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Coupled hydro-mechanical model for fractured rock masses using the discontinuous deformation analysis

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ABSTRACT

A coupling analysis model is proposed to study the hydro-mechanical response of the fluid flow in fractured rock mass with the method of discontinuous deformation analysis (DDA). The DDA coupled hydro-mechanical model is interpreted in details by expressing the fracture fluid flow equations, the coupling process and the global coupled equations. For the mechanical response, the hydraulic pressure is determined first, followed by the coupled motion equations expressed under the DDA framework, to study the interaction between the fluid flow along the fractures and the movement of the rock blocks. In the fluid flow analysis, the cubic law is applied to study the steady flow along the fractures using the finite difference method (FDM). A real case of cavern excavation is analyzed by the proposed DDA coupled 2D hydro-mechanical model, to study the influence of fluid flow on the rock cavern stability during the excavation phase. The results show that the DDA coupled hydro-mechanical model is suitable for the stability and seepage analysis of practical engineering problems.

1. Introduction

The coupling analysis between the fluid flow and stress/deformation in fractured rock mass has become increasingly important in rock mechanics and rock engineering, mainly due to the design requirement and performance assessment of underground facilities, such as storage cavern for liquefied petroleum gas, in which the interactions between the fluid and the rock mass play important roles. Under the influence of fluid, the apertures of the pre-existing joints in the rock mass may open or close, inducing the change of hydraulic transmissivity rapidly; at the same time, the alteration of the apertures, in turn, change the hydraulic pressure on the rock joints and may also alter the structure of the rock (Esaki et al., 1999; Rutqvist and Stephansson, 2003; Chen et al., 2007). During this process, the fractured structures are easy to lose their overall stability due to the reduction of the effective normal stresses. Therefore, it is necessary to understand the interactive mechanism between the hydraulic properties and the stress–deformation of the rock mass, so that the risk can be evaluated and reduced while sufficient protective measures can be provided during the construction and operation of underground facilities.

Conventional approaches for fluid flow in fractured rock mass can be classified as continuous method and discontinuous method. The coupled hydro-mechanical models based on continuous methods, such as the finite difference method (FDM) (Narasimhan and Witherspoon, 1976) and the finite element method (FEM) (Koyama et al., 2009), assume that if there are sufficient variable oriented and connected fractures in the rock mass, flow can be considered to be through the porous media (Lee et al., 1994; Zhou et al., 2008). The FEM method is more flexible in solving the fluid flow problems in the fractured media, but large-scale openings and slidings are not easy to be solved precisely without the complex computation schemes; in addition, ill-conditioning of the global stiffness matrix may appear when many fractures are incorporation (Jing, 2003). To solve the fracture elements incorporated problem, the boundary element method (BEM) can be combined with the FEM for the coupled hydro-mechanical model (Cammarata et al., 2007). However, the FEM/BEM hybrid approach often leads to a complex computational scheme. In the discontinuous method, fractures can be modeled individually and applied with joint material properties, so that influence can be checked for each fracture under the hydraulic pressure. The discrete element method (DEM), such as the UDEC code, can solve the transient flow problems and steady flow problems through fractures. However, if the joint roughness is not considered in UDEC, the aperture is only updated according to the approximated linear relationship between the aperture width and the contact stress. Furthermore, the time step should be chosen carefully in order to prevent the computational instability (Jing, 2003; Itasca, 2005), as UDEC uses the explicit time-marching scheme. The DDA is an implicit method that has some basic advantages over the DEM in the coupled hydro-mechanical analysis. Firstly, the time step can be larger without inducing instability; secondly, it is easy to convert an

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existing FEM code into the DDA code. Investigations on the hydro-mechanical analysis based on the DDA have been carried out over the last decade. Kim et al. (1999) developed a hydro-mechanical model with the hybrid DDA-FEM approach. The stress–deformation of the rock block was studied with the DDA, while the fluid flow through fractures was modeled by the FEM. Rouainia et al. (2006) used two modeling environments, HYDRO and DDA, to realize the coupled hydro-mechanical model. In their model, the hydraulic pressure was only represented as the nodal force and added on the boundary, which was simple in implementation. Jing et al. (2001) developed the coupled model with a flexible method. In his model, the fluid pressure was derived with closed-form expressions and applied to the block system, which has overcome the strain-block geometry incompatibility in some DDA formulations. Also, a residual flow method was introduced to the flow algorithm to solve the unconfined flow problems with free surfaces. However, in his publication, only simple experimental model was used to verify the flow through the fractured network, no case study was shown for the improved DDA coupled hydro-mechanical model.

The purpose of this study is to develop a conceptual coupled hydro-mechanical model based on the DDA framework, which can be used for the real engineering problems analysis. In this model, fractures are considered to be the only path for the fluid flow, which are treated as the plated model without considering the roughness. Only steady flow is considered, and the cubic law is applied to solve the fluid flow problems. As the blocky system is not considered to have larger deformation or movement in the simulation, the fracture network is fixed during the whole calculation process, and the new fracture generation and fractures propagation are not included. All the physical parameters used in the validation cases remain constant during the whole simulation, so that the changes of the parameters under the hydraulic pressure are not taken into consideration. Although the proposed numerical model is at its preliminary stage, it can be used to study the complex interactions between the flow and the corresponding stress in an efficient manner.

In the following sections, a comprehensive description of the coupled hydro-mechanical model is presented, and the details of the validation case study are discussed. The numerical results are compared with the site investigated data to verify the applicability of the proposed model. Also, a comparison between the coupled model and an uncoupled model shows that the coupled model can provide more realistic analysis results under the fluid flow conditions.

2. Governing equations for the coupled hydro-mechanical model

2.1. DDA equations for block deformation and movement

The discontinuous deformation analysis (DDA) is used for analyzing force–displacement interactions of the block systems. Similar to the FEM, it uses the displacements as the unknowns and solves the equilibrium equations. The DDA formulation is based on a dynamic equilibrium that kinematics of each blocks and frictions along the block interfaces are considered. Small displacements and deformations are updated in the previous time step. The large displacements and deformations of the whole block system are accumulated by the small displacements and deformations in each time step. All the blocks are considered to have constant stresses and constant strains, and each block has six degrees of freedom, so the displacement (u, v) at any point (x, y) inside block i can be represented by a complete first order approximation function (Shi, 1988; Bao, 2007; Sun et al., 2011a,b):

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} 1 & 0 & -(y-y_0) & (x-x_0) & 0 & (y-y_0)/2 \\ 0 & 1 & (x-x_0) & 0 & (y-y_0) & (x-x_0)/2 \end{pmatrix} \begin{pmatrix} u_0 \\ v_0 \\ r_0 \\ \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} \quad (1)$$

where u_0, v_0 are the rigid body translations at the point (x_0, y_0) along the x and y directions; r_0 is the rigid body rotation in radian around the point (x_0, y_0); ε_x, ε_y, γ_{xy} are normal and shear strains of the block. These six unknowns are corresponding to the general block deformation and movement.

As blocks are connected, a block system can be formed through the contacts between blocks and the constrained displacement on individual blocks (Shi, 1988; Sun et al., 2011a,b). Supposing that there are n blocks in the block system, the simultaneous equilibrium equations can be expressed in a matrix form as:

$$\begin{bmatrix} k_{11} & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{n1} & \cdots & k_{nn} \end{bmatrix} \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_n \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ \vdots \\ F_n \end{pmatrix} \quad (2)$$

where (d_i) represents the deformation vector, (F_i) is the loading vector distributed to the six deformation variables, and $[k_{ij}]$ is the material/contact matrix.

2.2. Hydraulic pressure equations under the DDA framework

Cubic law is used to determine the seepage rate along the fractures. However, cubic law is only suitable for the small size of the fractures, where the hydraulic pressure can be linearized. But for the long fracture, as the hydraulic pressure may vary along the fractured length, the seepage rate is changed section by section. In this coupled DDA-hydro mechanical model, cubic law is still applied and the hydraulic pressure is considered to distribute linearly along the long fractures. Because the aperture width will be deducted by the investigated seepage rate from site, some factors that influent the hydraulic pressure distribution and also the seepage rate have been considered when applying this aperture width into cubic law for calculation. Also, the linearized hydraulic pressure can help to simplify the coupled DDA-hydro mechanical model at this preliminary stage.

As hydraulic pressure is considered to be distributed linearly along the fractures, a line load can be used to represent the hydraulic pressure in the DDA coupled model (Fig. 1). The hydraulic pressure in the DDA is formulated with the energy minimization method, which can be derived as a 6×1 sub-matrix and added into the global sub-matrix $[F_i]$ in the DDA easily.

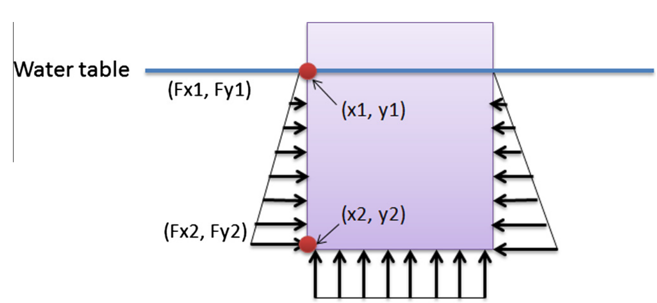

Fig. 1. Hydraulic pressure added on the block boundaries.