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Long-term stability analysis of the left bank abutment slope at Jinping I hydropower station

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ABSTRACT

The time-dependent behavior of the left bank abutment slope at Jinping I hydropower station has a major influence on the normal operation and long-term safety of the hydropower station. To solve this problem, a geomechanical model containing various faults and weak structural planes is established, and numerical simulation is conducted under normal water load condition using FLAC^{3D}, incorporating creep model proposed based on thermodynamics with internal state variables theory. The creep deformations of the left bank abutment slope are obtained, and the changes of principal stresses and deformations of the dam body are analyzed. The long-term stability of the left bank abutment slope is evaluated according to the integral curves of energy dissipation rate in domain and its derivative with respect to time, and the non-equilibrium evolution rules and the characteristic time can also be determined using these curves. Numerical results show that the left bank abutment slope tends to be stable in a global sense, and the stress concentration is released. It is also indicated that more attention should be paid to some weak regions within the slope in the long-term deformation process.

1. Introduction

The time-dependent deformation of rock mass is inevitable when a preexisting equilibrium of rock mass is disturbed by excavation, impounding, etc (Fakhimi and Fairhurst, 1994). The time-dependent mechanical behavior of rock mass directly affects normal operation and long-term safety of geotechnical engineering, and can be described by the creep model which is the key to stability analysis.

With the development of computation technology and analytical methods, numerical simulations combined with creep models are commonly used in geotechnical engineering (Desai and Zhang, 1987; Barla et al., 2008; Ghorbani and Sharifzadeh, 2009; Deng et al., 2014), for description of the time-dependent deformation of rock mass. The long-term stability of excavations can be evaluated qualitatively using empirical indices such as plastic zone (Zhang et al., 2010), creep damage zone (Chen et al., 2006), excavation damaged zone (Golshani et al., 2007). It is obvious that, at present, strict and quantitative indices are deficient in evaluating the long-term stability of excavations, and the unified and definite stability criteria are also rarely reported. One of the main reasons is probably that the conventional creep models based on rheology can merely consider the time-dependent behavior, and they can hardly describe the intrinsic energy change of material system in time-dependent mechanical processes, which is closely connected to the stability state of materials.

Thermodynamics with internal state variables (ISVs) proposed by Rice (1971) is a powerful method to construct the appealing constitutive equations (Horstemeyer and Bammann, 2010). The models based on thermodynamics with ISVs are thermodynamically consistent and can characterize the intrinsic energy dissipation process and physical changes of microstructure of materials (Lubliner, 1972; Park et al., 1996; Zhu and Sun, 2013). Thus, various researchers develop creep constitutive equations (Chaboche, 1997; Schapery, 1999; Voyiadjis and Zolochevsky, 2000; Challamel et al., 2005; Voyiadjis et al., 2011) based on thermodynamics with ISVs.

Jinping I hydropower station is located on Yalong River in Sichuan Province, China, and it is the topmost concrete arch dam in the world at present. The excavation height of left abutment slope is about 530 m, and the excavation volume is approximately 5.5 million cubic meters, one of the slope projects with the highest excavation height, the largest scale of excavation, and the worst geological condition in China (Xue et al., 2012). The monitoring data showed that the time-dependent deformation of the left abutment slope occurred after excavation (Wang et al., 2014).

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In this paper, a creep model with damage, which has been developed by Zhang et al. (2014a, b), is briefly introduced at first. Then the creep model is introduced to FLAC^{3D} (Itasca, 2003) and two calculation codes called CTV-E and CTV-P are developed, respectively. The changes of deformation and stress of dam body, caused by time-dependent deformation of the left bank abutment slope, are explored. Long-term stability of the left bank abutment slope is evaluated by integral curves of energy dissipation rate in domain and its derivative with respect to time. The non-equilibrium evolution rules and the characteristic time are also determined through these curves. Meanwhile, it is indicated that more attention should be paid to some weak regions, where relatively large energy dissipation rates are observed within the slope in the long-term deformation process.

2. Creep model with damage

In the creep model, total strain ε_{ij} is divided into elastic strain ε_{ij}^{e}, viscoelastic strain ε_{ij}^{ve} and viscoplastic strain ε_{ij}^{vp}, i.e.

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

where

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

$$\eta_e \dot{\varepsilon}_{ij}^{ve} + B\varepsilon_{ij}^{ve} = \frac{\partial A}{\partial \sigma_{ij}}A \tag{3}$$

$$\dot{\varepsilon}_{ij}^{vp} = \frac{\partial f_1^p}{\partial \sigma_{ij}}\dot{\lambda}_1 + \frac{\partial f_2^p}{\partial \sigma_{ij}}\dot{\lambda}_2 + \frac{\partial f_s}{\partial \sigma_{ij}}\dot{\chi} \tag{4}$$

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

$$\varepsilon_m^e = \sigma_m/(3K), \;\; e_{ij}^e = s_{ij}/(2G) \tag{5}$$

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

Eq. (3) is the viscoelastic constitutive equation, in which η_e is the viscoelastic coefficient of viscosity, B is the material constant in Pa, and A is a scalar function of stress. Specially, if we have

$$A = a\sqrt{s_{ij}s_{ij}/2} \tag{6}$$

then Eq. (3) can be rewritten as

$$s_{ij} = 2\eta_1\dot{e}_{ij}^{ve} + 2G_1 e_{ij}^{ve} \tag{7}$$

where $\eta_1 = \eta_e/a^2$, $G_1 = B/a^2$, a is a parameter, and e_{ij}^{ve} is the viscoelastic deviator strain. Obviously, the viscoelastic volumetric strain ε_m^{ve} can be written as

$$\varepsilon_m^{ve} = 0 \tag{8}$$

In fact, Eq. (3) is based on the kinetic equation of an internal variable, i.e.

$$\dot{\xi} = \frac{1}{\eta_e}f_e = \frac{1}{\eta_e}(A - B\xi) \tag{9}$$

where ξ is an ISV to describe the structure rearrangement in viscoelastic process, and f_e is the thermodynamic force conjugated to the variable ξ (Zhang et al., 2014a).

Eq. (4) is the viscoplastic constitutive equation, in which λ_1 and λ_2 are the macroscopic internal variables used for describing the intrinsic structure rearrangement in viscoplastic response; χ is used to account for the damage effect and other high-energy structure changes; f_1^p, f_2^p and f_s are the thermodynamic forces conjugated with internal variables, and they are all scalar functions of stress and internal variables. In this context, the following assumptions are made:

$$f_1^p = \sqrt{J_2} \tag{10}$$

$$f_2^p = (1 + b\chi)\left(cI_1 + \sqrt{J_2}\right) \tag{11}$$

$$f_s = b\lambda_2\left(cI_1 + \sqrt{J_2}\right) \tag{12}$$

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 the material parameters. From Eqs. (4) and (10)–(12), we can obtain the following equations:

$$\dot{\varepsilon}_m^{vp} = c\left[(1 + b\chi)\dot{\lambda}_2 + b\lambda_2\dot{\chi}\right] \tag{13}$$

$$\dot{e}_{ij}^{vp} = \left[\dot{\lambda}_1 + (1 + b\chi)\dot{\lambda}_2 + b\lambda_2\dot{\chi}\right]\frac{s_{ij}}{2\sqrt{J_2}} \tag{14}$$

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

It is clear that the rate of viscoplastic strain is controlled by the evolution of ISV. We assume the evolutions of λ_1, λ_2 and χ as follows:

$$\dot{\lambda}_1 = \frac{1}{\eta_{p1}}\langle f_1^p - h\lambda_1\rangle \tag{15}$$

$$\dot{\lambda}_2 = \kappa_{p2}\left\langle\frac{f_2^p - R}{R}\right\rangle^p \tag{16}$$

$$\dot{\chi} = \kappa_{p3}\exp(m\chi)\left(\frac{f_s}{R}\right)^2 \tag{17}$$

where η_{p1}, κ_{p2} and κ_{p3} are all viscosity coefficients; m, h, p and R are the material constants; and the symbol $\langle\cdot\rangle$ is the Macaulay bracket. Consider Eq. (11), the following equation is obtained:

$$F = cI_1 + \sqrt{J_2} - \overline{R}, \;\; \overline{R} = R/(1 + b\chi) \tag{18}$$

It is clear that Eq. (18) is similar to the Drucker–Prager (D–P) yield criterion. Only when F is larger than 0, the ISV λ_2 will increase. In fact, Eq. (18) can only describe the shear-compression case, thus the creep under tension condition should also be considered. For this, the following tension criterion is adopted:

$$G = \sigma_m - \sigma^{vt} = 0 \tag{19}$$

where σ^{vt} is the material coefficient like tensile strength. Using Eqs. (18) and (19), the domains used in definition of evolution equations are plotted in Fig. 1.

In Fig. 1, the criteria $F = 0$ and $G = 0$ are sketched in $(\sqrt{J_2}, \sigma_m)$ plane. The intersection point of $F = 0$ and $G = 0$ is $B1$, and the curve $h_s = 0$, which passes the intersection point $B1$, is defined as

$$\sqrt{J_2} - a^p\sigma_m - \overline{R} + (a^p + c_1)\sigma^{vt} = 0 \tag{20}$$

where $c_1 = 3c$, a^p is the slope of the curve $h_s = 0$ and defined as $a^p = \sqrt{1 + c_1^2} - c_1$ in this study.