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Research Paper

Seepage simulation using pipe network flow model in a discrete element system

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ABSTRACT

The pipe network flow model can simulate the seepage process with DEM conveniently because of its simple algorithm. However, whether it can recover the correct seepage process has not been verified. In this paper, the equation to update the fluid pressure is rebuilt according to the flow conservation. Through the steady seepage simulation, this algorithm is verified to be able to recover Darcy's law, and the equation to calibrate the aperture according to macro permeability is derived. Furthermore, the modified algorithm is used to simulate the unsteady seepage process, and the results show good agreement with the analytical solutions.

1. Introduction

Due to the explicit numerical scheme and simple motion equations, discrete element method (DEM) has been widely used to simulate geotechnical problems, especially those which show large deformation or failure. However, geotechnical materials such as soil or rock are multiphase media. Coupled physical processes between solids and fluids are commonly found in the engineering applications. So it is in demand to simulate the coupling between fluid flow and solid deformation with DEM.

There are several kinds of methods to combine seepage simulation with DEM. Methods which use a very fine discretization can be categorized as sub-particle-scale methods, such as Lattice–Boltzmann [1–4] and smooth particle hydrodynamic [5]. In these methods, the fluid is assumed to flow inside the pore region, and particles are seen as the boundary for fluid flow. This approach can capture the fluid flow precisely. However, it is complex and extremely computational demanding.

While the sub-particle-scale methods are more suitable to the fundamental study, simplified methods are more used in geomechanics. Coarse-grid method solves the averaged form of Navier-Stokes equation to determine the fluid flow. It was first proposed by Tsuji et al. [6]. The model is discretized as fluid cells which are about five to ten times the average particle size. The average fluid pressures and velocities of each fluid cell are calculated and used to determine the fluid flow. Kafui et al. [7], El Shamy [8], Zeghal [9] and Zhou et al. [10] all used this method to simulate fluid flow with DEM.

Essentially, the two types of methods above both simulate the fluid flow by solving the Navier-Stokes equation. The advantage of these methods is that the fluid scheme is accurate and dependable. But the disadvantage is that the integration of particle calculations and fluid calculations is needed, and information of the particle system such as porosity has to be transmitted to the fluid scheme to realize the coupling of stress and seepage, which is complex. The pipe network flow model was implemented in PFC models via the built-in programming language FISH [11]. Domains and pipes are introduced into the particle system. The flow is assumed to occur through pipes. The fluid flow is solved in an explicit time-stepping scheme, which only includes the flow equation through the pipe and the pressure-updating equation in the domain. So the algorithm of this model is much easier. In addition, because the solid and fluid are both calculated based on the particle model, the coupling of stress and seepage can be realized more conveniently, especially in the simulation of hydraulic fracturing. The pipe network model was used to simulate the crack propagation under fluid pressure and the consequent fluid inflow into cracks by Al-Busaidi [12], Shimizu [13] and Wang [14].

However, although the pipe network model was adopted to simulate the fluid flow in the discrete element system, its accuracy to illustrate correct seepage process has not been verified yet. As O'Sullivan suggested: "Quantitative correlations of this type of

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model with real soil response are likely to be difficult" [15]. In this paper, the new equation to calculate the increment of fluid pressure in each timestep is rebuilt and its physical meaning is explained. In addition, the calibration equation to determine the residual aperture according to the permeability is derived. With the modified pressure-updating equation, it is verified that the seepage process can be simulated quantitatively. With the calibration equation, the target permeability can be recovered with a small error so that the meso residual aperture can be easily determined.

2. Modeling methodology

2.1. Particle flow code

Two-dimensional particle flow code, PFC2D, models the movement and interaction of circular particles based on the discrete element method [16], also it can simulate continuum by introducing bonds between particles [17]. The intact rock can be represented by a dense packing of non-uniform-sized rigid particles. At first contacts are formed from the known particle positions. The force-displacement law is then applied to each contact to update the contact forces between the two entities at the contact, then the law of motion is applied to each particle to update its velocity and position based on the resultant force and moment. The time stepping calculation cycle consists of the repeated application of the force-displacement law to each contact and the law of motion to each particle. During the simulation, contacts are formed and broken automatically. Cracks are represented as broken bonds, and fracture can be formed by connection of these broken bonds.

2.2. Review of pipe network flow model

The pipe network flow model simulates the seepage field by introducing fluid domains and pipes into the particle system [11]. This model is based on the models of Tarumi [18], Hakuno [19], Thallak [20]. At first, the network of domains and pipes is formed by algorithm, as shown in Fig. 1. The blue particles are solid particles, and the green ones represent the pore pressures there. As shown in Fig. 2, each domain consists of a loop of closed particles. The pressure of the domain represents the pore pressure at the centroid of the domain. Each contact between adjacent particles in the loop is a pipe, which connects the domain and the adjacent domain. Seepage is considered to occur in the pipes. The flow rate is controlled by the aperture of the pipes. After each step, the pore pressures in the domains are updated to take into account the change of seepage field.

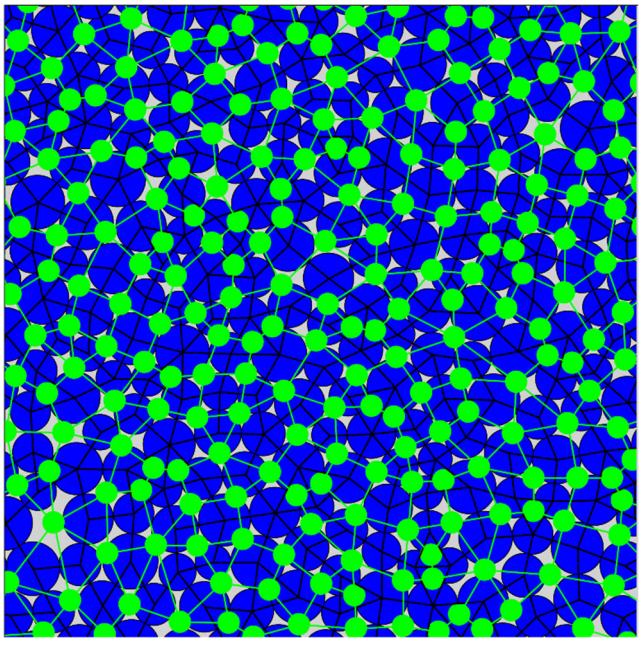

Fig. 1. Network of domains and pipes. Domains (green disks) and solid particles (blue disks) and bonds (black lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Flow in the pipe is seen as parallel-plate seepage. The flow rate (volume per unit time) into the domain is given by:

$$q = \frac{a^3}{12\mu}\frac{\Delta P}{L} \tag{1}$$

where a is the aperture, μ is the viscosity of the fluid, ΔP is the pressure difference between the two adjacent domains, L is the length of the pipe, which is taken as the sum of the radii of the particles adjacent to the contact in question. To consider the influence of stress on the permeability coefficient, the aperture is equal to the residual aperture (a_0) for zero normal force, and then decreases asymptotically to zero as the normal force approaches infinity.

$$a = \frac{a_0 F_0}{F + F_0} \tag{2}$$

where F is the compressive normal force at the contact and F_0 is the normal force at which the aperture decreases to half of its residual aperture. If the normal contact force is tensile or zero, the aperture is equal to the sum of residual aperture and normal distance between the two particles.

$$a = a_0 + mg \tag{3}$$

where g is the normal distance between particles, and g is scaled by a dimensionless multiplier, m.

Within one timestep, Δt, each domain will receive all the flow from the domains around assuming inflow is positive. Then the increment of the fluid pressure can be calculated from the fluid bulk modulus, K_f, and the apparent volume of the domain, V_d.

$$\Delta P = \frac{K_f}{V_d}(\Sigma q \Delta t - \Delta V_d) \tag{4}$$

For numerical stability, the critical timestep of the seepage algorithm can be calculated as follows. More details about the calculation of critical timestep can be found in the manual of PFC2D [11]

$$\Delta t_{crit} = \frac{24\mu \bar{R} V_d}{N K_f a^3} \tag{5}$$

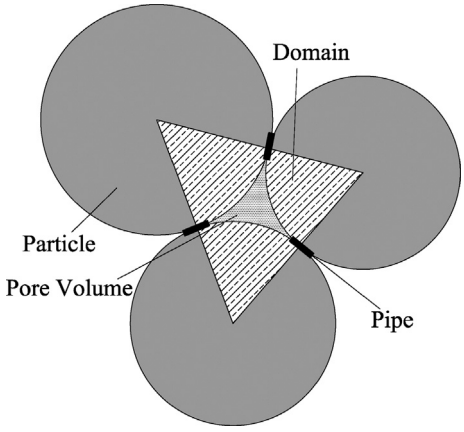

Fig. 2. Domain and pipe model.