XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Numerical analysis of twin tunnels including long-term effects considering the creep and shrinkage of concrete

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Abstract. This paper aims to show, through three-dimensional numerical analysis on finite element method, the effect that the twin tunnel causes on the convergence profile considering several constitutive models of rockmass: elastic, elastoplastic and viscoplastic. The elastic and viscoelastic constitutive models for the lining are considered. For the viscoelastic constitutive model of the lining, the concrete creep and shrinkage are considered. For the case studied in this paper a difference in the magnitude of the convergence profile of up to 9% for the twin tunnel was observed, considering the rockmass and the lining with elastic behavior. For the other models, plastic rockmass with elastic lining, viscoplastic rockmass with elastic lining and viscoplastic rockmass with viscoelastic lining, minor differences were observed. Considering the viscoplastic rockmass, the presence of the viscoelastic lining increased the deformations by about 20% (at the end of tunnel construction) and by about 40% in the long-term behavior, in relation to the elastic lining.

Keywords: Constitutive models, Elastoplasticity, Viscoplasticity, Deep Tunnel, Finite Element Method.

1 Introduction

The structural design of deep tunnels involves several geotechnical parameters. The field of strain and stresses around the cavity depends on several interrelated factors, such as the depth of the tunnel, the geometry of the cross section, the anisotropy of stresses in situ, the heterogeneity of the rockmass, the mechanical behavior of the rockmass and the lining as well as the interaction between both during the construction of the tunnel. Depending on the distance between the tunnels, the presence of the twin tunnel significantly affects the field of deformations and stresses within the rockmass.

Several numerical analyzes between adjacent tunnels are in the literature, such as Addenbrook and Potts [1], Hefny et al. [2], Chakeri et al. [3], Ng et al. [4], Hage Chehade and Shahrour [5], Liu et al. [6], Do et al. [7], Fang et al. [8], Do et al. [9], Soga et al. [10], Yin-Fu et al. [11]. However, in these studies, there is no relationship of the long-term effect involving the creep and shrinkage of the concrete lining. Therefore, the objective of this paper is to present a study of the difference in the magnitude of the convergence profile in the long-term due to the presence of the twin tunnels considering creep and shrinkage of the concrete lining. This model implemented in the ANSYS is compared with other constitutive models of rockmass (elastic, elastoplastic and viscoplastic) and lining (elastic).

2 Constitutive model of the rockmass

The viscosity of the rockmass characterized by slow and continuous deformation, even under constant stresses, temperature, and humidity, is called creep. This phenomenon involves several physical mechanisms inside the rockmass, and most of these effects occur due to the redistribution of pore pressure and the advance of cracks and fissures. From a phenomenological point of view, this behavior can be characterized through creep tests. In this test, the samples extracted from the rockmass are subjected to a triaxial condition with stress, humidity, and temperature constant for a long time. Figure 1 show an example of this test with different constant stress state.

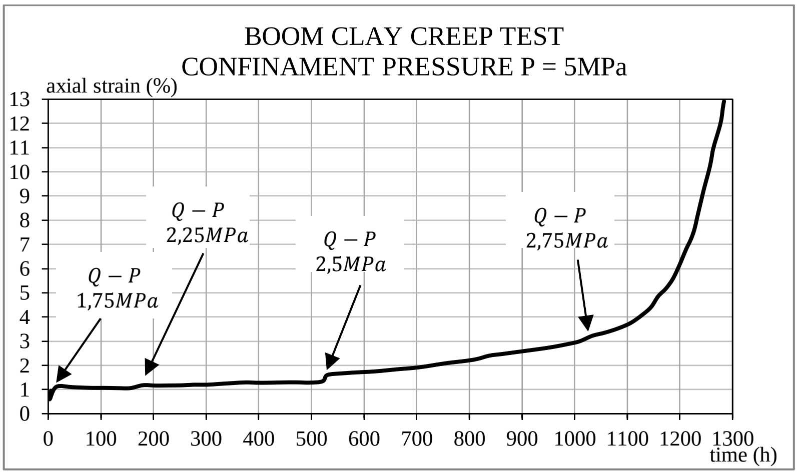

Figure 1. Boom clay creep test (Rousset [12])

For simulation of this phenomenon, Perzyna's viscoplastic constitutive model is used with an associated flow rule deduced from von-Mises yield surface, a model that is already in the ANSYS. More details of this model are in Quevedo [13].

3 Constitutive model of lining

The long-term effect of concrete is separated into creep and shrinkage. The main difference between both is that creep depends on the stress history, while shrinkage does not. Figure 2 shows the behavior of concrete about each of these phenomena.

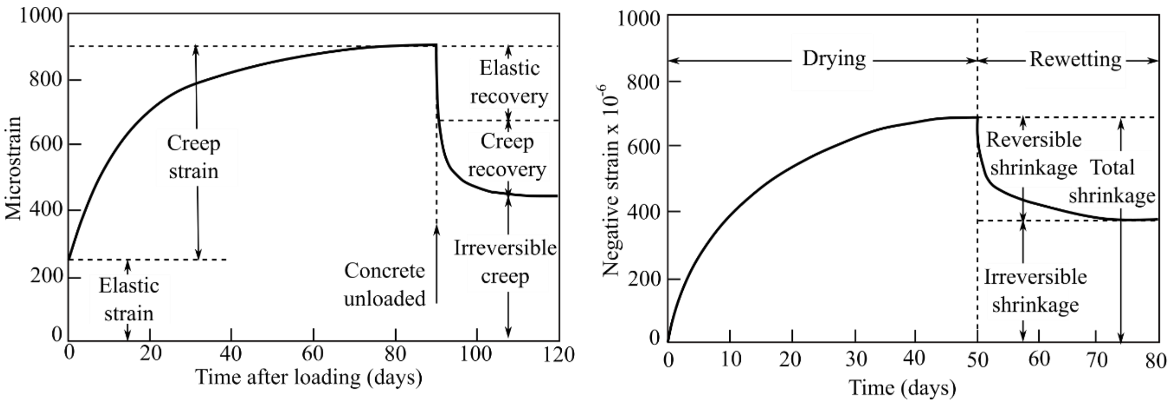

Figure 2. (a) typical shrinkage curve of concrete, (b) typical creep curve of concrete (MINDESS et al. [14])

To simulate this phenomenon, a viscoelastic model was implemented in ANSYS using the USERMAT customization feature. The shrinkage is given by the CEB-MC90 formulation [15] and the creep part is modeled through a Kelvin-Generalized chain, according to the Solidification Theory of Bazant and Prasannan [16,17], whose parameters are adjusted with the CEB-MC90 formulation. More details of this model are in Quevedo [13] and Quevedo et al. [18].

4 Spatial and temporal discretization

For the spatial discretization of the domain, a mesh with 67300 three-dimensional SOLID185 elements is used, totaling 67796 nodes. Figure 3 shows the mesh, geometric parameters and boundary conditions. The double symmetry is considered. The advance of the excavation and placement of the lining is simulated by activating and deactivating of the finite elements. The time step used during the solution process is 0.02 days during each excavation time $TESC = p/V = 1.667 days$, and three days between the final time of construction of the tunnel, $TCONST = 39\,p/V = 65 days$ and the final time of the analysis $TFINAL = 7.5 years$. This final time corresponds to the characteristic time of concrete creep-shrinkage curve, which corresponds to 84% for the 50-year total deformation of concrete with strength and rheological characteristics of the Tab. 1.

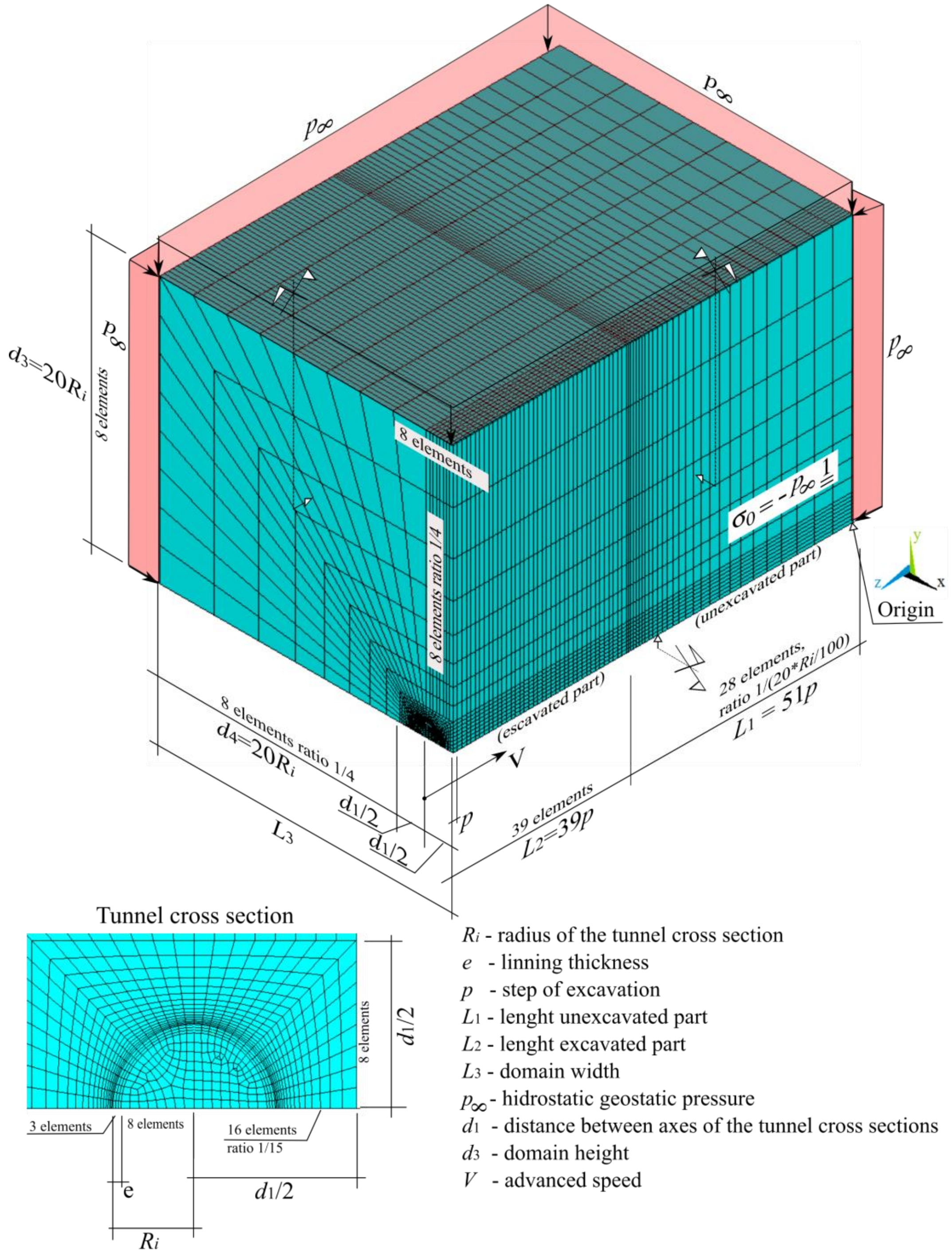

Figure 3. Mesh, geometric parameters and boundary conditions for twin tunnels

5 Verification of the models

To verify the concrete constitutive model, the numerical solution is compared with the results of the analytical formulation of CEB-MC90 applied on Ross's experimental data [19]. Figure 4 shows two comparisons for creep considering $f_{ck} = 38MPa$, $s = 0.2$, $\upsilon = 0.15$, $RH = 93\%$, $h_f = 3.93939cm$, $t_s = 7days$, $\beta_{esc} = 8$, $T = 17°C$, $\alpha = 1$. The definition of each constitutive parameters is shown in Tab. 1. More verifications are in Quevedo [13].

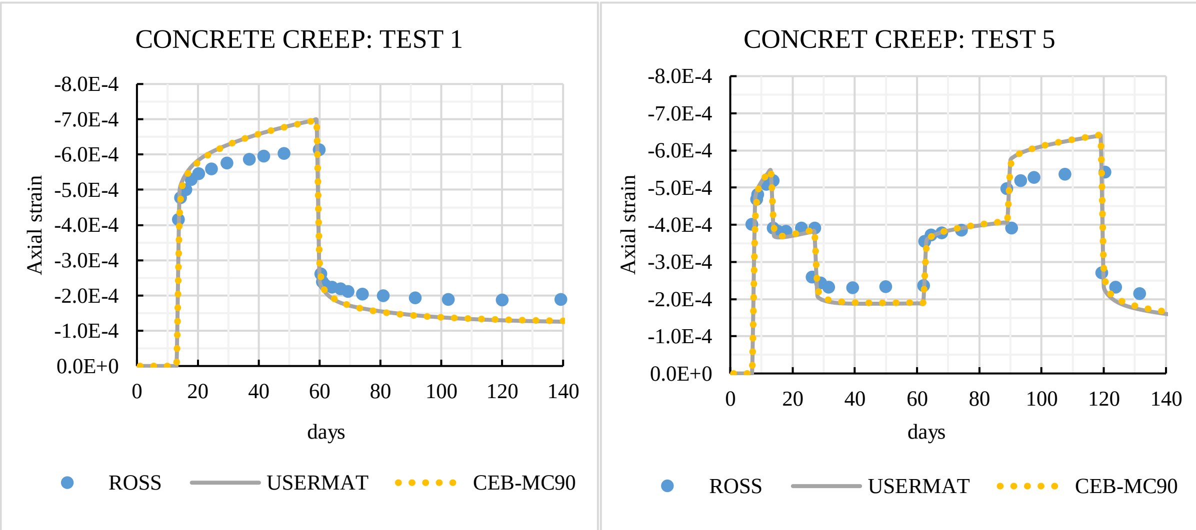

Figure 4. Examples of verification of the concrete constitutive model

The verification of the models of the rockmass as well as the study of mesh convergence were made through comparisons with analytical solutions in elasticity and elastoplasticity considering only one tunnel. The mesh is similar of Fig. 3 and can be found in Quevedo [13]. The verification was also made for cases involving the elastic lining and viscoplastic rockmass with numerical solutions in axisymmetry obtained by the GEOMEC91 software [20]. The results obtained by GEOMEC91 are based on the Bingham's model for rockmass viscosity, according to Zienckievicz and Cormeau [21], while the calculations of ANSYS are based on the Perzyna's model [22]. However, the models are equivalent, and their parameters can be related as shown in [13].

Figure 5 and Fig. 6 shows some results of these comparisons considering $R_i = 100cm$, $e = 10cm$, $p = 1/3R_i$, $p_\infty = 4MPa$, $C = 0.86602MPa$ and $C = 2.59806MPa$, $V = 10m/day$, $d_0 = 2/3R_i$, $E_r = [300, 3000, 30000]MPa$. The definition of each constitutive parameters is shown in Tab. 1.

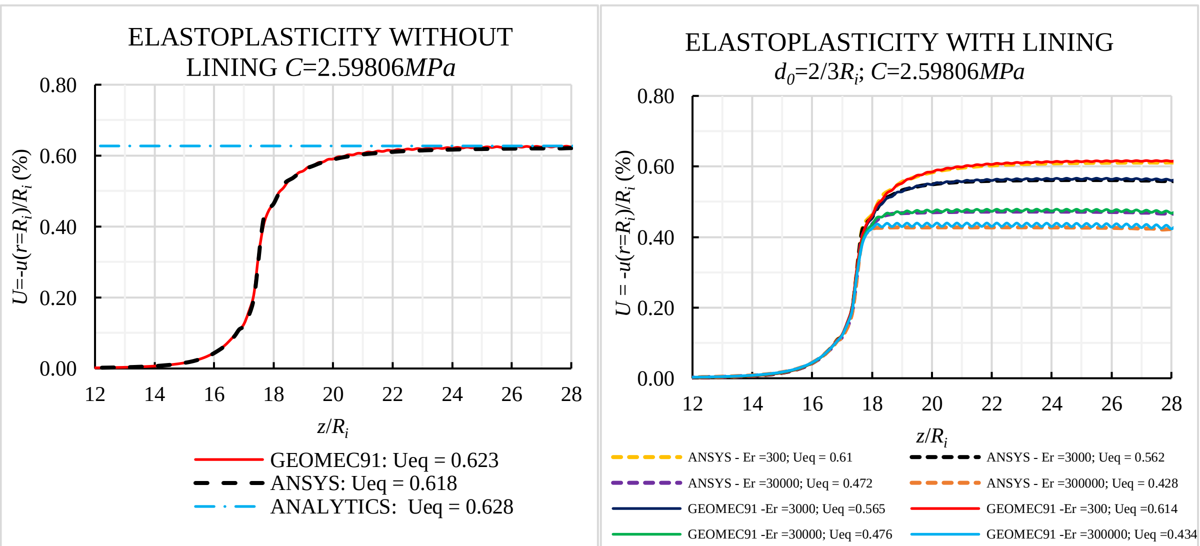

Figure 5. Examples of verification of the tunnel models in elastoplasticity without/with elastic lining

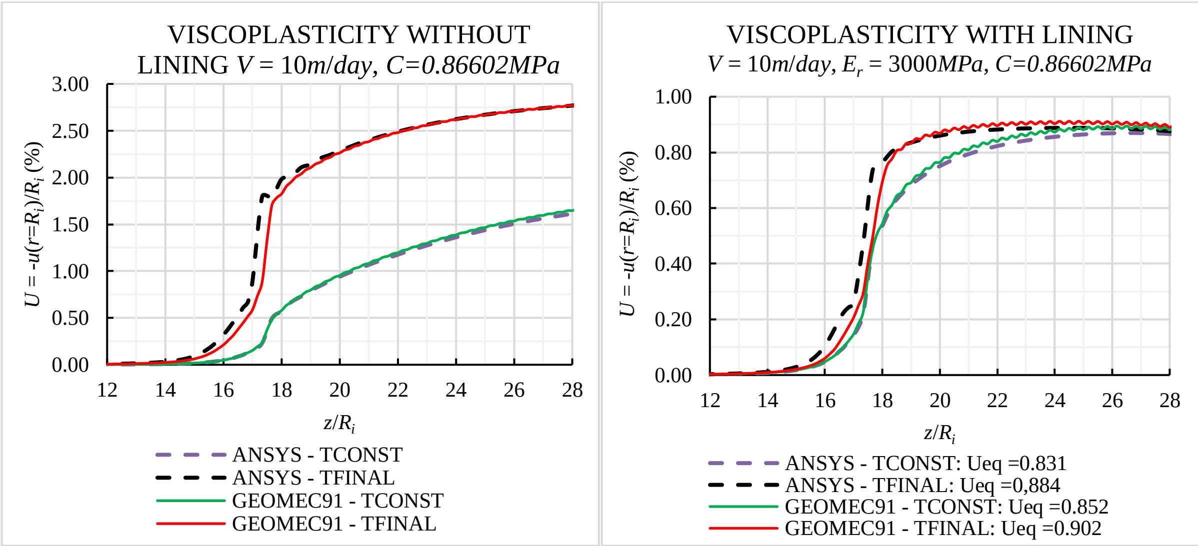

Figure 6. Examples of verification of the tunnel models in viscoplasticity without/with elastic lining

6 Results

For the analysis the following geometric parameters are used: $R_i = 500cm$, $e = 20cm$, $d_0 = 0cm$, $d_1 = 4R_i$ $p = 1/3R_i$. In the boundary conditions, a geostatic hydrostatic pressure $p_\infty = 5MPa$ and an advanced speed $V = 1m/day$ is used. The Table 1 shows the values of the constitutive parameters used.

Table 1. Constitutive parameters used in the analyzes

PARAMETERS	SYMBOL	UNIT	VALUES
CONSTITUTIVE MODEL OF ROCKMASS			
Young's module	E_s	*MPa*	1000
Poisson's ratio	υ_s	*adm*	0.4
Cohesion (von-Mises' criterion)	C	*MPa*	0.86602
Viscosity coefficient (GEOMEC91)	η	*day*	94.50
Power law parameter (GEOMEC91)	n	*adm*	1
Reference parameter (GEOMEC91)	F_0	*MPa*	1
Material viscosity parameter (ANSYS)	γ	*1/day*	0.01832
Strain rate hardening parameter (ANSYS)	m	*adm*	1
CONSTITUTIVE MODEL OF LINING			
Characteristic compressive strength of concrete	f_{ck}	*MPa*	20
Young's module of concrete	E_r	*MPa*	30303.4
Poisson's ratio	υ_r	*adm*	0.2
Coefficient which depends on concrete type	s	*adm*	0.2
Relative humidity of ambient environmental	RH	%	70
Fictitious thickness	h_f	*cm*	40.83
Age at the beginning of shrinkage	t_s	*day*	7
Coefficient which depends on concrete type - shrinkage	β_{sc}	*adm*	8
Temperature	T	*°C*	20
Coefficient which depends on concrete type	α	*adm*	1
Age at which the load was applied	t_0	*day*	1

In Tab. 1, the parameters of the Bingham's and Perzyna's models for rockmass are shown. The viscoelastic lining has $f_{ck} = 20MPa$, with high initial strength characteristics cured for 7 days (as if it were shotcrete). Figure 7 shows the results. The convergence profiles at the top of the cross section U_{90} are presented for the case of one tunnel $d_1 = \infty$ (dotted line), and for the case of twin tunnels with a distance between axes of the cross section $d_1 = 4R_i$ (continuous line). The equilibrium convergence U_{90eq} is the convergence average between $z/R_i = 22$ and $z/R_i = 26$. For viscous cases, the solution is presented in the final time of the tunnel construction (TCONST) and in the final time of the analysis (TFINAL).

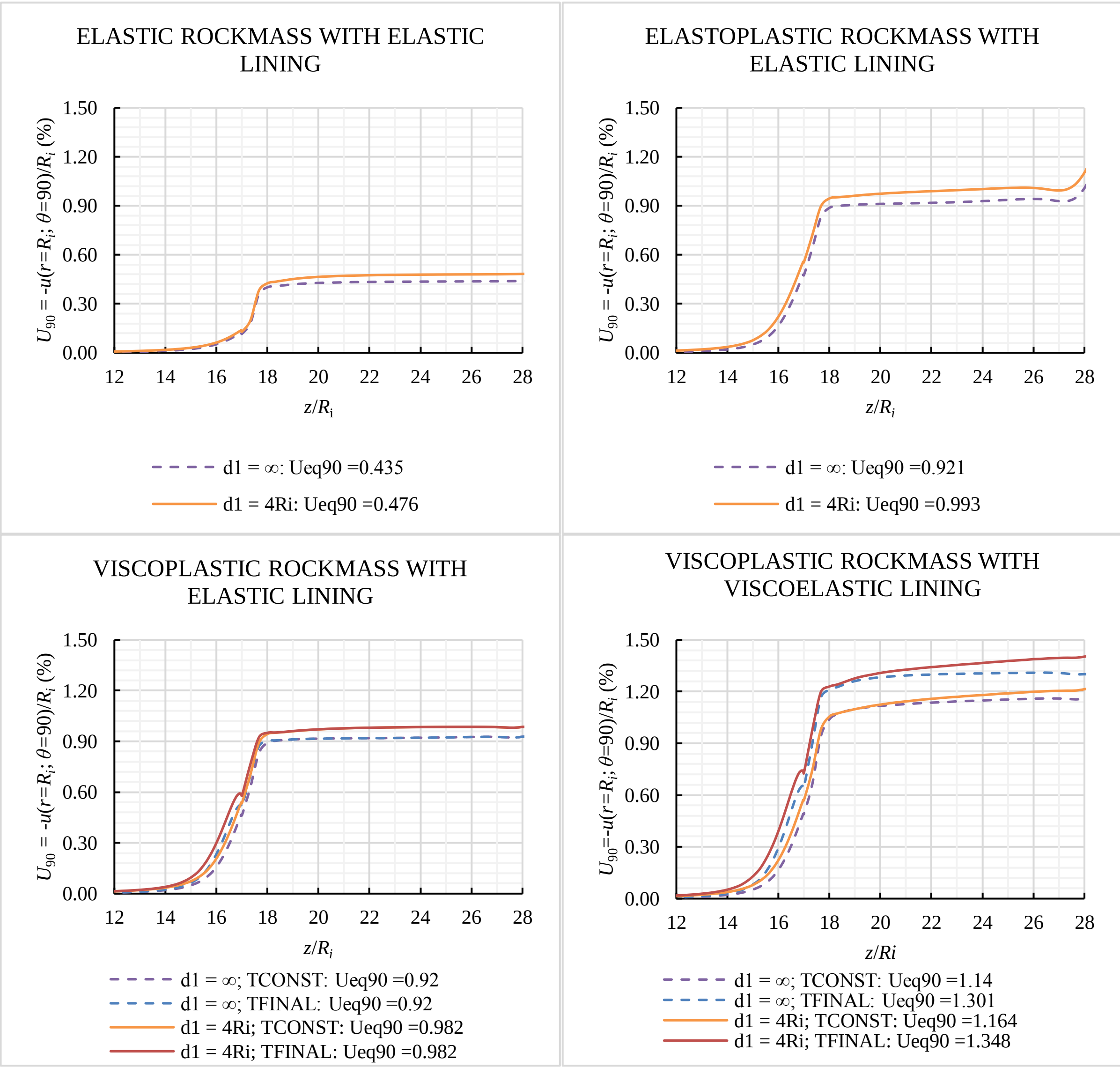

Figure 7. Results of the analyses

7 Conclusions

Comparing the equilibrium convergences of Fig. 7, some conclusions can be listed:

a) the difference caused by the presence of the twin tunnel was 9% for the elastic rockmass with elastic lining; 8% for the elastoplastic rockmass with elastic lining, 7% for viscoplastic rockmass with elastic lining and 4% for the viscoplastic rockmass with viscoelastic lining.

b) in the viscoplastic rockmass, in comparison with the elastic lining, the viscoelastic lining increases deformations by about 20% at the end of the tunnel construction (TCONST) and about 40% at the end of the analysis (TFINAL).

c) the consideration of the viscoelastic lining is more significant in the magnitude of the deformations than the proximity of the twin tunnels: the elastic lining block the viscous deformation of the rockmass, which did not happen with the viscoelastic lining.

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