Numerical analysis of the rock deformation in twin tunnels with transverse galleries considering plasticity and time-dependent constitutive models

Quevedo, F. P. M.*a*,×, Colombo, C. A. M. M.*a*, Bernaud, D.*a* and Maghous, S.*a*

*aFederal University of Rio Grande do Sul, Av. Osvaldo Aranha, 99, Porto Alegre, 90.035-190, RS, Brazil*

A R T I C L E I N F O

*Keywords*:

twin tunnels transverse gallery

elastoplasticity-viscoplasticity cou- pling

viscoelastic lining finite element method

A B S T R A C T

Resorting a three-dimensional finite element analysis, this paper investigates the instantaneous and long-term implications induced by the time-dependent constitutive behavior of constituents on the convergence profile of twin tunnels linked with transverse galleries. Several constitutive models for rock mass mechanical behavior are examined at the material level, encompassing elastoplasticity, viscoplasticity, or coupled elastoplasticity-viscoplasticity frameworks. Plasticity state equations are based on a Drucker-Prager yield surface with an associated flow rule, while the viscoplasticity formulation relies on the Perzyna model with a Drucker-Prager flow surface. Tunnel lining behavior is modeled using either elastic or viscoelastic constitutive models. The viscoelastic behavior is described by a Generalized Kelvin rheological model based on Bazant and Prassanann’s Solidification Theory, with model parameters derived from CEB-FIP MC90 formulations. From a computational viewpoint, the deactivation-activation method is employed to simulate the excavation process and lining installation. The accuracy of finite element predictions is assessed through comparisons with available analytical solutions formulated in a simplified setting for the twin tunnels’ configuration. A parametric study delves into the mutual interaction induced by tunnels proximity, emphasizing the crucial role of concrete lining stiffness in twin tunnels’ deformation. Numerical simulations indicate a highly localized influence of a transverse gallery on twin tunnels deformation, extending up to four radii from each side of the gallery axis. Finally, the paper investigates the effects of twin tunnels proximity and those induced by an interconnecting gallery on the instantaneous and long-term convergence of tunnels, contrasting these outcomes with the convergence of a single tunnel.

# Introduction

Many design methods often focus on single tunnels, but twin tunnels are a common occurrence. The interaction between tunnels can be significant, especially when the spacing between them is minimal. Additionally, many twin tunnels incorporate transverse galleries, introducing a localized effect on displacements and stresses. Also, the rheological behavior of the rock mass and lining plays a crucial role in how stress and displacements fields evolve over time. Some recent studies on deep twin tunnels can be found at [[19](#_bookmark51), [6](#_bookmark38), [11](#_bookmark43), [7](#_bookmark39),[8](#_bookmark40), [12](#_bookmark44), [9](#_bookmark41), [10](#_bookmark42)].

Chortis and Kavvadas [[7](#_bookmark39)] considered the calculation of the axial forces acting on the primary support in the intersection zone before, during, and after the construction of a perpendicular tunnel intersection. The results of the analysis indicated that the zone of influence extends approximately two diameters from the main tunnel to each side from the center of the intersection and that the interaction effects are practically eliminated when they exceed this influence zone.

In another study, Chortis and Kavvadas [[8](#_bookmark40)] carried out parametric 3D finite element analyses to verify the

interaction between deep twin tunnel, with circular and non-circular cross-section, supported by a shotcrete elastic linear lining. Was considering the rock mass with linear elastic behavior and perfectly plastic, with Mohr-Coulumb failure criteria. The study investigates the axial forces that develop in the primary lining of the twin tunnels as a function

×Corresponding author.

[motta.quevedo@ufrgs.br](mailto:motta.quevedo@ufrgs.br) (Q.F.P. M.); [ca-colombo@hotmail.com](mailto:ca-colombo@hotmail.com) (C.C.A.M. M.); [denise.bernaud@ufrgs.br](mailto:denise.bernaud@ufrgs.br) (B. D.);

[samir.maghous@ufrgs.br](mailto:samir.maghous@ufrgs.br) (M. S.)

<https://www.researchgate.net/profile/Felipe-Pinto-Da-Motta-Quevedo>(Q.F.P. M.); <http://lattes.cnpq.br/4919388217690564>(C.C.A.M. M.); <http://lattes.cnpq.br/2809615143819128>(B. D.); <https://www.researchgate.net/profile/Samir-Maghous>(M. S.)

ORCID(s): 0000-0003-4171-1696 (Q.F.P. M.); 0000-0001-6365-3269 (B. D.); 0000-0002-1123-3411 (M. S.)

Quevedo et al.: *Preprint submitted to Elsevier* Page 1 of 28

of the main geometric and geomaterial parameters, but without considering the potential time-dependent deformations (creep effect) that occur in some types of rock masses.

Chen et al. [[6](#_bookmark38)], through analytical solutions in elasticity using complex variables, Fourier transformation, and the alternating Schwarz method, demonstrate that the mutual interaction between twin tunnels disappears if the spacing between the tunnels is greater than six times the tunnel radius. The lining effectively reduces the stress concentration, especially at high lateral stress coefficients.

Guo et al. [[12](#_bookmark44)] develop an elastic analytical solution for the stress field around twin circular tunnels with hydrostatic

pressure using the complex variable and the superposition principle. They found that stress concentration in tunnel wall increased as the distance between the parallel tunnels decreased and the supporting pressure leads to the radial stress increasing and the tangential stress decreasing.

Ma et al. [[13](#_bookmark45)] proposed an analytical method, verified by a numerical solution using FLAC3D software for determining the plastic zones around deep circular twin tunnels without linings, restricting themselves where there is no overlap between the two plastic zones. In this case, the authors adopted the elastoplastic perfectly constitutive model for the homogeneous and isotropic rock mass, with the Mohr-Coulomb criterion. Also carried out parametric studies to understand the influence of the distance between the twin tunnels, cohesion, the angle of internal friction, and the vertical and horizontal initial stresses acting on the shape and depth of the plastic zones. These authors stated that the plastic zone around the tunnel provides a relevant theoretical basis for defining and designing the support. In that respect, an excessive plastic zone would significantly affect the stability and functionality of a tunnel. Reducing the extension of the plastic zone around tunnels is therefore of great importance in engineering tunnel design projects.

Using parametric three-dimensional numerical analyses, Chortis and Kavvadas [[9](#_bookmark41), [10](#_bookmark42)] investigated the effect of

building a transverse tunnel that intersected deep twin tunnels perpendicularly, focusing the study on the axial forces and the circumferential and longitudinal bending moments acting on the primary support of the intersection regions, respectively. According to the authors, the potential interaction between deep twin tunnels lined with shotcrete must be taken into account, especially when the distance between them is less than or equal to twice their diameter.

According to Fortsakis [[11](#_bookmark43)], in a realistic construction context, twin tunnels are excavated and supported with a delay, so that the second tunnel is usually built after the first one has advanced enough to maintain a longitudinal separation distance between the faces. The advance of the subsequent tunnel mobilizes the redistribution of stresses and deformations in the zone between the tunnels, resulting in additional loading of the preceding tunnel.

As for transverse tunnels, these are generally built far enough behind the advanced face of the main tunnel to

ensure that their excavation has virtually no effect during the construction of the junction tunnel [[7](#_bookmark39)]. The interaction at the intersection, between the main tunnel and the transverse tunnel, significantly modifies the stress state of the primary support and that of the surrounding rock mass in these areas, compared to that of the singular tunnel, making three-dimensional finite element analyses essential for developing a realistic and safe design for tunnel junctions [[19](#_bookmark51)]. During the construction of the transverse tunnel, the surrounding rock mass is subjected to a redistribution of stresses, causing an additional load on the main tunnel, precisely in the intersection zone. If these additional loads exceed the load capacity of the primary support of the main tunnel, a potentially unstable region can develop, leading

to failure, especially in adverse geotechnical conditions [[7](#_bookmark39)].

While the simulation of tunnel convergence in single tunnels has been widely investigated and reported in published literature, few works have actually addressed the computational evaluation of deformation in twin tunnels. Less attention has been dedicated to assess the mutual mechanical interaction induced by the excavation of the transverse gallery connecting the twin tunnels. In this context, the main contributions of this paper may be summarized at both the material and tunnel analysis levels. At the material level, the constitutive state equations of the rock mass are formulated within the framework of coupled plasticity-viscoplasticity, which is relevant for clayey rocks. Such a framework allows capturing the irreversible instantaneous tunnel response (plasticity) as well as the delayed irreversible response (viscoplasticity). As regards the mechanical behavior of concrete material defining the lining, which is classically modeled by means of linear elastic relationships, the present analysis considers an ageing viscoelastic rheological model relying upon the Bažantand Prasannan Solidification theory [2, 3]. At the structure analysis level, the simulation of deformation in the highly interacting material system components (namely, rock mass and lining), resulting from excavation process of twin tunnels and transverse gallery, is handled by means of finite element simulations performed in a three-dimensional setting. From the computational viewpoint, the constitutive models formulated for the rock mass and lining constituent are implemented into the same software utilizing the USERMAT customization tool of ANSYS standard software, together with the related numerical integration schemes. In this context, the finite element analysis specifically investigates the three-dimensional interaction induced by the construction process of twin tunnels proximity and transverse gallery.

# Fundamental assumptions

The basic assumptions of the constitutive and computational modelling as well as related limitations are summarized as follows:

1. Only the configuration of deep tunnels shall be considered in the subsequent analysis, thus neglecting deformations caused by surface loads and settlements arising from the excavation process.
2. Although material heterogeneity and behavior anisotropy are inherent features of soils and rocks, the rock mass is modeled throughout the paper as a homogeneous and isotropic continuous medium. At the scale adopted for tunnel modeling (macroscopic scale), this assumption means in particular that the possible micro-heterogeneities, such isotropic distributions of joints or cracks present at the finer scale, are accounted for in the homogenized behaviour by means of a preliminary homogenization process (e.g., Nemat-Nasser and Horii, 1993; Deudé et al., 2002; de Buhan et al., 2002; Marmier et al., 2007; Aguiar and Maghous, 2023). Clearly enough, the framework of continuum modelling adopted in the paper would reveal questionable when the rock mass is cut by few macro-scale fracture joints.
3. The rock mass is phenomenologically modeled using an elastoplastic-viscoplastic rheological law to capture instantaneous and long-term responses. This approach disregards the aspect connected with temperature gradients, water flow, and poromechanics coupling.
4. Despite the complexity of the stress distribution prevailing in the rock mass before the process of tunnel excavation, which is mainly affected by the geological history, the present study assumes a geostatic initial stress reflected by an isotropic state of stress.
5. Twin tunnels are often designed considering a time gap between excavation fronts. The finite element simulations assume synchronous excavation steps to ensure symmetry conditions.
6. The simulation excavation processes are curried out assuming a constant tunnel advancement rate (i.e., constant excavation speed), together with a constant thickness of concrete lining.
7. Effects of temperature and humidity that may affect the viscoelastic behaviour of concrete lining are disregarded.
8. Perfect bonding is assumed at the interface between concrete lining and the rock mass.
9. The framework of infinitesimal strain analysis together with quasi-static evolutions are adopted in the paper. In particular, dynamic excitations and related inertial forces, such as those induced for instance by earthquakes or explosions, shall not be considered in the numerical analysis.

# Constitutive Model of the Rock Material

Justificar a escolha do modelo+ citar artigo Denise e Rousset + citar o teu trabalho. An elastoplastic-viscoplastic constitutive model is formulated and implemented in ANSYS using the UPF/USERMAT customization tool [[1](#_bookmark33)] to simulate rock mass. This model is formulated based on a serial association of elastoplastic and viscoplastic constitutive models. The local strain rate ***s˙*** is split into three contributions ***s˙*** = ***s˙*** *e* + ***s˙*** *p* + ***s˙*** *up* and the constitutive relationships are therefore expressed as:

Sigma denotes the local Cauchy stress tensor.

S. Nemat-Nasser, H. Horii. Micromechanics: overall properties of heterogeneous materials.

North-Holland, Amsterdam (1993).

V. Deudé, L. Dormieux, D. Kondo, S. Maghous. Micromechanics approach to nonlinear poroelasticity: application to cracked rocks. J Eng Mech ASCE, 128 (2002), pp. 848-855.

[**P. de Buhan**](https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9399%282002%29128%3A8%28869%29#con1)**,** [**J. Fréard**](https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9399%282002%29128%3A8%28869%29#con2)**,** [**D. Garnier**](https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9399%282002%29128%3A8%28869%29#con3)**, and** [**S. Maghous**](https://ascelibrary.org/doi/10.1061/%28ASCE%290733-9399%282002%29128%3A8%28869%29#con4)**. Failure Properties of Fractured Rock Masses as Anisotropic Homogenized Media.** Journal of Engineering Mechanics. Volume 128, Issue 8, 2002

R. Marmier, L. Jeannin and J. F. Barthélémy. Homogenized constitutive laws for rocks withelastoplastic fractures. Int. J. Numer. Anal. Meth. Geomech., 2007;31:1217–1237.

Cássio B. Aguiar, Samir Maghous. A micromechanics-based approach to damage propagation criterion in viscoelastic fractured materials regarded as homogenized media. Int J Numer Anal Methods Geomech.2023;47:936–971.