Highlights

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Numerical analysis of the twin tunnels with transverse galleries using plastic and viscous constitutive models for rockmass and lining

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ABSTRACT

This paper aims to demonstrate the long-term implications of the rheological constitutive behavior of rock mass and concrete lining in the convergence of the intersection area of twin tunnel galleries using a three-dimensional numerical analysis based on the finite-element method. A Drucker-Prager-Perzyna elastoplastic-viscoplastic constitutive law represents the rock mass and, for the lining, an elastic and viscoelastic law. The deactivation-activation methods simulate the excavation process. Comparisons of convergence reveal that the viscous effects of the rock mass and the lining significantly influence the peak convergence within the intersection zone, resulting in differences of approximately 10% in convergence values.

1. Introduction

The structural design of deep twin tunnels involves estimating cross-section convergence, lining pressure, and the size of the plastic zone within the rock mass caused by the excavation process. The final convergence and stress field around the tunnel depend on *in situ* initial stresses, cross-section geometry, and the coupling between the lining and the rock mass during construction. Unlinke a single tunnel, the proximity between twin tunnels break the symmetry of deformations in tunnel wall. Many twin tunnels have transverse galleries that serve as emergency routes. These galleries will introduce a local effect on the convergence profile of the longitudinal tunnel.

Additionaly, the rheological behavior of the rockmass and lining plays a crucial role in how stress and displacements fields evolve over time.

Indicar os objectivos do trabalho e fornecer um contexto adequado, evitando uma pesquisa bibliográfica ou um resumo dos resultados.

2. Problem description and assumptions

3. Constitutive Model of the Rock Mass

An elastoplastic-viscoplastic model was implemented in ANSYS using the UPF/USERMAT customization tool to simulate rock mass. This model concern a serial association of the plastic and viscoplastic constitutive models, i.e., $\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^e + \dot{\boldsymbol{\varepsilon}}^p + \dot{\boldsymbol{\varepsilon}}^{vp}$, which leads to the following linear constitutive relationship:

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

where $\dot{\boldsymbol{\varepsilon}}$, $\dot{\boldsymbol{\varepsilon}}^e$, $\dot{\boldsymbol{\varepsilon}}^p$ and $\dot{\boldsymbol{\varepsilon}}^{vp}$, represent the total, elastic, plastic and viscoplastic strain rate, respectively. The one-dimensional representation in Fig. 1 shows this association.

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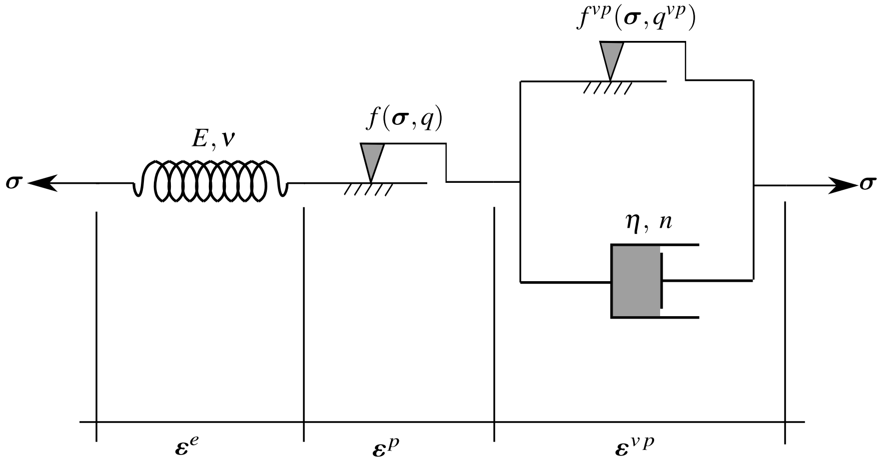

Figure 1: Rheological representation of the elastoplastic-viscoplastic model.

In this model is used a Drucker-Prager plastic flow surface given by

$$f(\boldsymbol{\sigma}, q) = f(I_1, J_2, q) = \beta_1 I_1 + \beta_2 \sqrt{J_2} - q(\alpha), \tag{2}$$

where β_1, β_2 and $q(\alpha)$ are strength parameters related to the friction angle ϕ and cohesion $c(\alpha)$, respectively. We chose the expression of the strength parameters to insribe Drucker-Prager surface within the Mohr-Coulomb surface [4], i.e.,

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

where $k = (1 + \sin\phi)/(1 - \sin\phi)$. The internal variable α represents 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 constant parameter. For the viscoplasticity f^{vp} surface a similar plasticity 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 parameter.

The plastic flow rule is given by:

$$\dot{\varepsilon^p} = \begin{cases} \dot{\lambda}\dfrac{\partial g}{\partial \boldsymbol{\sigma}} & \text{for } f > 0 \\ \mathbf{0}, & \text{for } f < 0 \end{cases}, \tag{4}$$

where $\dot{\lambda}$ is the plasticity multiplier and g is a potencial flow analogous to f to simulate the volume dilatation during the evolution of plastic deformations. However, in this study, was used associated plasticity, i.e., $f = g$. The plastic multiplier is obtained through the consistency condition $\dot{f} = 0$. Numerical details of this implementation can be found in [9].

To the viscoplasticity flow rule is adopted:

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

In contrast to the plastic multiplier, the viscoplastic multiplier is independent of a consistency condition. As a result, its expression is explicit. For this study, we utilize the Perzyna model 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 null when $* < 0$, i.e. viscoplastic flow will only occur when the overstress function is positive.

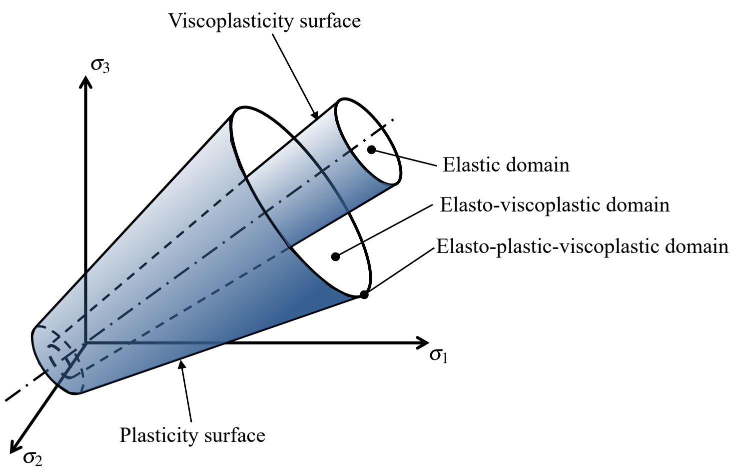

Figure 2: Elastoplastic-viscoplastic domains.

An aspect of the coupled model, utilizing the Drucker-Prager criteria f and f^{vp} for plasticity and viscoplasticity with $\phi = \phi^{vp}$, is that cohesion entirely controls the evolution of local mechanical fields. Specifically, when $c \to \infty$ and $c^{vp} \to \infty$, the solution is purely elastic. Furthermore, the purely elastoviscoplastic solution occurs when $c \to \infty$, whereas a purely elastoplastic solution arises when $c^{vp} \to \infty$. In the coupled analysis in this study, we have adopted $c^{vp} < c$ which means that the viscoplastic domain can occur without plasticity. However, in the presence of plasticity, viscous effects will inevitably occur. Fig. 2 illustrates these domains in principal stress space.

Futher details of this model, validations and application of in single tunnels can be found at [9] and the details of the algorithm implemented in FORNTRAN in the USERMAT subroutine, is given in [7].

4. Constitutive Model of the Lining

We implemented a viscoelastic model in ANSYS using the UPF/USERMAT customization feature [1]. The model simulates concrete creep through a Generalized Kelvin chain, based on Bažant and Prasannan's Solidification Theory [2; 3], with parameter adjustments performed using the CEB-FIP MC90 formulation. The CEB-FIP MC90 formulation [5] determines the shrinkage component.

In this model, the constitutive relationship between stress and strain is

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}}^{e} = \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}} - \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}}^{sh} - \boldsymbol{D}^{*} : \dot{\boldsymbol{\varepsilon}}^{cr} \tag{7}$$

where $\dot{\boldsymbol{\varepsilon}}^{sh}$ and $\dot{\boldsymbol{\varepsilon}}^{cr}$ are the shrinkage and creep strain rate, respectively, while $\boldsymbol{D}^{*}$ denotes the modified constitutive tensor that incorporates the aging of the concrete. Due to the time integration scheme for Newton-Raphson algorithm, the Eq. (7) is given by:

$$\boldsymbol{\sigma}_{n+1} = \boldsymbol{\sigma}_{n} + \boldsymbol{D} : \Delta\boldsymbol{\varepsilon} - \boldsymbol{D} : \Delta\boldsymbol{\varepsilon}^{sh} - \boldsymbol{D}^{*} : \Delta\boldsymbol{\varepsilon}^{cr} \tag{8}$$

in which the increment of shrinkage strain is:

$$\Delta\boldsymbol{\varepsilon}^{sh} = \Delta\varepsilon_{sh}(t_s)\mathbf{1} \tag{9}$$

where t_s represents the concrete curing time, and $\Delta\varepsilon_{sh}$ is the variation of magnitude of the concrete deformation by shrinkage, determined using the expressions of CEB-FIP MC90 [5]. To calculate the increment of creep strain, denoted as $\Delta\boldsymbol{\varepsilon}^{cr}$, we use the incremental algorithm developed by Bažant and Prasannan [2; 3], with an adjustment to incorporate CEB-FIP MC90 formulation. This adaptation is possible comparing the creep functions $\boldsymbol{J}(t, t_0)$ of both references. This gives to the following equivalence:

$$E_0 = E_c(t_0),\ \gamma_c(t - t_0) = \beta_c(t - t_0),\ \frac{1}{v(t)} = \frac{\phi_0}{E_{ci}} \text{ and } \frac{1}{\eta(t)} = 0 \tag{10}$$

in which, according to Bažant and Prasannan [2; 3], E_0 is the modulus of elasticity of the concrete aggregates and microscopic particles of the cement paste, $\gamma_c(t - t_0)$ is the microviscoelastic deformation of the volume fraction of solidified concrete $v(t)$, $\eta(t)$ is the apparent macroscopic viscosity and, according to CEB-FIP MC90 [5], $E_c(t_0)$ is the tangent elastic modulus of the concrete at the instant of loading application t_0, $\beta_c(t - t_0)$ is a coefficient that depends on the loading age $t - t_0$, ϕ_0 is a coefficient that depends on the age of the concrete at the instant of loading application and E_{ci} the tangent elasticity modulus of the concrete at the age of 28 day.

Futher details of this model, validations and application of in single tunnels can be found at [8] and the details of the algorithm implemented in FORNTRAN in the USERMAT subroutine, is given in [6].

5. Description of numerical model

6. Verification with analytical solutions

7. Results and Discussion

Resultados devem ser claros e concisos

7.1. Influência do afastamento entre os túneis

7.2. A influência da rigidez do revestimento

7.3. A influência da presença da galeria no túnel longitudinal

7.4. Abrangencia da região de influência da galeria

7.5. A influência dos modelos que envolve efeitos diferidos

8. Conclusions

As principais conclusões do estudo podem ser apresentadas numa breve secção de Conclusões, que pode ser autónoma ou constituir uma subsecção de uma secção de Discussão ou de Resultados e Discussão.

9. Appendices

Se houver mais do que um apêndice, estes devem ser identificados como A, B, etc. As fórmulas e equações dos apêndices devem ser numeradas separadamente: Eq. (A.1), Eq. (A.2), etc.; num apêndice seguinte, Eq. (B.1) e assim por diante. O mesmo se aplica aos quadros e figuras: Tabe a A.1; Fig. A.1, etc.

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