Finite Element Analysis of Rock Deformation in Deep Twin Tunnels

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Abstract. Relying upon a three-dimensional finite element analysis, this contribution investigates the instantaneous irreversivel response induced by the constitutive behavior of the rock mass in the convergence profile of twin tunnels. At the rock material level, elastoplastic state equations based on a Drucker-Prager yield surface with an associated flow rule are adopted in the modeling. As regards the tunnel support, the formulation accounts for the presence of an elastic shotcrete-like lining. From a computational point of view, the deactivation-activation method is used to simulate the excavation process and the installation of the lining. The accuracy of the finite element predictions is assessed through comparisons with the available analytical solutions formulated in a simplified scenario for the twin tunnel configuration. A parametric study investigates the mutual interaction induced by the proximity of the tunnels.

Keywords: Twin tunnels, Elastoplasticity, Finite element modeling

1 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. While the simulation of tunnel convergence in single tunnels has been widely investigated and reported in published literature, few works have addressed the computational evaluation of deformation in twin tunnels. Some studies on deep twin tunnels can be found at Spyridis and Bergmeister [1], Chen et al. [2], Ma et al. [3], Fortsakis et al. [4], Chortis and Kavvadas [5], Chortis and Kavvadas [6], Guo et al. [7], Chortis and Kavvadas [8], Chortis and Kavvadas [9]. But less attention has been dedicated to assessing 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 can be summarized at both the material and tunnel analysis levels. At the material level, the constitutive state equations of the rock mass are developed using a coupled plasticity-viscoplasticity framework, which is suitable for clayey rocks. Both the immediate irreversible tunnel response (plasticity) and the delayed irreversible response (viscoplasticity) are captured using this approach. For the mechanical behavior of the concrete lining, the traditional linear elastic model are employed. At the structural analysis level, the deformation of the highly interactive components of the material system (i.e., rock mass and lining) resulting from the excavation of twin tunnels and transverse gallery is simulated using three-dimensional finite element simulations. The excavation and lining placement processes are simulated through the activation/deactivation technique. The constitutive models for the rock mass and lining and the associated numerical integration schemes, are implemented into the UPF/USERMAT customization tool [10] of the ANSYS standard software. This three-dimensional finite element analysis is specifically designed to address the interactions induced by the construction process, the proximity of twin tunnels, and the presence of the transverse gallery.

2 Constitutive Model of the materials

The delayed behavior of constitutive materials is crucial in understanding the deformation of tunnel structures in deep clayey rocks (see for instance Rousset [11], Nguyen Minh and Rousset [12] or Giraud and Rousset [13]).

However, during the early stages of tunnel excavation, the rock mass around the tunnel undergoes severe loading and high strain rates, leading to significant instantaneous irreversible strains near the tunnel wall, which can impact the structure's long-term stability. The model formulation is based on earlier works by Nguyen Minh and Rousset [12] and Rousset [11]. For brevity, only the main features of this model are summarized here, with detailed descriptions, applications, and validations available in Quevedo et al. [14]. The finite element implementation of this model in the USERMAT procedure of ANSYS software is detailed in Quevedo [15].

The elastoplastic-viscoplastic model for the rock mass is formulated based on a serial association of the elastoplastic and viscoplastic constitutive models. The local strain rate $\dot{\boldsymbol{\varepsilon}}$ is split into three contributions $\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^e + \dot{\boldsymbol{\varepsilon}}^p + \dot{\boldsymbol{\varepsilon}}^{vp}$, so that the constitutive relationships relating the Cauchy stress rate $\dot{\boldsymbol{\sigma}}$ and strain rate components can be written as:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}}^e = \boldsymbol{D} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^p - \dot{\boldsymbol{\varepsilon}}^{vp}). \tag{1}$$

In the above relationship, $\dot{\boldsymbol{\varepsilon}}^e$, $\dot{\boldsymbol{\varepsilon}}^p$ and $\dot{\boldsymbol{\varepsilon}}^{vp}$, represent respectively the elastic, plastic and viscoplastic strain rate, and $\boldsymbol{D}$ denote the fourth-order isotropic elastic linear constitutive tensor. Tensor $\boldsymbol{D}$ is defined by the rock mass elastic Young modulus E and Poisson ratio ν. The plastic strain rate is given by flow rule:

$$\dot{\boldsymbol{\varepsilon}}^p = \begin{cases} \dot{\lambda}\dfrac{\partial g}{\partial \boldsymbol{\sigma}} & \text{for } f > 0 \\ \boldsymbol{0}, & \text{for } f \leq 0 \end{cases}, \tag{2}$$

where $\dot{\lambda}$ is the plasticity multiplier (obtained through the consistency condition $\dot{f} = 0$) and g is a potential flow function analogous to f used to simulate the volume dilatation during the evolution of plastic deformations. However, for this analysis, was used associated plasticity, i.e., $g = f$. In this model is used a Drucker-Prager plastic flow surface given by

$$f(\boldsymbol{\sigma}, q) = f(I_1, J_2, q) = \beta_1 I_1 + \beta_2\sqrt{J_2} - q(\alpha), \tag{3}$$

which I_1 is the first invariant of the stress tensor, J_2 the second invariant of the deviator tensor and β_1, β_2 and $q(\alpha)$ are strength parameters related to the friction angle ϕ and cohesion $c(\alpha)$, respectively. In the present model Drucker-Prager surface been inner of the Mohr-Coulomb surface [16], that is,

$$\beta_1 = \frac{(k-1)}{3}, \quad \beta_2 = \frac{(2k+1)}{\sqrt{3}}, \quad q(\alpha) = 2\sqrt{k}\, c(\alpha), \tag{4}$$

where $k = (1+\sin\phi)/(1-\sin\phi)$. The internal variable α is the equivalent plastic strain $\bar{\varepsilon}^p$ used to simulate strain hardening/softening phenomena. However, for this study, we adopt perfect plasticity, meaning that c is a constant. For the viscoplasticity surface f^{vp} the same surface is empolyed, but with ϕ^{vp} in β_1 and β_2, and $q^{vp} = 2\sqrt{k^{vp}} - c^{vp}$ where $k^{vp} = (1+\sin\phi^{vp})/(1-\sin\phi^{vp})$ and c^{vp} is a constant, i.e., perfect viscoplasticity. Numerical details of this implementation can be found in [14]. For viscoplastic flow rule we have,

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\lambda}^{vp}\frac{\partial f^{vp}}{\partial \boldsymbol{\sigma}} \tag{5}$$

In contrast to the plastic multiplier, the viscoplastic multiplier λ^{vp} is independent of a consistency like condition. As a result, its expression is explicit. Based on the framework of generalized Perzyna's overstress theory [17], its expression may be derived as follows:

$$\dot{\lambda}^{vp} = \frac{\Phi(\boldsymbol{\sigma}, q^{vp})}{\eta} \quad \text{and} \quad \Phi = \left\langle \frac{f^{vp}(\boldsymbol{\sigma}, q^{vp})}{f_0} \right\rangle^n, \tag{6}$$

where Φ is the overstress function, η is the dynamic viscosity constant, n is the dimensionless parameter that gives the form of the power law, f_0 a parameter conveniently adopted and $\langle * \rangle$ is the McCauley function which is 0 when $* < 0$, i.e. viscoplastic flow will only occur when the overstress function is positive.

In this coupled model, when $\phi = \phi^{vp}$, cohesion entirely controls the evolution of local mechanical fields. Specifically, when $c \to \infty$ and $c^{vp} \to \infty$, the system achieves a purely elastic solution. The solution becomes purely elastoviscoplastic with $c \to \infty$, while a pure elastoplastic solution emerges with $c^{vp} \to \infty$. In the coupled analysis, condition $c^{vp} < c$ is adopted, allowing the viscoplastic domain to occur without plasticity. However, in the presence of plasticity, viscous effects become inevitable. Fig. 1 illustrates these domains in principal stress space.

A linear elastic constitutive model is used for the concrete lining, which can be expressed, within the framework of infinitesimal analysis, as:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}}^e; \tag{7}$$

where, $\dot{\boldsymbol{\varepsilon}}^e$ and $\boldsymbol{D}$ are respectively the elastic strain rate and the fourth-order isotrpoic elastic constitutive tensor dfined by the lining elastic Young modulus E and Poisson ratio ν.

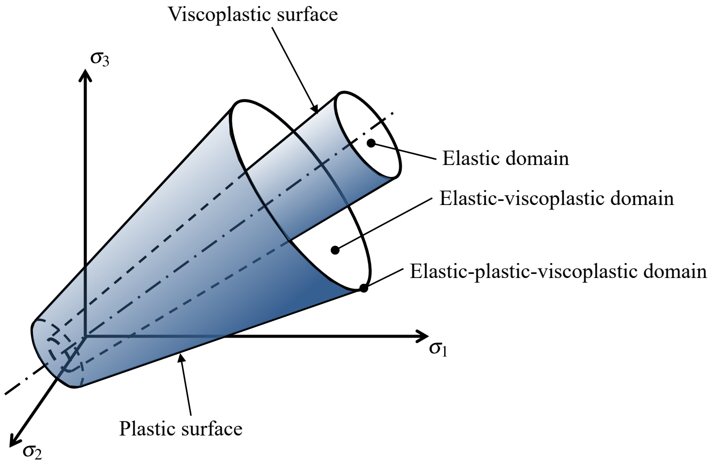

Figure 1. Elastoplastic-viscoplastic domains.

3 Spatial and time discretization of the domain

4 Verification with unlined twin tunnel in elastoplastic medium

5 Numerical Results and Discussion

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$$q_r = -4pr^2 k \frac{dT}{dr}. \tag{8}$$

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Table 1. Coefficients in constitutive relations

Constitutive relation	Nomenclature	Value
Turbulent tensor	C_{μ}	0.09
Turbulent tensor	$C_{\mu b}$	0.69
Lateral lift	C_{L}	0.08
Virtual mass	C_{VM}	0.8

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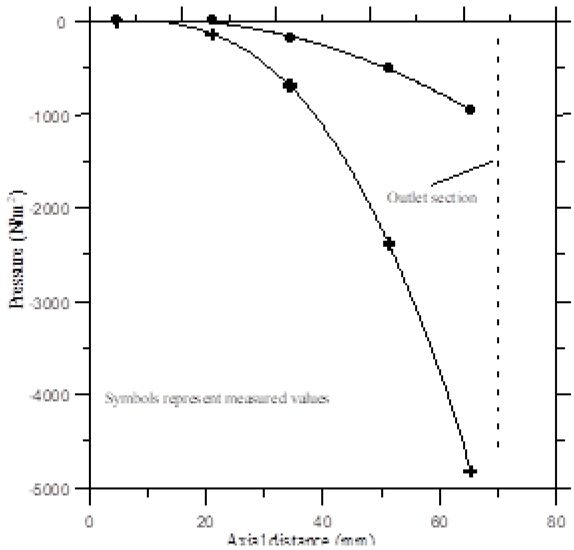

Figure 2. Pressure variation along the nozzle: experimental data

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