# The Cenkova tunnel construction with intermediate reinforced concrete wall

# Gradnja predora Cenkova z vmesno armiranobetonsko steno

Jakob Likar[1, *]

[1]University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva cesta 12, SI-1000 Ljubljana, Slovenia

*Corresponding author. E-mail: jakob.likar@ntf.uni-lj.si

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**Abstract:** Basic design of the twin road tunnel with two traffic lanes with central reinforced concrete wall is a consequence of the short length of the tunnel and existing geological and geotechnical conditions, which build surrounding area and available space for motorway construction. The ground space, where tunnel was built, mainly consists of soil layers with clayey sands, silts and clays with different consistence. Besides the construction was carried out in difficult ground, the built of tunnel done step by step, included different construction phases. At the same time, permanent adaptation of excavation process and primary lining installing were adjusting to real geotechnical conditions. The central gallery with reinforced concrete wall was constructed first. Design of the construction is relatively stiff, because primary lining which was made by reinforced shotcrete at the both sides of the central reinforced concrete wall and connected with it. All construction elements were proved by numerical analyses which were carried out with 3D Finite Difference Method included space effect. The results of the geological observation and geotechnical measurements during construction of the central gallery and both tunnel tubes had shown that static resistant of the construction is adequate to all existing loads. During construction, the measurement on the surface had shown minimal movements which mean that method of construction was adequate.

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*Original scientific paper*

**Izvleček:** Zasnova gradnje dvocevnega dvopasovnega predora z vmesno armirano betonsko steno je posledica kratke dolžine objekta, geološko-geotehničnih značilnosti hribin tega območja ter velikosti prostora, ki je na voljo za avtocestno povezavo. V pretežni meri se gradi na območju, ki je na nekaterih predelih plazovito ali pogojno stabilno, z zemljinskimi materiali, kot so zaglinjeni peski, melji in gline v različnih konsistentnih stanjih. Čeprav je gradnja potekala v zahtevnih hribinskih razmerah, je bila faznost gradnje upoštevana ob stalnem prilagajanju načina izkopa in primarnega podpiranja v dejanskih razmerah. Najprej je bil zgrajen vmesni rov z armirano betonsko steno, ki se je obenem uporabljal kot raziskovalni rov, kar je omogočilo natančno geološko in geotehnično spremljavo z namenom, da se ugotovijo dejanske geotehnične razmere gradnje. Konstrukcijska zasnova objekta je toga, saj sta obe primarni oblogi v bočnem in talnem delu na obeh straneh spojeni z vmesnim AB-stebrom. Vsi konstrukcijski elementi predora so bili predhodno statično preverjeni z uporabo metode končnih diferenc v prostoru (3D), tako da je bil upoštevan t. i. prostorski učinek. Geološko-geotehnična spremljava je pokazala, da je v statičnem pogledu načrtovana predorska konstrukcija zadoščala obtežbam, ki so bile posledica prerazporeditve napetostnih stanj med samo gradnjo. Prav tako so bili izmerjeni vplivi na površino nad predorom minimalni, kar pomeni, da je bil način gradnje ustrezen v danih hribinskih razmerah in kakovosten.

**Key words:** twin two lance road tunnel, reinforced concrete wall, tunneling in soil ground, geostatic 3D analysis, geotechnical measurement

**Ključne besede**: cestni dvocevni dvopasovni predor, gradnja predora v zemljinskih tleh, vmesna armiranobetonska stena, geostatične 3D-analize, geotehnične meritve

## INTRODUCTION

Tunnel Cenkova is part of a motorway section between Maribor and the Hungarian border, subsection Sp. Senarska–Cogetinci. The distance between the tunnel axes is only 12 m, so for the first time in Slovenia, the structure of a tunnel with a middle pillar was designed. The length of the right tunnel tube is 370 m and length of the left tube is 363.80 m. The area above the tunnel is inhabited, so a number of analyses were carried out during the design. Figure 1 shows the tunnel layout.

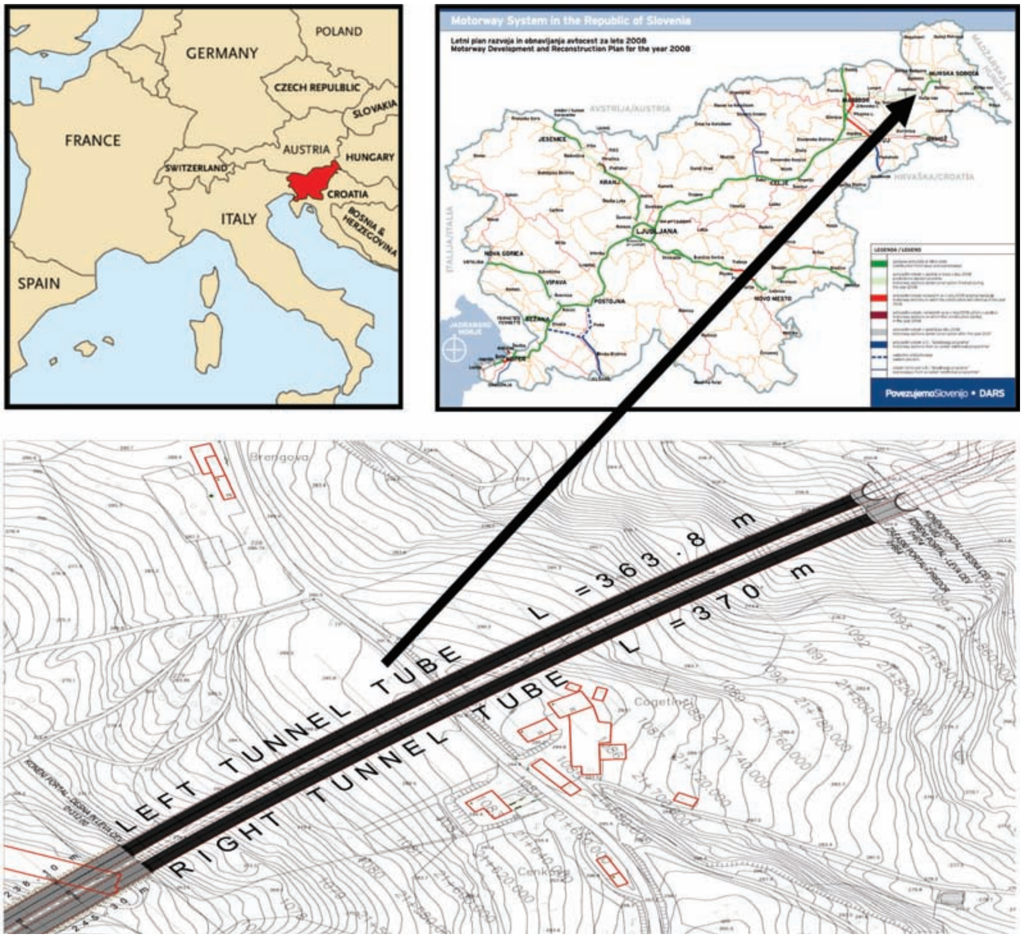

**Figure 1.** Layout of the tunnel Cenkova

## Geological conditions in the tunnel foreseen in the tender

Upper Miocene clay, silt, sand, gravel and poorly lithified sandy marl were foreseen in the tunnel alignment (Tender, 2006). On the surface a few meters thick Plio-Quaternary layer of sandy clay, sand and gravel was foreseen (Figure 2). This region tectonically belongs to Slovenske gorice with fractures of direction NW-SE. Geotechnical characteristics of the sediment material from the tender are presented in Table 1.

## Construction remarks

The small distance between the tunnel axis dictates that first a middle pillar

**Table 1.** Geotechnical properties of the sediment material foreseen in the Tender (2006)

| Chainage | Volume weight $\gamma$ /(kN/m$^3$) | Uniaxial Compressive Strength $q_u$ /kPa | Young Mod. $E$ /MPa | Cohesion $c$'/kPa | Angle of friction $\varphi$'/° |
|---|---|---|---|---|---|
| 21866-21750<br>(eastern portal) | 19 | 200 | 110 | 2 | 19 |
| 21750-21545<br>tunnel | 19 | 400 | 250 | 18 | 27 |
| 21545-21512<br>(western portal) | 19 | 200 | 105 | 2 | 18 |

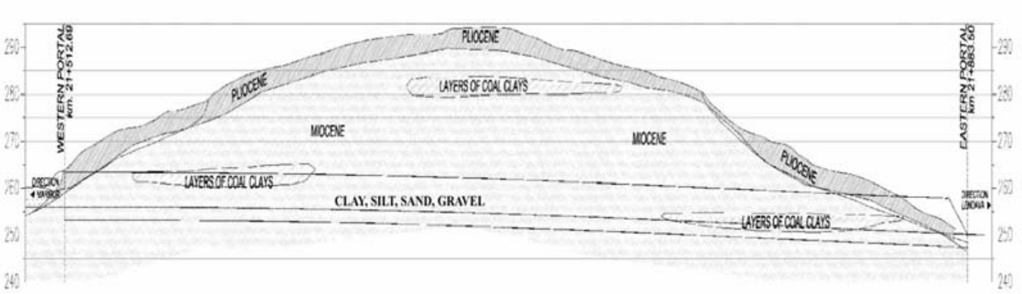

**Figure 2.** Tender geological longitudinal profile in the tunnel Cenkova (Tender, 2006)

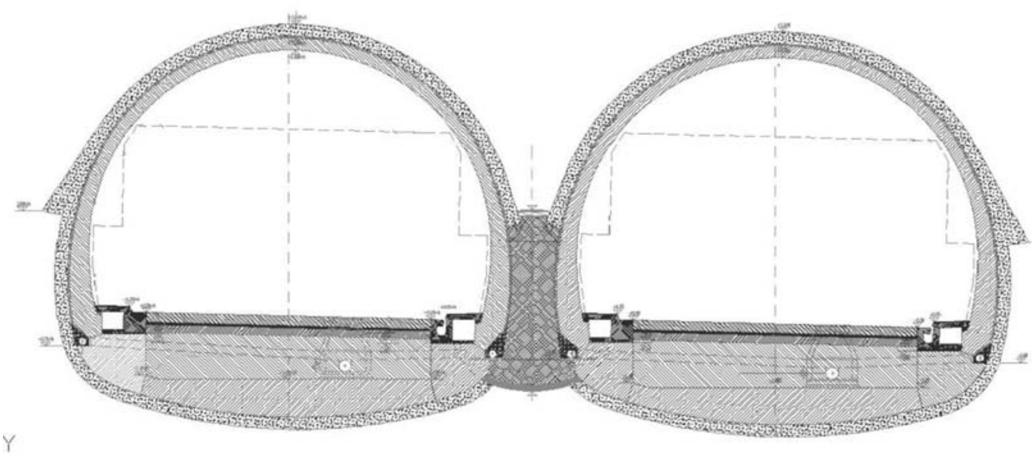

**Figure 3.** Characteristic cross-section of the tunnel Cenkova

must be constructed to insure the stability of the structure during the excavation phases and later during the exploitation. The pillar dimensions were defined according to the expected loads and available space for the construction. Height of the middle pillar is 3.50 m and the minimum width is 1.05 m. The excavation profile of the middle gallery, where the middle pillar is constructed, is about 16 m$^2$. Figure 3 shows the typical profile of the tunnel Cenkova.

To ensure the stability of the structure during the excavation phase and provide primary support, the shotcrete, installed during the top heading excavation, was placed on the top of the middle pillar in the left and right tubes. During the phase of the invert excavation, the shotcrete invert made a closure of the primary structure. Especially important are joints between top heading shotcrete and the top of the middle pillar and the joints of the abutment of the middle pillar and the tunnel shotcrete invert. The geometry of the structure is set to transfer the load from the left and right tubes, through shotcrete primary lining, to the middle pillar as a way to prevent overturning of the middle pillar in case of eccentric loading (excavation of one tube at the time) and the concentration of the stress in the middle pillar, which would cause the overloading of the structure.

## CONSTRUCTION PHASES

First a middle gallery was constructed from the east portal to approximately half of the length of the tunnel. After that, the excavation of the middle gallery started from the west side and from the current face of the middle gallery toward the east abutment for the pillar and the middle pillar was constructed. Next the excavation of the top heading of the left and right tubes was carried out, with 16–32 m delay between excavation faces of the top heading in the left and right tubes. In this way the structure remained stable and the middle pillar was eccentrically loaded for the period not exceeding 14 days. The design provided the bench and invert excavation after finishing the top heading excavation in the left and right tubes.

Figure 4 shows the excavation phases as follows:

- Phase 1: Excavation of the middle gallery
- Phase 2: Abutment and middle pillar installation
- Phase 3: Excavation of the top heading in the left tube and support installation
- Phase 4: Excavation of the top heading in the right tube and support installation
- Phase 5: Excavation of the bench and invert in the left tube and support installation
- Phase 6: Excavation of the bench and invert in the right tube and support installation
- Phase 7: Inner lining and abutment installation
- Phase 8: Final construction of the tunnel

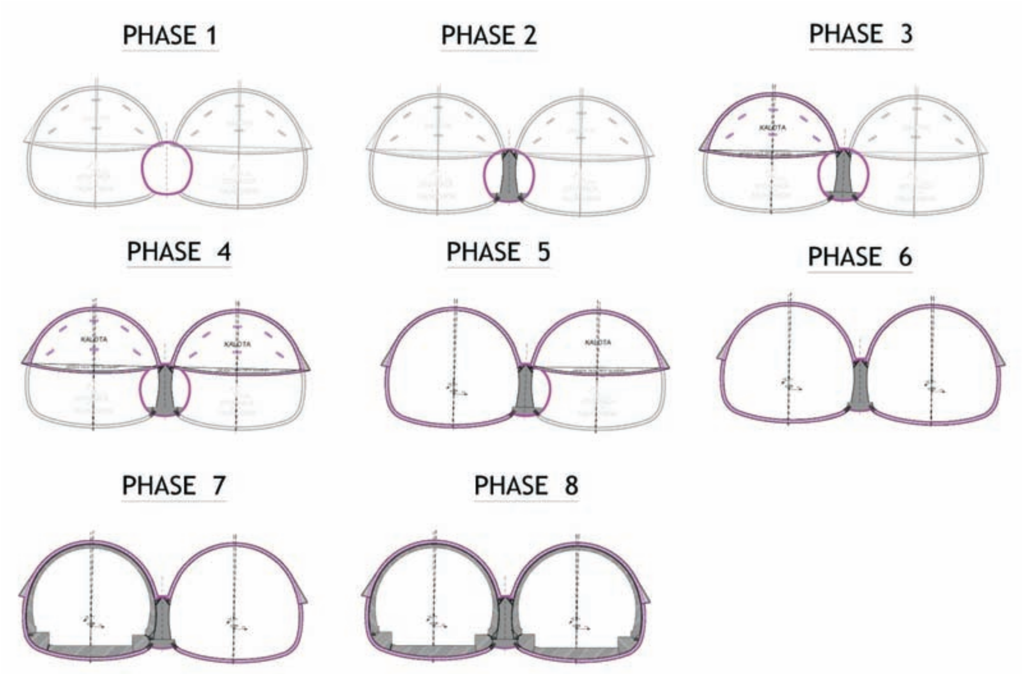

**Figure 4.** Phases of the tunnel construction

## SUPPORT MEASURES

For the primary support in the main tunnel tubes a 30 cm thick and in the middle gallery a 20 cm thick reinforced shotcrete layer was foreseen in the Tender with steel arches and two layers of wire mesh, but actually the quantity of the shotcrete for the primary tunnel lining was increased by a factor 2.1 in some sections, due to unavoidable geological overbreaks. For the excavation of face support, the IBO anchors were installed, if required. To prevent overbreaks of sandy - silty sediments, installation of steel bars instead of steel laggings, was provided. Because the excavation phases in the top heading and the invert were at a reasonable distance, temporary shotcrete invert arch was provided in some sections to stabilize the top heading until the excavation of bench and invert.

## NUMERICAL ANALYSIS

During the design phase, a number of analyses were carried out to determine the behavior of the structure and the influence of the tunnel excavation on the surface objects. Because 3D effect of the tunnel excavation should be important, one of the analyses was carried out using *FLAC*$^{3D}$ (Itasca 2006).

The *FLAC*$^{3D}$ analyses should provide the following parameters:

1 Expected deformation and loading of the support elements.
2 The effect of the tunnel excavation on the surface objects.
3 Loads in the middle pillar in case of eccentric loading (only one tube excavated at the time) and final loading.

## Mesh geometry

The stability of this type of structure highly depends on the details like excavation phases, support installation and joints between the shotcrete and the middle pillar. As a result, detailed mesh geometry around the tunnel structure area is required. The mesh must allow the surface settlement calculation so the mesh must be created to the top of the surface in such way that boundary conditions don't affect surface deformation results in the objects area.

To take these requirements into account, mesh of the area between chainages 0+460 and 0+535 e.c. 75 m long was created. Figure 5 shows the mesh geometry of the tunnel structure. Note that the surface of the mesh matches surface geometry. The mesh is then 75 m long, approximately 75 m high and 150 m wide. To set the number of elements to allow relatively fast calculation, a 5 m long excavation step is chosen. The model consists of approximately 50,000 elements. The geometry allows the simulation of construction phases 1 to 6.

## Support considered for the numerical analysis

For the support, only the shotcrete has been taken into account as shown in Figure 6. The shotcrete has been simulated using shell elements, with properties and dimensions shown in Table 2.

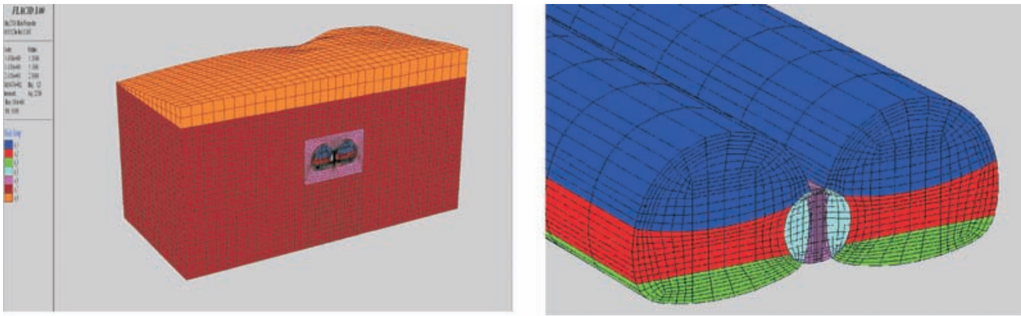

**Figure 5.** Input geometry

**Table 2.** Properties of the tunnel support used in the numerical simulation of tunnel construction.

| Object | Type | Elastic modulus (MPa) | Thickness (m) |
|---|---|---|---|
| Middle gallery | Shell elements | 3000 | 0.2 |
| Left & right top heading, bench & invert | Shell elements | 3000 | 0.3 |
| Temporary invert in top heading, left & right tube | Shell elements | 3000 | 0.2 |

**Table 3.** Simulation of the tunnel construction sequences

| Object | Task | Steps | Comment |
|---|---|---|---|
| Middle gallery | Excavation & support | 15 | Support (shell elements) is installed 1 step (5 m) behind the excavation face. |
| Middle pillar & abutment | Installation | 1 | Middle pillar and abutment consist of finite difference elements. |
| Excavation & support of the left top heading | Excavation & support | 15 | Support (shell elements) is installed 1 step (5 m) behind the excavation face. Support consists of shells in top heading and temporary invert.<br>Shells, installed as the middle gallery support, are deleted at area of middle pillar-top heading support joints. |
| Excavation & support of the right top heading | Excavation & support | 15 | The construction sequence is the same as in the previous sequence. Support (shell elements) is installed 1 step (5 m) behind the excavation face.<br>Support consists of shells in top heading and temporary invert. Shells, installed as the middle gallery support, are deleted at area of middle pillar-top heading support joints. |
| Excavation & support of the left bench and invert | Excavation & support | 15 | Support (shell elements) is installed 1 step (5 m) behind the excavation face. Support consists of shells in bench and invert. Shells, installed as the middle gallery support, are deleted at area of middle pillar-invert support joints. |
| Excavation & support of the right bench | Excavation & support | 15 | The construction sequence is the same as in the previous sequence. Support (shell elements) is installed 1 step (5 m) behind the excavation face.<br>Support consists of shells in bench and invert.<br>Shells, installed as the middle gallery support, are deleted at area of middle pillar-invert support joints. |

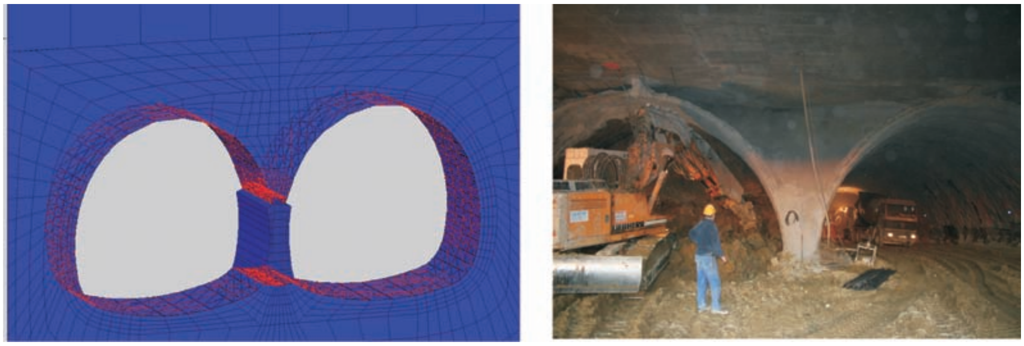

**Figure 6.** Support of the tunnel (shell element)

## SIMULATION OF THE TUNNEL CONSTRUCTION SEQUENCES

Simulation steps generally follow the tunnel construction phases from 1 to 6. The excavation sequences are presented in Table 3. All together 76 steps were carried out. At each step the prescribed unbalance force was reached.

## RESULTS OF THE NUMERICAL ANALYSES

### Calculated tunnel deformation and ground loading of the support

Deformations occurring after the middle gallery excavation, reached values of approximately 1.5 cm in the middle gallery top heading. The surface deformations were minor. Deformations after excavation of the left tube top heading reached values of approximately 4 cm. A similar level of deformations was measured after the right tube top heading excavation and the increase of the deformation in the left tube because of the right tube excavation was not considerable.

Excavation of the bench and the invert in both tubes caused the deformation of several centimeters in the invert, but it did not significantly affect the deformations in the top heading. The deformation contours around the tunnel structure are presented in Figure 7.

Moments, axial and shear forces did not exceed the limit values, except at the joint between shotcrete and the middle pillar. Thus reinforcement was provided in that area.

### Calculated Surface deformation

Surface deformations after the middle gallery excavation were negligible. The final calculated surface deformation reached a value between 3–4 cm above the middle gallery axis. Under the objects, the deformations reached values of about 1.5 cm. Most of these deformations were consequences of

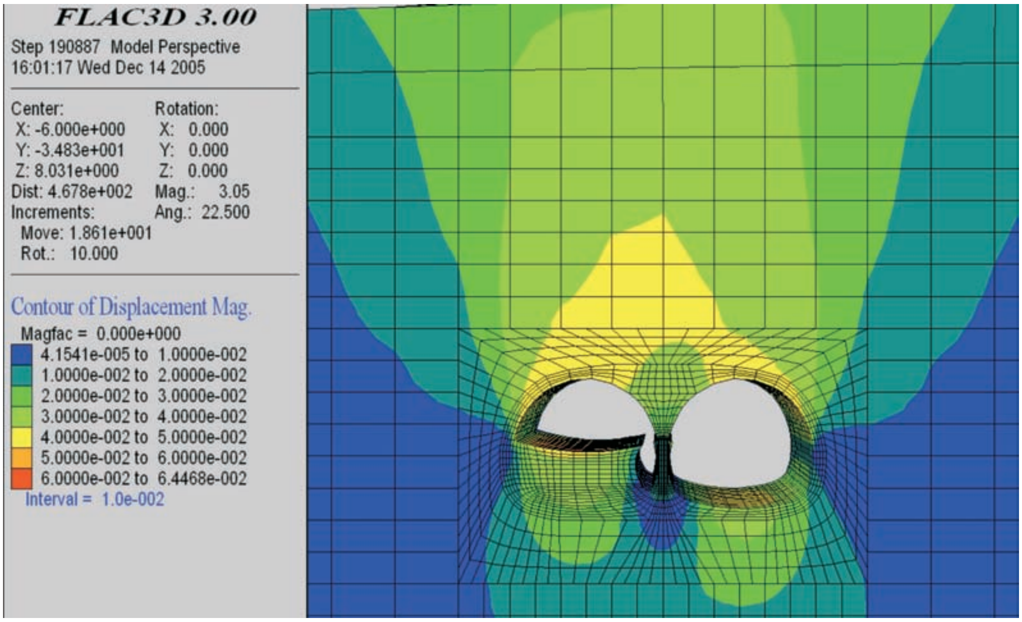

**Figure 7.** Deformations around the tunnel (after left tunnel tube top heading excavation finished)

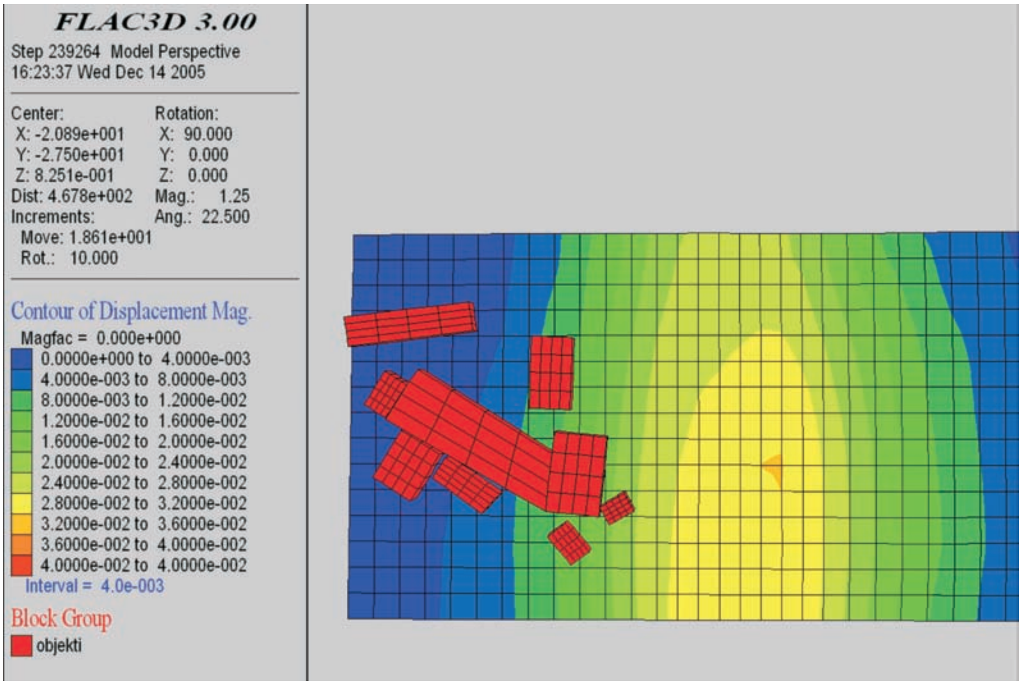

**Figure 8.** Calculated surface displacement

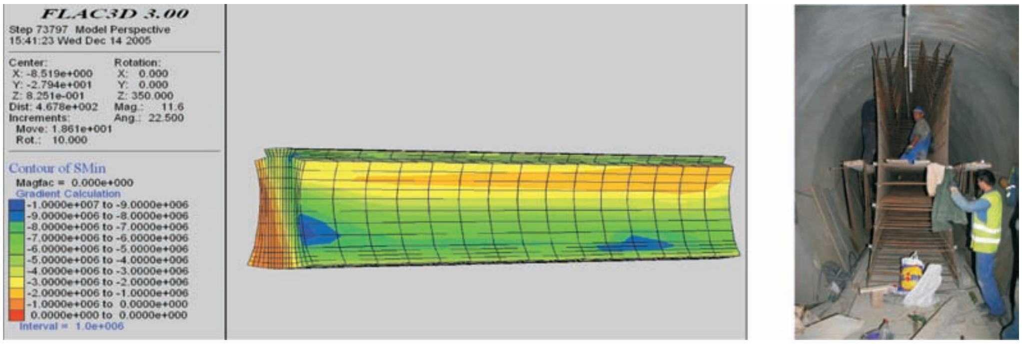

**Figure 9.** Contours of stresses SMin (excavated one tube only)

top heading excavation of the left and right tubes.

The deformations reached the objects when the excavation face was approximately 30 m away. The deformation field on the surface is shown in Figure 8. Note that elements which show the objects position are not a part of the simulation.

## Simulation of the middle pillar loading

Figure 9 shows the stress state in the middle reinforced concrete wall after eccentric loading (excavation of only left tunnel tube). Maximum compressive stress in the pillar is approximately 10 MPa. About 1/3 of the middle pillar on other side is practically unloaded. Maximum tension stress in the middle pillar reaches values of about 0.5 MPa. The maximum stress reached values approximately 15 MPa after the tunnel was fully constructed. All values were below the limit values.

## GEOLOGICAL CONDITIONS OBSERVED DURING THE TUNNEL EXCAVATION

Miocene sediments in the tunnel alignment were composed of sand, silty sand, clayey sand, silt, sandy silt, clay and clayey silt. Figure 10 shows a section of interpreted geological longitudinal profile of the left tunnel tube on the chainages between 21740 and 21780. In clayey – silty layers also thin layers (up to 0.5 m thick) of black lignitified organic material were found too. General inclination of the layers was SE; 140/10. Normal gravitational fractures were found mainly in the region of both portals, which were formed due to the creeping soil slope. Two main groups of cracks were found with inclinations: SWW; 200–260/60–80 and SES; 120–170/55–65. Occasionally also cracks with inclinations: NW; 300–340/45–85 and NE; 22–72/80 occurred.

One possibility of overbreak occurrences was in the connection excavation with water filled layers of sand and in similar cases. Actually, the water was present locally only in the form of water drops where water did not exceed 0.05 l/s.

Two main geotechnical behavior types (BT) of sediments were found during the excavation of unsupported ground (Elea-iC, 2008). Behavior type BT3 (Figure 11b) indicates the regions where shallow shear overbreaks due to the burden, in combination with overbreaks due to the gravity and due to the discontinuities could occurred, while BT8 (Figure 11a) indicates the regions where a flow of sediment material with no cohesion or very low cohesion value could

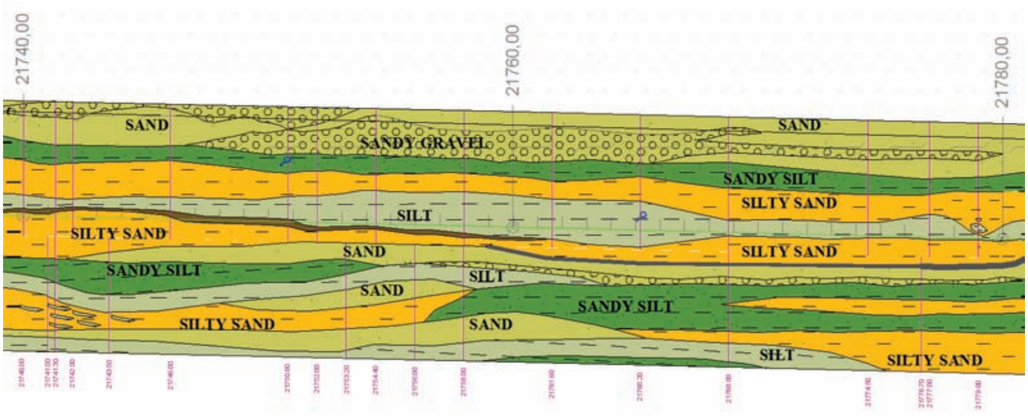

**Figure 10.** Actual geological longitudinal profile of the left tunnel tube on the chainages between 21740 and 21780 (Elea iC 2008)

**Figure 11.** Flow of sand from the ceiling of the top heading (BT8) in the right tube at the ch. 21672 (a) and the top heading in the right tube at the ch. 21659 (b), which indicates consequences of shallow shear overbreak due to discontinuities (BT3) on the right side of the excavation face.

occurred. Regions with behavior types in the middle gallery, left and right tunnel tubes are presented in Figure 12.

Very low cohesion of the sand layers and intensity of secondary stress states around tunnel tubes were caused several geological overbreaks of volume 4–60 m$^3$ occurred during the excavation of the eastern part of the middle gallery and both main tunnel tubes in the area of the portal.

These overbreaks occurred in spite that the primary tunnel lining was installed on time. Unavoidable overbreaks sometimes continued also during the shotcrete installation, in the phase before the shotcrete got adequate compressive strength. The fact is, that foreseen cohesion values of the sediments on the 60 % length of the tunnel (chainages between 21545 and 21750 in the Table 1) were substantial higher (*c'* = 18 kPa, *φ'* = 27°) than those measured in the laboratory in the sediment samples from this part of the tunnel (*c'* = 0–10 kPa, *φ'* = 35°–38°), which means that in these parts unpredictable physical conditions were encountered. For this reason, the excavation methods and the primary tunnel lining were adjusted to the actual geotechnical conditions. Therefore, the tunnel excavation

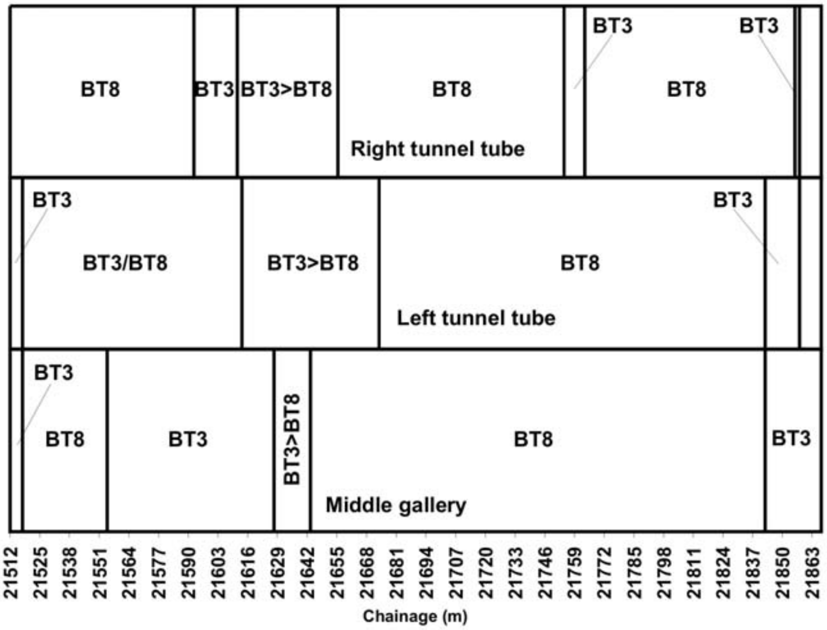

**Figure 12.** Behavior types (BT) in the middle gallery, in the left and right tunnel tube. BT3 > BT8 indicates that the main type is BT3, subordinated by BT8. BT3/BT8 means BT3 mixed with BT8 (Elea iC 2008)

was performed in several phases. In spite that overbreaks occurred during the tunnel excavation, actual displacements in the tunnel did not exceed foreseen deformation tolerance.

## MEASURED DISPLACEMENTS IN THE TUNNEL CONSTRUCTION

Method of measuring displacement of the measuring points installed in the primary

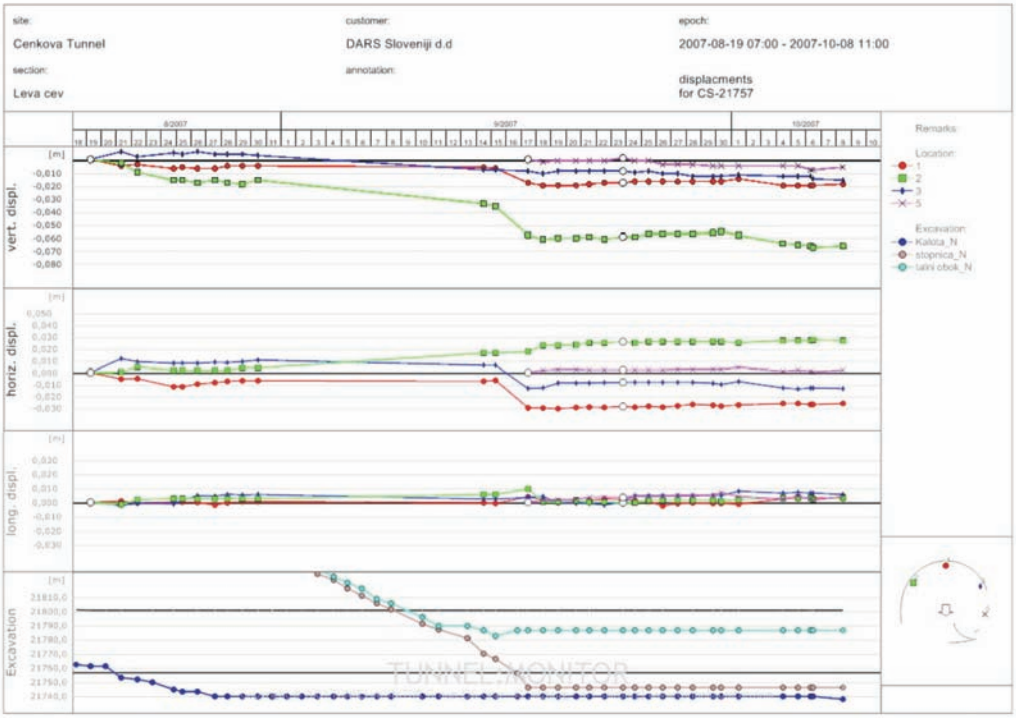

**Figure 13.** Diagram of measured displacements in the left tunnel tube at the chainage 21757 (Elea iC, 2008)

**Figure 14.** Tunnel Cenkova in phase of construction and after it on operation

lining based on geodetic instruction used special automatic theodolite. In different location in the tunnel tubes including central gallery, the measures were taken. Maximal vertical displacements in the top heading of the middle gallery was measured up to 4.6 cm. Maximal horizontal movements did not exceed 2.2 cm.

Average value of maximal vertical displacements in the top heading of the left tunnel tube was 4 cm. In the Figure 13 diagram of displacements versus time is shown for the left tunnel tube on the chainage 21757.

Average value of maximal vertical displacements in the top heading of the right tunnel tube was about 4 cm. Maximal vertical displacements in the top heading of the right tunnel tube of up to 13.3 cm were measured on the chainages 21520. Maximal horizontal displacements in the top heading of the right tunnel tube of up to 5.9 cm were measured on the chainage 21532 In spite that many geological overbreaks occurred during the tunnel excavation, actual maximal displacements in the tunnel did not exceed foreseen deformation tolerance, which indicates that the method of construction was adequate.

## COMPARISON BETWEEN CALCULATED AND ACTUAL DEFORMATIONS

The measured values of deformations in the tunnel did not exceed the calculated values. The typical deformation level after tunnel excavation was from 4 cm to 6 cm, which is a good fit to the calculated results. Surface deformation was also below calculated results based on 3D model. During the tunnel construction and after it, no deformation on the houses on the surface, caused by tunnel construction, have not been detected.

## CONCLUSION

- Tunnel Cenkova is the first tunnel in Slovenia constructed as a two-tube tunnel with a middle pillar as part of the structure in the soft soil ground (Figure 14).
- The geological and geotechnical conditions with sediment layers are relatively demanding. The tunnel is constructed in an inhabited area, which needs special attention and continued control of deformations in the tunnel and on the ground surface.
- Because of this, during the design some additional calculations and analysis were carried out, including *FLAC*$^{3D}$ numerical analyses, which answered questions about the middle pillar loading. The level of possible deformations in the tunnel structure and on the surface was calculated as well. These numerical analyses indicate that calculated deformations are in good agreement with measured deformations in the tunnel.

- In spite that many geological overbreaks occurred during the tunnel excavation, actual maximal displacements in the tunnel did not exceed foreseen deformation tolerance, which indicates that the method of construction was adequate.

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