Some Tunnel Construction Sequences in Carboniferous Soft Rocks Analysed by Rheological Model

Evgen Dervarič[1], Jakob Likar[2], Brane Merhar[3]

[1]Velenje Coal Mine, Partizanska 78, SI-3320 Velenje, SLOVENIA
[2]University of Ljubljana, Faculty for Natural Sciences and Engineering, Askerceva 12, 1000 Ljubljana, SLOVENIA; E-mail: jakob.likar@ntf.uni-lj.si
[3]IRGO, Institute for Mining, Geotechnology and Environment, Slovenceva 93, 1000 Ljubljana, SLOVENIA

Received: November 17, 2004 **Accepted:** December 10, 2004

Abstract: The usage of underground structures is increasing which is the reason that in many cases construction takes place in heavy geological geotechnical conditions. Due to this, the appropriate constitutive equations describing the time dependent reactions of the rocks with signification rheological properties, is necessarily to be applied. The excavation of the tunnel Trojane had run through distinctive rheological rocks with variable geotechnical properties. The construction process was modelled with *PLAXIS 3D tunnel program*. Input parameters were determined by 3D back analyses with Soft-Soil-Creep (SSC) constitutive material model, which takes into account rheological phenomena. 3D development of stress-strain fields during the tunnel excavation was performed to show major stress-strain changes in the surrounding rocks and support elements. Analyses with SSC material model was also made to show how the excavation of the top heading influences on development of deformations ahead of excavation. The calculations showed, that during excavation of the top heading substantial deformations are developed ahead of the top heading. Good agreement between measurement and calculated movements were obtained.

Key words: underground structures, geological geotechnical conditions, road tunnel, finite element method, 3D analyses, support elements, surface ground movements.

Soft soil creep material model

The SSC material model was developed on the basis of oedometer tests, which enable us to observe the relatively quick development of deformations in the primary consolidation phase in most soils and soft rocks. The primary phase is followed by a secondary consolidation or creep phase, which can last much longer. This secondary phase contributes an important part of the deformation and can cause material failure. The SSC model is an upgrade of the one-dimensional logarithmical model, which is written in incremental form, and also includes the creep observed in oedometer tests. It was designed for a 3D stress state, with consideration of the Modified Cam Clay (MCC) model, and concepts of viscoplasticity of materials (BRINKGREVE & VERMEER, 2001). The generalized form of the material model is displayed below:

$$\dot{\varepsilon} = \bar{D}^{-1}\dot{\sigma} + \frac{\dot{\varepsilon}_v^c}{\alpha}\frac{\partial p^{eq}}{\partial \bar{\sigma}} = \bar{D}^{-1}\dot{\sigma} + \frac{\mu^*}{\alpha\tau}\left(\frac{p^{eq}}{p_p^{eq}}\right)^{\frac{\lambda^*-\kappa^*}{\mu^*}}\frac{\partial p^{eq}}{\partial \bar{\sigma}} \tag{1}$$

Where $\vec{\dot{\varepsilon}}$ is Strain vector, $\vec{\dot{\sigma}}$ is Stress vector and $\vec{D}$ is Elastic Matrix.

$$p_p^{eq} = p_{p0}^{eq} e^{\left(\frac{\varepsilon_v^c}{\lambda^*-\kappa^*}\right)} \quad \text{or} \quad \varepsilon_v^c = \left(\lambda^*-\kappa^*\right)\ln\frac{p_p^{eq}}{p_{p0}^{eq}} \tag{2}$$

p_p^{eq}	Preconsolidation stress	κ^*	Modifed swelling index	λ^*	Modified compression index
p^{eq}	Plastic potential function	μ^*	Modifed creep index	ε_v^c	Volumetric strain caused by creep

GEOLOGICAL AND GEOTECHNICAL TUNNEL CONSTRUCTION CONDITIONS

The double tube – double lane Trojane tunnel, with its length of 2900m, is the longest tunnel on the highway route between Ljubljana and Celje. It is also the longest double tube tunnel in Slovenia.

The tunnel excavation was carried out under extremely difficult conditions, in low bearing rocks. The rocks had a very heterogeneous primary structure and composition, and many fracture zones that intersected the tunnel tube. Geotechnical properties of the rock were variable along the tunnel, tube and often deviated from the values defined in the laboratory test. The cleavage and layering of the rocks were especially unfavourable, because they often dipped into the excavation area, which resulted in lowering of the stability of the excavation space. During the excavation, some special characteristics of the appearing rocks were ascertained, which classified them as rheologicaly extremely sensitive.

The tunnel excavation was carried out under the guidelines of the New Austrian Tunnel Excavation Method (NATM), which enables real-time adaptation of support measures with regards to the actual geological conditions. The excavation was carried out in B2, C2 and C3 categories (Austrian classification ÖNORM B 2203), with regards to the geotechnical rock characteristics and height of the overburden. The category SCC (low overburden category) was applied in the tunnel sections under the Trojane village and infrastructure objects. In those sections, the overburden was just 20 to 40m. Such sections comprised 700m of the total tunnel length.

Table 1. Input parameters for numeric analyses (Vukadin, 2001; Merhar, 2004).

	Volume mass, γ (kNm^{-3})	Cohesion, c (kPa)	Angl e of internal friction, Φ (°)	Modulus of elasticity, E (MPa)	Poisson Rati o, ν (/)	Modified creeping index, μ^* (/)	Modified compression index, λ^* (/)	Modified swelling index, κ^* (/)
Sandstone	25	40	32	200	0.25	/	/	/
Siltstone	24	30	32	120	0.33	/	/	/
Claystone	24	30	26	65	0.33	/	/	/
Tectonic clay	24	10	27	18	0.33	/	/	/
Tectonic ally remoulded claystone and siltstone	24	28	26	8	0.33	$3.3.10^{-4}$	$8.3.10^{-3}$	$2.2.10^{-4}$
Schist and siltstone	24	25 to 30	27 to 28	10	0.33	$1.5.10^{-4}$	$9.0.10^{-3}$	$2.0.10^{-4}$

Conducted analyses

Introduction

3D back stability analyses were performed in the two characteristic sections, which were mapped during the excavation. The first analysed cross-section (high overburden) represents the typical rock of the Trojane tunnel – shale and siltstone, while the second one (low overburden) represents the section under Trojane village. Detailed analysis of deformations development in front of excavation face was conducted in this section (Figure 1).

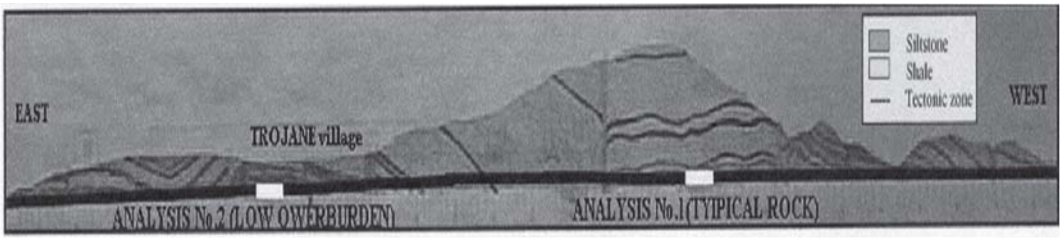

Figure 1. Geological longitudinal section of the Trojane tunnel.

The analyses were conducted with the Soft Soil Creep (SSC) material model. The model's advantage is that it also incorporates creep, which was observed in rock mass in Trojane tunnel. The timeline parameter enables a more realistic excavation model (Table 1), because we can model the advance of the excavation face and bench on a real-time basis.

Results of the back analysis

The results of the 3D model showed three major areas of time dependent deformations, which occurred during the tunnel excavation. These areas are: increased deformation at the excavation face, increased deformation in the rock above the tunnel roof, and a heave effect at a bench caused by excavation of the top heading (Figure 2).

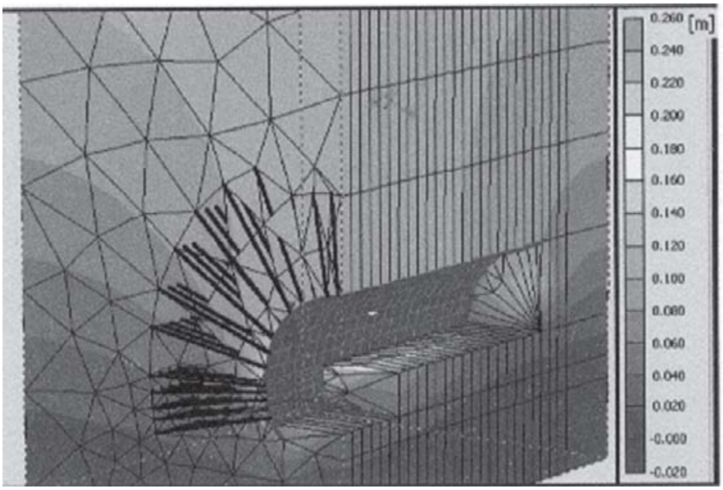

Figure 2. 3D deformation after excavation 22 m of top heading and 6m of bench, time = 25 days.

Calculations, which were carried out using the input parameters gathered in Table 2, showed that the majority of the deformation field (the shape and direction of deformation) was formed during excavation of top heading. The bench excavation phase has only a small influence on the increase of deformations (Figure 3).

Table 2. Input data for primary lining (MERHAR, 2004).

PRIMARY LINING		ROCK BOLTS	
d … primary lining thickness	0.35m	E_s ... Young's modulus of steel	207000 MPa
E … Young's modulus of shotcrete	10000 MPa	A_b … rock bolt cross section	$6.16\ 10^{-4}\ m^2$
EA … axial rigidity of the primary lining	$8.75.10^6$ kN/m	E_sA_b … axial rigidity of the rock bolt	$1.275\ 10^5$ kN
EI … bending rigidity of primary lining	$8.93.10^4$ kNm^2	F_{max} … maximum force in the anchor	350kN
ν… Poisson ratio	0.15		

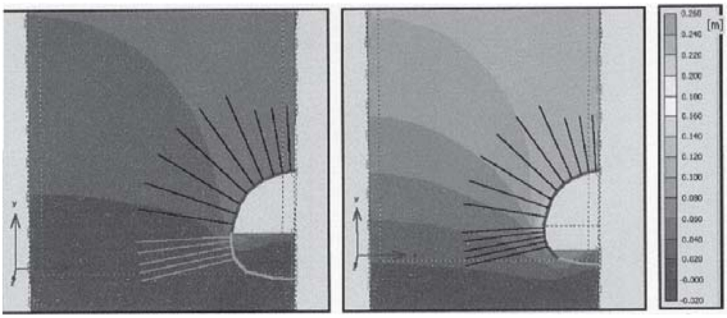

Figure 3. Deformation in cross section after excavation 10 m of top heading; time = 6 days and deformation in the same cross section after excavation of the bench, time = 25 days.

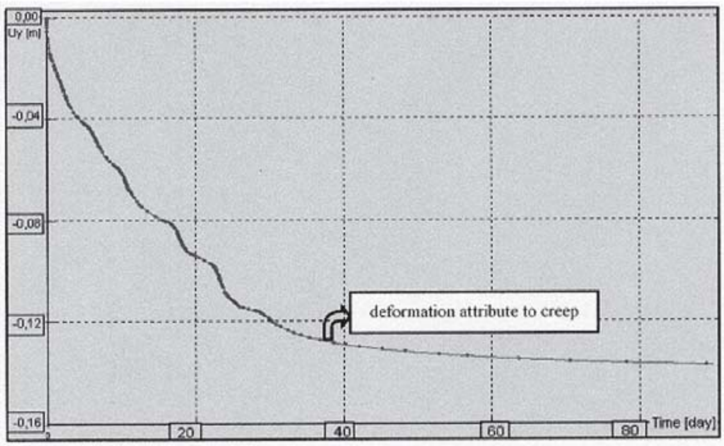

Figure 4. Time dependent vertical movements (Uy) at tunnel roof, calculated with SSC model.

Figure 4 shows the calculated vertical movements (U_y) of the tunnel roof vs. time, where the creep phenomenon is exposed. On a larger time scale a small increase of movement is noticed, after the realization of all excavation phases that is attribute to rock creep.

The analysis results of deformations development in front of the excavation face

An analysis with SSC material model was also performed to show how the excavation of the top heading influences on development of deformations ahead of the excavation. This analysis was carried out for a section with low overburden (17m). This overburden height is characteristic for the eastern part of the tunnel, where it runs under populated areas.

Calculations showed that immediately behind the tunnel face (at the top of the excavation), around 8cm of deformations developed, while 10m ahead of the face, 2-3cm developed. This deformation field expands towards the surface at an angle of 30°- 40°.

On the surface these deformations appear up to 40m in front of the excavation face (Figure 5), which was confirmed by some field measurements.

Calculations showed that during the excavation time, the deformations of around 6-8cm are instantaneously developing just above tunnel roof. Two days after the excavation, additional deformations of around 4cm develop. Therefore, the total deformation that usually cannot be encompassed by tunnel lining measurements, amounts to around 12cm. These calculations correspond well with certain field measurements, which were done in the Trojane tunnel. After that, the increment of the deformation begins to decrease gradually, but because of the rheological characteristics of the rocks and the creep phenomena, they completely stop after approximately 3 months (Figure 6).

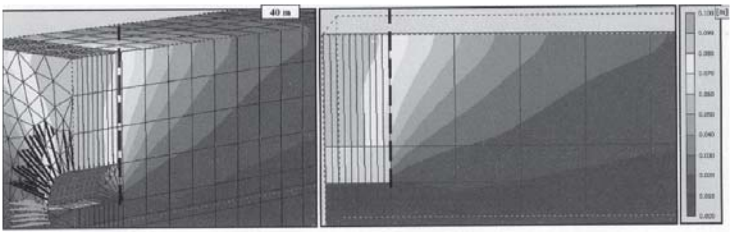

Figure 5. Develop of deformation field in 3D model and longitudinal section.

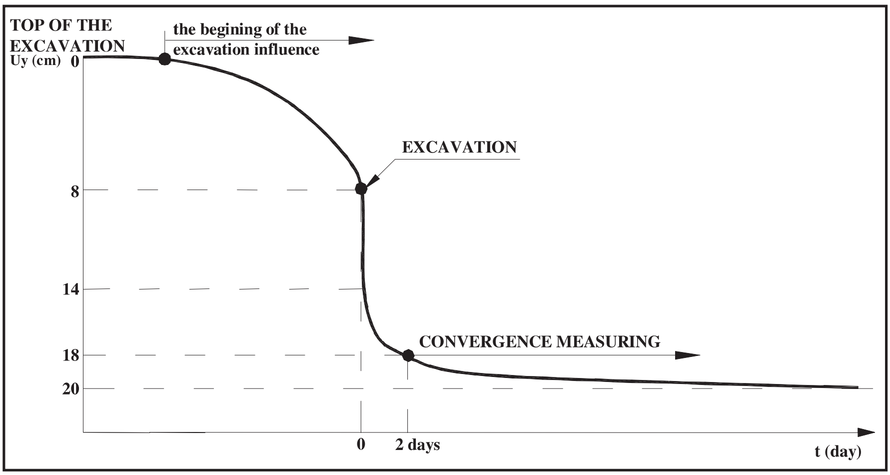

Figure 6. Time dependent develop of deformation at the top of excavation during tunnel excavation.

CONCLUSIONS

- The calculations of time dependant deformation fields are an essential part of planning the excavation process of tunnels in rheologicaly sensitive rocks.
- The material model that was used in analyses enables us to calculate time-dependent developments of deformations during the tunnel excavation in soft rocks.
- The level of rigidness of the support structure and the preserving of the excavation face are essential for maintaining expectable surface deformations above the tunnel.

POVZETEK

Uporaba podzemnih objektov narašča, kar je vzrok, da so lokacije teh konstrukcij umeščene v prostor v zahtevnih geološko tehničnih pogojih. Za čimbolj realen opis obnašanja geoloških materialov je potrebno v konstitutivnih materialnih modelih upoštevati tudi časovno odvisne lastnosti kamnin. Izkop predora Trojane je potekal skozi reološko občutljive kamnine in zemljine s spremenljivimi geotehničnimi lastnostmi. Ta dejstva so se med gradnjo različno kazala tako v deformacijskih procesih v predorskih ceveh kot na površini na vplivnem območju. Gradnja predora- izkop in primarno podpiranje- je bila simulirana z računalniškim programom PLAXIS 3D *tunnel program*. Vhodni parametri so bili določeni s 3D povratnimi analizami z uporabo Soft Soil Creep (SSC) materialnega modela, ki upošteva tudi reološke značilnosti kamnin. Računsko je bil ugotovljen 3D razvoj napetostno deformacijskih polj med izkopom predora, kateri je pokazal glavne napetostno deformacijske spremembe v okoliških kamninah in podpornih elementih. Analize s SSC materialnim modelom so bile narejene tudi zato, da so pokazale kako izkop kalote vpliva na razvoj deformacij pred izkopnim čelom. Ugotovljeno je bilo dobro soglasje z izmerjenimi vrednostmi.

REFERENCES

BRINKGREVE, R. B. J. & VERMEER, P. A. (2001): *Plaxis 3D Tunnel, Version 1*. A.A.Balkema, Netherlands.

MERHAR, B. (2004): *Time-Dependent Changes of Stress-Strain States in the Rocks During Construction of the Underground Structures*. M.Sc. Thesis. University of Ljubljana, Ljubljana.