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Research Paper

Inverse modelling of groundwater flow around a large-scale underground cavern system considering the excavation-induced hydraulic conductivity variation

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ABSTRACT

This study proposed an inverse modelling procedure for evaluating the anisotropic hydraulic conductivity and its variation induced by excavation in fractured rocks by integrating a strain-dependent hydraulic conductivity model. The time-series measurements of both hydraulic head and discharge were used to construct the objective function for improving the reliability, which was solved with a combined method of orthogonal design, transient groundwater flow modelling, artificial neural network and genetic algorithm-based optimization for reducing the computational cost. The proposed methodology proves its effectiveness by successful inverse modelling of the groundwater flow around the underground caverns at the Jinping-I Hydropower Station.

1. Introduction

The hydraulic conductivity of fractured rocks is an important hydraulic property for the modelling of groundwater flow and the design of engineering barriers in fractured aquifers [29,25,40,22]. Macroscopically, this property is mainly controlled by the geometry and connectivity of the fracture system, and may become highly anisotropic as a result of directional fracture development associated with geologic processes. As the fracture geometry changes under excavation and loading conditions, the hydraulic conductivity varies accordingly [27,32,3,21,9]. In civil engineering practices, the magnitude of hydraulic conductivity in fractured rocks is commonly estimated by means of single-hole packer tests for their low cost and easy operation [12]. The test data interpretation, however, suffers from the difficulties in characterizing the anisotropy of fractured rocks, assessing the excavation-induced change in permeability and selecting a value representative of the formations at the site scale, which may lead to improper design of drains and barriers for control of groundwater flow [33,36,37,40,10]. Analytical models based on the statistical data of fracture geometries (e.g. [31,26,19,24]) and inverse models based on field observations (e.g. [13,30,40,10,11]) become effective alternatives for more reasonably estimating the hydraulic conductivity of fractured aquifers in field conditions.

The inverse modelling of groundwater flow is mostly performed based on hydraulic head measurements and/or under steady-state flow conditions (e.g. [38,13,14,2,17,34]). These inverse procedures could be more easily implemented, but the inverse results may be plagued with the non-uniqueness problem and fail to reflect the transient nature of field observations. To improve the accuracy of inverse modelling, Zhou et al. [40] and Chen et al. [10] proposed an inverse modelling technique that utilizes the time series measurements of both hydraulic head and flow rate for improving the accuracy of the modelling results. With this technique, both the magnitudes and directions of the principal hydraulic conductivities (or hydraulic conductivity tensors) could be reliably back-calculated for rock formations by properly integrating the site investigation data. The excavation-induced variation in hydraulic properties, even could be hopefully estimated by stepwise inverse calculations, remains to be more efficiently addressed in the inverse modelling.

It has been long observed that the excavation of rock foundations and underground openings induces a dramatic increase of permeability in the damaged zones, typically by 2–4 orders of magnitude [18,27,32]. Quite a number of damage- or fracture deformation-based analytical models were proposed for characterizing the permeability changes induced by excavation or mechan-

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ical loading [20,3,16,1], with some of them being successfully applied in engineering practices [21,9]. These models relate the structural alterations such as microcracking in rocks and deformation in fracture systems to the induced permeability variations, but suffer from the difficulties in directly measuring the geometric or hydraulic parameters that represent the initial permeability of fractured rocks.

This study proposes to integrate the strain-dependent hydraulic conductivity model into the inverse modelling procedure developed by the authors [3,40,10], for more efficiently and representatively estimating the anisotropic hydraulic conductivity and its variation in fractured rocks. The basic idea is to quantify the excavation-induced permeability changes with the analytical model, but leave the initial apertures or equivalent hydraulic conductivities of the critically-oriented fracture groups in rock formations, which are hard to measure in field conditions, for back analysis. The goal of the inverse modelling is to minimize an error function constructed with the hydraulic head and discharge time series measurements, such that the back-calculated geometric or hydraulic parameters of fractures are well representative of the site conditions. The proposed method is applied to inverse modelling of the groundwater flow behaviors in the surrounding rocks of the underground cavern system at the Jinping-I Hydropower Station. The initial anisotropic hydraulic conductivities of the surrounding rocks before construction were determined, and the excavation-induced hydraulic conductivity changes were characterized. The groundwater flow behaviors around the cavern system and the performance of the seepage control system were finally assessed.

2. Methodology

2.1. Characterization of hydraulic conductivity variation

The hydraulic conductivity of fractured rocks depends in essence on the geometric properties (e.g. orientation, density, aperture, roughness, spacing and connectivity) of the fractures ubiquitously developed in the rocks. It evolves, therefore, as the fractures deform or the rock structures alter under excavation or loading. A great number of analytical models have been developed to characterize the anisotropic hydraulic conductivity and its variation in rocks, typically by relating it to the growth of damage (e.g. [28,16,7,8]) or the deformation of fractures (e.g. [31,26,20,19,3,39]). Among them, the model developed by Snow [31] is simple in form by directly adding the respective components of permeability contributed by each group of fractures, and provides an upper-bound estimate of permeability for fractured rocks. Although this model does not directly consider the effects of the scale and the connectivity of fractures, it well represents the anisotropy of permeability based on the limited geometric data of fractures and hence serves as an important basis for further development (e.g. [20,3,39]).

The model developed by Chen et al. [3] is one based on Snow's model and on the fact that natural fractures are most often clustered in certain critical orientations as a result of their geological modes and history of formation. The normal compression and shear dilatancy of fractures are characterized with an equivalent elasto-plastic constitutive model, by treating the fractured rocks as an anisotropic continuum containing both rock matrix and fractures. Without going into the details, Chen's model is given by

$$\boldsymbol{K} = \sum_f k_{0f}\left(1 + \frac{s_f}{b_{0f}}\Delta\varepsilon_{zf}\right)^3 (\boldsymbol{\delta} - \boldsymbol{n}_f \otimes \boldsymbol{n}_f) \tag{1}$$

where $\boldsymbol{K}$ is the equivalent hydraulic conductivity tensor, k_{0f}, b_{0f}, s_f and $\boldsymbol{n}_f$ are, respectively, the initial hydraulic conductivity, initial mean aperture, spacing and normal vector of the fth critically-oriented group of fractures, and $\boldsymbol{\delta}$ is the second-order identity tensor. $\Delta\varepsilon_{zf}$ is the increment of the normal strain of the fth group of fractures, which is calculated with the equivalent elasto-plastic constitutive model [3]. When both fractures and rock matrix are modeled with the associated Mohr-Coulomb yield criterion, the constitutive model 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 group of fractures [9].

In Eq. (1), k_{0f} is related to b_{0f} by applying the cubic law [31,20]:

$$k_{0f} = \frac{g b_{0f}^3}{12 \nu s_f} \tag{2}$$

where ν is the kinematic viscosity of groundwater, and g is the gravitational acceleration.

Note that in Eq. (1), s_f is generally available by statistics of the fracture mapping data, while k_{0f} or b_{0f} is hard to be accurately measured in field conditions without performing time-consuming and expensive hydraulic tests. In this study, inverse modelling will be used to obtain a more representative estimate of k_{0f} or b_{0f}, and hence the anisotropic hydraulic conductivity, for each rock formation on the field scale. In this way, the connectivity and interaction of fractures, although not explicitly represented in the model, could be overall reflected with the back-calculated mean initial apertures.

2.2. Inverse modelling of groundwater flow

Besides the difficulty in estimating the initial aperture or permeability of fractures, as clarified above, another difficulty posed in the analysis of groundwater flow is to properly determine the boundary conditions, given that the concerned site scale in dam engineering is generally much smaller than the scale of a hydrogeological unit. The latter difficulty could also be addressed with inverse modelling. Therefore, the goal of the inverse modelling is to seek a representative set of parameters, $\boldsymbol{k}_0$ and $\bar{\boldsymbol{\phi}}$, such that the following objective function is minimized:

$$\min f(\boldsymbol{k}_0, \bar{\boldsymbol{\phi}}) = \sum_{i=1}^{M} \frac{\|\boldsymbol{\phi}_i(\boldsymbol{k}_0, \bar{\boldsymbol{\phi}}) - \tilde{\boldsymbol{\phi}}_i\|_2^2}{\dim \boldsymbol{\phi}_i} + w \sum_{i=1}^{N} \frac{\|\boldsymbol{Q}_i(\boldsymbol{k}_0, \bar{\boldsymbol{\phi}}) - \tilde{\boldsymbol{Q}}_i\|_2^2}{\dim \boldsymbol{Q}_i} \tag{3}$$

where $\boldsymbol{k}_0$ is a vector representing the initial aperture of fractures, with its dimension determined by the number of rock formations and the number of fracture groups in each formation; $\bar{\boldsymbol{\phi}}$ is a small set of parameters that represent the water head boundary conditions; M is the number of piezometers, $\tilde{\boldsymbol{\phi}}_i$ and $\boldsymbol{\phi}_i$ are the time series measurements of hydraulic head and the corresponding numerical results at piezometer i, respectively; N is the number of weirs or flowmeters, $\tilde{\boldsymbol{Q}}_i$ and $\boldsymbol{Q}_i$ are the time series measurements of flow rate and the numerical results at weir i, respectively; $\|\cdot\|_2$ and dim $(\cdot)$ denote the Euclidean norm and the dimension of a vector, respectively; and w is a weight coefficient to ensure a balance between the relative errors of the hydraulic head and flow rate measurements. Here it is to be mentioned that the weight coefficient w is essentially introduced to address a multi-objective optimization problem (where the first and second error terms in Eq. (3) should be respectively minimized) using the single-objective optimization technique. The choice of w depends on the absolute errors of hydraulic head and discharge (which are related to the units and data points of the measurements as well as the number of piezometers and the number of weirs). Interested readers may refer to Zhou et al. [40] for more details about the influence of w on the inverse modelling results.

The utilization of the time series observations of both hydraulic head and flow rate improves the reliability of the inverse mod-