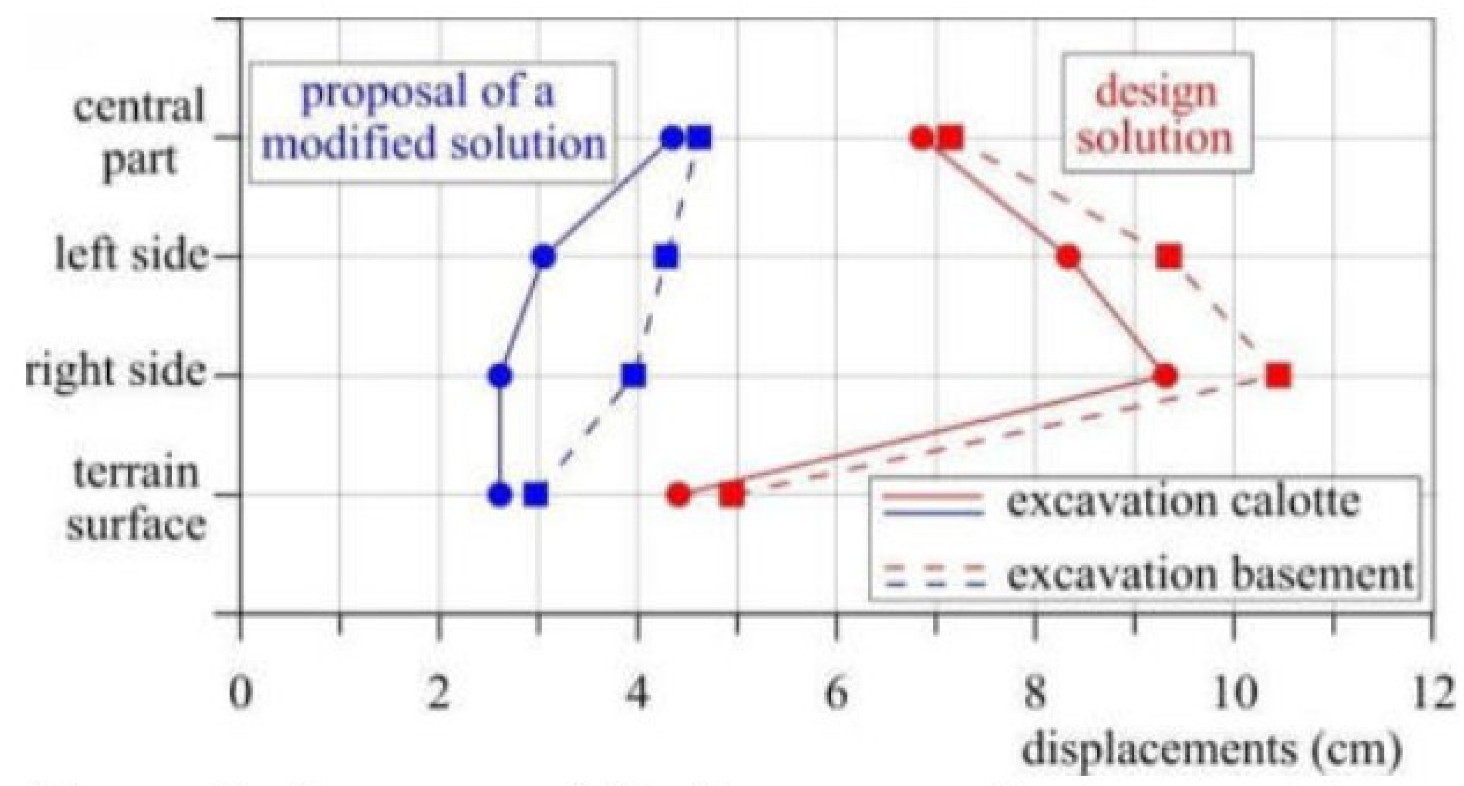

Figure 5. Summary of displacements of calotte and invert arch for design and modified solution.

5 CONCLUSIONS

For the construction of the "Debelo brdo" tunnel, the geotechnical conditions related to the excavation of the tunnel in the open excavation, and in the part of the underground excavation, were analysed separately.

For the construction of the tunnel in the open excavation, it is planned to secure the excavation by installing piles. Geotechnical analyses have shown that temporary slopes, above the level of the working plateau, can be performed with the proposed slope inclination of 1:2, but with a 4 m wide berm at a height of 5 m above the working plateau.

When it comes to the underground excavation, for the proposed design solution, geotechnical analyses obtained significant displacements of the rock mass, which are also manifested on the surface of the terrain. For these reasons, the analysis was also performed for a partially modified solution with an extended pipe shield, but without the application of the elephant foot and micropiles at the calotte level. With this variant, significantly smaller deformations around the tunnel excavation and negligible deformations on the terrain surface were obtained.

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