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Excavation-induced relaxation effects and hydraulic conductivity variations in the surrounding rocks of a large-scale underground powerhouse cavern system

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ABSTRACT

Located in the middle reach of Yalong River in China, the Jinping-I Hydropower Station consists of a large-scale cavern system for water conveyance and power generation. Compared to other typical large-scale underground powerhouse cavern systems in Southwestern China, the construction site is characteristic of higher in situ geostresses, lower uniaxial compressive strength (UCS) and poorer quality of the surrounding rocks, resulting in greater depth of the disturbed zone. In this study, the excavation-induced relaxation effects and their impacts on the hydraulic conductivity variations and seepage behaviors in the surrounding rocks of the Jinping-I underground powerhouse caverns were assessed with site characterization data and numerical simulations. The excavation-induced disturbance zones around the caverns were modeled using the plastic yield zone predicted with an equivalent elasto-plastic model and a constant deviatoric stress criterion based on the Hoek–Brown parameters of the surrounding rocks, respectively. The predicted results agree rather well with the disturbed zones detected by the in situ acoustic wave velocity measurements and borehole TV images. The excavation-induced permeability changes in the surrounding rocks were characterized with a strain-dependent hydraulic conductivity model that accounts for the development patterns and deformation behaviors of the critically-oriented fractures. The seepage behaviors with consideration of the permeability changes in the surrounding rocks were modeled with a variational inequality method at a steady state, and the numerical results imply the significance of proper characterizations of the excavation-induced disturbance effects and permeability changes in better understanding the groundwater flow and its controlled effect in the surrounding rocks.

1. Introduction

The excavation of underground caverns induces stress redistribution and concentration, fracture deformation and propagation, as well as crack initiation and growth in the surrounding rocks, leading to formation of an excavation-disturbed (damaged) zone (EDZ). In EDZ, remarkable deterioration of mechanical behaviors and drastic enhancement of hydraulic properties are induced, which influences the stability of the caverns and the groundwater flow in the surrounding rocks. In engineering practices, the EDZ around an excavation is commonly assessed by changes in the magnitudes of deformation (Bizjak and Petkovšek, 2004; Li et al., 2008; Zhu et al., 2014), acoustic wave (Deng et al., 2001; Kwon et al., 2009; Lu et al., 2013), microvelocity and transmissivity (Martino and Chandler, 2004) and acoustic emission and microseismic events (Cai et al., 2001; Malmgren et al., 2007), together with borehole TV technique (Wu et al., 2009; Li et al., 2013b) and electrical resistivity tomography (Suzuki et al., 2004; Zhu et al., 2014), etc. In situ measurements have shown that the excavation of a tunnel with several meters in diameter, even within intact crystalline rocks but under high geostress conditions, would lead to a dramatic increase of permeability up to or over three orders of magnitude in the EDZ near the excavation surface (Kelsall et al., 1984; Pusch, 1989; Souley et al., 2001; Martino and Chandler, 2004). In Southwestern China, tens of large-scale underground powerhouse cavern systems have been completed or under construction in narrow valley areas, with the EDZs most

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commonly detected by the deformation and acoustic wave monitoring techniques because of their low cost, high accuracy and convenience (Li, 1999; Zou and Xiao, 2010; Li et al., 2013a; Zhu et al., 2013). The size of the EDZs around the caverns and the resultant hydraulic property alteration are expected to be larger due to difficult geological conditions, large scale and interaction of caverns.

Numerical tools have also been widely used for characterization of the mechanical behaviors in the EDZs, using an elasto-plastic model (Chen et al., 2007), a brittle model (Sheng et al., 2002; Martin et al., 1999), a time-dependent model (Chen et al., 2012), a damage model (Shao et al., 1999; Souley et al., 2001) or a micromechanical model (Cai and Kaiser, 2005; Chen et al., 2014a, 2014b). The hydraulic properties in the EDZs are then assessed using an averaging or homogenization method with consideration of the geometries and connectivity of fractures and cracks (Oda, 1986; Liu et al., 1999; Souley et al., 2001; Chen et al., 2007, 2014a). Among them, the strain-dependent hydraulic conductivity model developed by Chen et al. (2007) uses an equivalent elasto-plastic approach for characterizing the normal compression and shear dilatancy of factures and overall representing the mechanical and hydraulic responses in the EDZs. This model was validated against field test data (Chen et al., 2007), and has been applied to characterization of the coupled hydro-mechanical properties of the EDZ around a large-scale underground cavern system in Southwestern China (Li et al., 2014).

In this study, the EDZ of the underground powerhouse caverns at Jinping-I Hydropower Project is characterized with the above-mentioned equivalent continuum model, with the EDZ estimated by the plastic yield zone and a deviatoric stress threshold determined by the Hoek–Brown parameters (Martin et al., 1999), respectively. The numerical results are compared with the zones assessed by the acoustic wave monitoring data and borehole TV images. The excavation-induced variation in hydraulic conductivity in the surrounding rocks is then assessed. The seepage field in the surrounding rocks of the caverns is calculated with a variational inequality method (Chen et al., 2008), and the results are compared against the field monitoring data.

2. A brief review of the strain-dependent hydraulic conductivity model

Consider a representative elementary volume (REV) of a fractured rock cutting by multiple sets of planar and parallel fractures with different apertures, orientations, scales and densities, as motivated by the observations that natural fractures in fractured rocks are mostly clustered in certain critical orientations resulting from their geological modes and history of formation (Jing, 2003). Following the idea by Chen and Egger (1999), we assume that in a global coordinate frame, the fractures and rock matrix share the same stress applied to the boundary of the REV, while the total strain of the REV is composed of the components from rock matrix and fractures:

$$\mathrm{d}\boldsymbol{\sigma}' = \mathrm{d}\boldsymbol{\sigma}'^R = \mathrm{d}\boldsymbol{\sigma}'^F \tag{1a}$$

$$\mathrm{d}\boldsymbol{\varepsilon} = \mathrm{d}\boldsymbol{\varepsilon}^R + \sum_F \mathrm{d}\boldsymbol{\varepsilon}^F \tag{1b}$$

where $\boldsymbol{\sigma}'$ and $\boldsymbol{\varepsilon}$ are the effective stress and strain prescribed on the boundary of the REV, $\boldsymbol{\sigma}'^R$ and $\boldsymbol{\sigma}'^F$ are the effective stresses of rock matrix and the fth set of fractures defined in the global coordinate frame, respectively, and $\boldsymbol{\varepsilon}^R$ and $\boldsymbol{\varepsilon}^F$ the strains of rock matrix and the fth set of fractures, respectively.

The assumptions in Eq. (1) neglect the interactions and spatial correlations between fractures and rock matrix, and lead to the following Reuss (or lower-bound) estimate of the effective elastic moduli of the fractured rock:

$$\mathrm{d}\boldsymbol{\varepsilon} = \boldsymbol{S}^{ep} : \mathrm{d}\boldsymbol{\sigma}' \tag{2a}$$

$$\boldsymbol{S}^{ep} = \left(\boldsymbol{C}^{R,ep}\right)^{-1} + \sum_F \left(\boldsymbol{C}^{F,ep}\right)^{-1} \tag{2b}$$

where $\boldsymbol{S}^{ep}$ is the equivalent elasto-plastic compliance tensor of the fractured rock, $\boldsymbol{C}^{R,ep}$ and $\boldsymbol{C}^{F,ep}$ the elasto-plastic modulus tensors of rock matrix and the fth set of fractures, respectively. In this study, both fractures and rock matrix are modeled with the associated Mohr–Coulomb yield criterion. Interested readers may refer to Chen et al. (2007) for details of the constitutive model, which contains 8 parameters, i.e. the elastic modulus E, Poisson's ratio μ, cohesion c_r and friction angle ϕ_r of rock matrix and the normal stiffness k_{nf}, shear stiffness k_{sf}, cohesion c_f and friction angle ϕ_f of the fth set of fractures.

At any loading or excavation step, the local strain $\boldsymbol{\varepsilon}^f$ pertinent to the fth set of fractures can be expressed as follows:

$$\mathrm{d}\boldsymbol{\varepsilon}^F = \left(\boldsymbol{C}^{F,ep}\right)^{-1} : \mathrm{d}\boldsymbol{\sigma}' \tag{3a}$$

$$\mathrm{d}\varepsilon_{ij}^f = l_{im} l_{jn} \mathrm{d}\varepsilon_{mn}^F \tag{3b}$$

where l is a second order tensor for transforming physical quantities from the global frame to the local frame attached on the fth set of fractures.

Let the mean initial aperture and spacing of the fth set of fractures be b_{f0} and s_f, respectively. The contribution of the fth set of fractures to the hydraulic conductivity of the fractured tock, k_{f0}, can be represented as (Snow, 1969; Liu et al., 1999):

$$k_{f0} = \xi \frac{g b_{f0}^3}{\nu s_f} \tag{4}$$

where ν is the kinematic viscosity of groundwater, g the gravitational acceleration, and ξ $(0 < \xi < 1/12)$ a dimensionless constant introduced for considering the deviation of the flow behavior in rock fractures with rough walls, material fillings and finite scales from the ideal conditions assumed in the parallel smooth plate model.

Given the fact that the change in the spacing of fractures, s_f, is negligible under small deformation condition, Eq. (4) can be rewritten to the following form as the fractures are subjected to normal and shear stress loading:

$$k_f = \xi \frac{g b_f^3}{\nu s_f} = \xi \frac{g(b_{f0} + \Delta b_f)^3}{\nu s_f} \tag{5}$$

where Δb_f is the increment of the aperture of the fth set of fractures under loading, and it can be approximated by:

$$\Delta b_f = s_f \Delta\varepsilon_{zf} \tag{6}$$

where $\Delta\varepsilon_{zf}$ is the increment of the normal strain of the fth set of fractures, which is directly obtained from Eq. (3).

Substituting Eq. (6) into Eq. (5) then yields:

$$k_f = k_{f0}\left(1 + \frac{s_f}{b_{f0}}\Delta\varepsilon_{zf}\right)^3 \tag{7}$$

Following the theory proposed by Snow (1969), the effective hydraulic conductivity of a fractured rock with n sets of fractures is finally represented as:

$$\boldsymbol{K} = \sum_f k_{f0}\left(1 + \frac{s_f}{b_{f0}}\Delta\varepsilon_{zf}\right)^3 (\boldsymbol{\delta} - \boldsymbol{n}_f \otimes \boldsymbol{n}_f) \tag{8}$$

where $\boldsymbol{n}_f$ is the unit vector normal to the fth set of fractures, and $\boldsymbol{\delta}$ the Kronecker delta tensor.

The above model was implemented in a computer code, THYME3D, initially developed for coupled deformation/multiphase