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Study on time-dependent behavior and stability assessment of deep-buried tunnels based on internal state variable theory

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ABSTRACT

The creep model based on thermodynamics with internal state variables theory can simulate complex time-dependent deformation of rock mass, describe process of energy dissipation of material system, and can be used to evaluate the long-term stability of underground structures quantitatively. In this paper, the creep model proposed by author is improved further and recast to be central difference equation. The redevelopment interface of *FLAC*^{3D} is used to develop a new calculation program, which is based on thermodynamics for vsico-plasticity (PTV-P). Program validation has been conducted by comparing the results from *FLAC*^{3D} and *Matlab* software under uniaxial compression condition. Then the developed program has been applied to analyze the time-dependent behavior of deep-buried double tunnels. The integral values of energy dissipation rate and its time derivative in domain can be calculated and are used to evaluate the long-term stability of tunnels quantitatively, and the evaluation criterion is also proposed. Moreover, the contour map of energy dissipation rate is used to exhibits the local non-equilibrium region clearly.

1. Introduction

It is clearly manifested by many engineering practices that the deformation and failure of the disturbed rock mass are time dependent. This kind of deformation and failure directly affect normal operation and long-term stability of rock engineering (Malan, 2002; Hou, 2003).

There are various creep models proposed to describe the time-dependent behavior of rock mass, such as empirical models based on laboratory test (Boukharov et al., 1995; Yang et al., 1999; Aubertin et al., 1999), component models (Li and Xia, 2000; Xia et al., 2008), classical viscoplastic models (Wang et al., 1997; Jin and Cristescu, 1998), and creep models based on fractional derivatives (Koeller, 1984; Zhou et al., 2011).

Numerical analysis method such as finite element method and finite difference method have been employed comprehensively in structural response analysis. Desai and Zhang (1987) introduced a general flow rule in viscoplastic model for geological materials and implemented it in a non-linear finite element procedure to analyze time-dependent behavior of a cavity in rock salt. Golshani et al. (2007) applied the micromechanics-based damage model to assess the safety of underground repositories. Three creep models are adopted by Barla et al. (2008) to study the tunnel response in terms of convergence monitored during excavation. Ghorbani and Sharifzadeh (2009) assessed the long-term stability of powerhouse cavern based on displacement back analysis method. Sharifzadeh et al. (2013) simulated numerically the time-dependent behavior of the rock tunnel considering Burger-creep visco-plastic model. Deng et al. (2014) incorporate the viscoelastic and viscoplastic models into deformation reinforcement theory, simulate the time-dependent deformation and evaluate the stability of gas storage in salt rock.

The time-dependent deformation can be described easily. However, it is hard to assess the long-term stability of underground structures quantitatively. At present, the long-term stability of structure is assessed by displacement, stress fields and some qualitative and empirical indexes like plastic zone (Zhang et al., 2010), creep damage zone (Chen et al., 2006), excavation damaged zone (Golshani et al., 2007) etc. These indexes, strictly speaking, are not quantitative and universal. The traditional creep constitutive model mentioned above can describe time-dependent behavior, but can't represent energy change of structural system, thus the long-term stability analytical method of structure can't be established further.

It is known that thermodynamics with internal state variables theory is a powerful method to construct an appealing constitutive model (Horstemeyer and Bammann, 2010). The models based on

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thermodynamics with internal state variables theory are thermodynamically consistent and could represent the intrinsic energy dissipation process and physical changes of microstructure of material (Lubliner, 1972; Park et al., 1996; Zhu and Sun, 2013). Thus more and more experts have developed creep constitutive equation based on thermodynamics with internal state variables theory (Chaboche, 1997; Schapery, 1997; Voyiadjis and Zolochevsky, 2000, Voyiadjis et al., 2011; Challamel et al., 2005).

Authors has developed a creep model with damage (Zhang et al., 2014a,b) based on thermodynamics with internal state variables theory worked by Rice (1971), and the model can describe viscoelasticity and, preferably, three phases of creep. We also proposed that the integral value of energy dissipation rate and its time derivative in volume domain can be regard as quantitative indexes to evaluate the long-term stability of structure (Zhang et al., 2014a,b). Those works are all theoretical analysis, and the proposed creep model hasn't been used to apply in underground structures analysis.

In this paper, the creep model with damage proposed by authors is improved, and the constitutive equation of the model in central difference form is derived. The redevelopment program interface of *FLAC*^{3D} is used to compile new calculation code based on the proposed creep model, and the new developed program can be called PTV-P for short. Program validation is conducted by comparing results from *FLAC*^{3D} and *Matlab* program considering uniaxial compression condition. Then the developed program is applied to analyze the time-dependent deformation of deep-buried double tunnels, the contour map of energy dissipation rate is used to exhibits the local non-equilibrium region clearly, and the integral values of energy dissipation rate and its time derivative in domain are used to evaluate long-term stability of tunnels quantitatively.

2. A creep model based on thermodynamics with internal state variable

A creep model with damage was derived by authors through giving the complementary energy density function and kinetic equations of internal state variables (Zhang et al., 2014a,b). However, the equations of this model are universal rather than specific form which is available. Moreover, the creep model should be revised under tension condition. In this model, the total strain of material is divided into elastic strain ε_{ij}^{e}, viscoelastic strain ε_{ij}^{ve} and viscoplastic strain ε_{ij}^{vp}.

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{ve} + \varepsilon_{ij}^{vp} \tag{1}$$

where

$$\varepsilon_{ij}^{e} = C_{ijkl}\sigma_{kl} \tag{2a}$$

$$\eta_e\dot{\varepsilon}_{ij}^{ve} + B\varepsilon_{ij}^{ve} = \frac{\partial A}{\partial \sigma_{ij}}A \tag{2b}$$

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\partial f_1}{\partial \sigma_{ij}}\dot{\lambda}_1 + \frac{\partial f_2^p}{\partial \sigma_{ij}}\dot{\lambda}_2 + \frac{\partial f_s}{\partial \sigma_{ij}}\dot{\chi} \tag{2c}$$

Eq. (2a) is elastic constitutive equation. C_{ijkl} is forth-order compliance tensor and σ_{kl} is stress tensor. Eq. (2a) can be rewritten under the hypothesis of isotropy,

$$\varepsilon_{m}^{e} = \sigma_m/3K, \quad e_{ij}^{e} = s_{ij}/2G \tag{3a}$$

where K is elastic bulk modulus, G is elastic shear modulus, ε_m^e is elastic volumetric strain, σ_m is the volumetric stress, e_{ij}^e is elastic deviator strain and s_{ij} is deviator stress.

Eq. (2b) is viscoelastic constitutive equation. η_e is viscoelastic coefficient of viscosity, B is positive material constant with unit of stress, and A is a scalar function of stress. If $A = a\sqrt{s_{ij}s_{ij}/2}$, the Eq. (2b) can be rewritten as

$$s_{ij} = 2\eta_1\dot{e}_{ij}^{ve} + 2G_1e_{ij}^{ve} \tag{3b}$$

where $\eta_1 = \eta_e/a^2, G_1 = B/a^2$, a is a parameter of equation, and e_{ij}^{ve} is viscoelastic deviator strain.

Eq. (2c) is viscoplastic constitutive equation, where λ_1 and λ_2 are macroscopic internal variables used for describing intrinsic structural rearrangement in viscoplastic response, and χ is used to account for the damage effect and other high-energy structural changes. $f_1{}^p$, $f_2{}^p$ and f_s are thermodynamic forces conjugated with internal variables respectively, and they are all scalar function of stress and internal variables. The following assumptions are made,

$$f_1^p = \sqrt{J_2} \tag{4a}$$

$$f_2^p = (1 + b\chi)\left(cI_1 + \sqrt{J_2}\right) \tag{4b}$$

$$f_s = \frac{\partial f_2^p}{\partial \chi}\lambda_2 = b\lambda_2\left(cI_1 + \sqrt{J_2}\right) \tag{4c}$$

where I_1 is the first invariant of stress tensor, J_2 is the second invariant of deviatoric stress tensor, and b and c are all material parameters. Considering Eqs. (2c) and (4), we can get

$$\dot{\varepsilon}_m^{vp} = c[(1 + b\chi)\dot{\lambda}_2 + b\lambda_2\dot{\chi}] \tag{5a}$$

$$\dot{e}_{ij}^{vp} = [\dot{\lambda}_1 + (1 + b\chi)\dot{\lambda}_2 + b\lambda_2\dot{\chi}]\frac{s_{ij}}{2\sqrt{J_2}} \tag{5b}$$

where ε_m^{vp} is viscoplastic volumetric strain and e_{ij}^{vp} is viscoplastic deviator strain.

Eqs. (1), (3) and (5) are the creep constitutive equations with internal state variables. It is clear that the creep strain is controlled by evolution of internal state variable, namely the time-dependent deformation of material which results from internal structural adjustment which is characterized by change of internal state variables. Thus, kinetic equations of internal state variables should be determined. In fact, the kinetic equation of internal variable which on the viscoelastic constitutive Eq. (3b) based is

$$\dot{\xi} = \frac{1}{\eta_e}f_e = \frac{1}{\eta_e}(A - B\xi) \tag{6}$$

where ξ is a internal state variable to describes structural rearrangement in viscoelastic response, and f_e is thermodynamic force conjugated to ξ (Zhang et al., 2014b). Assume that the evolutions of λ_1, λ_2 and χ are as following:

$$\dot{\lambda}_1 = \frac{1}{\eta_{p1}}\langle f_1^p - h\lambda_1\rangle \tag{7a}$$

$$\dot{\lambda}_2 = \kappa_{p2}\left\langle\frac{f_2^p - R}{R}\right\rangle^p \tag{7b}$$

$$\dot{\chi} = \kappa_{p3}\exp(m\chi)\left(\frac{f_s}{R}\right)^2 \tag{7c}$$

where η_{p1}, κ_{p2} and κ_{p3} are all viscosity coefficients, m is parameters of equation, h and R are material constant. Symbol $\langle\,\rangle$ is Macaulay bracket and means

$$\langle x\rangle = \begin{cases} x & x > 0 \\ 0 & x \leqslant 0 \end{cases} \tag{8}$$

Consider Eqs. (4b) and (7b), the following equation is obtained,

$$F = c_1\sigma_m + \sqrt{J_2} - \bar{R}, \quad \bar{R} = R/(1 + b\chi) \tag{9}$$