AN OVERVIEW OF FLUID FLOW COUPLED DISCRETE ELEMENT METHOD – APPLICATIONS IN GEOTECHNICAL ENGINEERING

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ABSTRACT: Flow coupled Discrete Element Method is an effective technique that helps to model the interactions of fluid flow with particles. Coupled models allow particle level studies and have wide range of applications in geotechnical engineering. This paper gives an overview of the fluid coupled methods, explains briefly the forces that act on the soil particles as a result of fluid flow through the system and the formulations that are used. The method of coupling between solid phase and fluid phase is explained. The paper illustrates the applications of fluid coupled models in geotechnical engineering.

INTRODUCTION

The discrete element method is an effective tool by which we can model granular soils and other geo materials. It uses Lagrangian numerical technique that considers a set of discrete particles. This method was originally developed by Cundall in 1971 and was applied to modeling of granular assemblies [1]. The discrete particles that simulate the domain interact themselves through contacts. In discrete element method finite displacements and rotations including complete detachment are allowed and new contacts are recognized automatically as the calculation progresses [2]. In fluid flow coupled modeling, fluid flow is modeled as a continuum by finite element or finite difference methods and later gets coupled with the discrete element model. An overview of the coupling methods and the applications of coupled models in geotechnical engineering are presented in this paper.

DISCRETE ELEMENT METHOD

In a discrete element method the numerical equation is solved by an explicit time integration procedure. The time step considering for the analysis is small, and hence the disturbance that originates at a point on the particle will not propagate more than one particle difference [1]. The calculations performed in the method are based on Newton’s second law, for particles and force – displacement law for contacts. By means of force displacement relation, the contact force, which is developed when two particles come in contact, is calculated. The changes in forces at existing contacts are also calculated in a similar manner. Having calculated all the contact forces, pertaining to a particle, its acceleration is found out by Newton’s second law and the acceleration obtained here is integrated to determine the velocity. Once all the velocities are calculated for the assembly, relative velocities are calculated and integrated to obtain relative displacements and new set of contact forces are computed. This procedure is repeated for each step.

The energy dissipation in the model is adopted through friction, contact and global damping. In order to establish the equilibrium of assemblies, damping forces are required other than frictional force. Friction damping occurs when the absolute value of shear force at contact is \( F_s \)max and contact damping is proportional to the relative velocities of the particles at contact. Global damping is related to the absolute velocities of particles and is introduced during calculations of motion.

COUPLED FLUID PARTICLE MODELS

In a fluid coupled DEM model, fluid flow forces are incorporated into the solid phase and the equations pertaining to both phases are solved simultaneously. The coupled system is disintegrated to solid and fluid phases as shown in Fig.1 [3] and then each system is solved simultaneously.

Fluid Particle interactions

The forces that are exerted by the fluid on the particles can be generally classified as (a) hydrostatic forces and (b) hydrodynamic forces. Hydrostatic force, which is also called the buoyant force, is caused by the pressure gradient around the particle and is given by the eq. (1)[4]

\[
F_b = (\nabla U) V_p
\]

where \( F_b \) is the buoyant force on the particle, \( V_p \) is the volume of the particle and \( \nabla U \) is the pressure gradient around.
Hydrodynamic forces include lift, drag and virtual mass forces. Of them, lift and virtual mass forces are negligible for the flow of pore fluid through a soil matrix. The drag forces are usually calculated using semi empirical equations, and most widely used one is Ergun’s equation [5]

\[ F_d = \frac{(1-n)}{n} \left( \frac{150 \mu (1-n)^2}{d^2} + 1.75 \frac{\rho_d (1-n)^2}{d} \right) (v_f - v_p) \]  

(2)

where \( n \) is the porosity of soil mass, \( \mu \) is the pore fluid viscosity, \( d \) is the mean diameter of the particles, \( \rho \) is the fluid density, \( v_i \) is the average fluid velocity vector and \( v_p \) is the average particle velocity vector. In DEM the fluid interaction forces act on the particles in addition to the contact, gravity and boundary forces. The particles’ motion obey Newton’s second law of motion [3]

\[ m_p v_p = f_c + \sum f_c + f_f + f_d \]  

(3)

\[ I_p \omega_p = \sum r_i \times f_c + M_d \]  

(4)

where \( m_p \) and \( v_p \) indicate the mass of particle and linear velocity vector of particle respectively, \( f_c \), the body force on the particle, \( f_c \), the contacting force between two contacting particles, \( f_f \), the fluid force on the particle and \( f_d \), the damping forces on the particle. \( I_p \) is the moment of inertia of particle, \( \omega_p \), the angular velocity vector of the particle, \( r_i \) is the vector connecting the centre of the particle to the point of contact, \( M_d \) is the moment introduced in the model to reach the equilibrium state.

METHODS ADOPTED IN DEM

The methods that incorporate fluid effects into DEM can generally be divided into: (a) constant volume method (b) coupled methods, i.e., methods considering fluid particle interactions.

Constant Volume Method

Due to the low compressibility of fluid and particles, undrained tests are usually considered as constant volume tests. According to this method, a constant volume is equivalent to an undrained test. Excess pore pressures are estimated by taking the difference between drained and constant volume tests. Many researchers, [6,7,8] have used this method to model the undrained behavior of geo materials and the results obtained by this method have shown good correlation with the experimental results. Vinod [9] used this constant volume method for the investigation of liquefaction behavior, pore water pressure generation and dynamic properties of granular materials. Solving the fluid flow equations is not necessary in this method. But, microscopic level of studies of fluid interaction is not possible in this method.

Coupled Methods

Even though DEM modeling of undrained behavior of saturated soils was first proposed by Cundal; Hakuno and Tarumi [10] were the first to introduce a technique to include pore fluid effects into DEM. Tsuji et al [11] and Kawaguchi et al [12] used the fluid coupled methods to simulate the two dimensional fluidized beds. Hydro fracturing was modeled by Sitharam [13] using the same concept, and had developed a fluid coupled DEM.

There are different methods for modeling the fluid flow through the particles. Hakuno and Tarumi [10], in their sand liquefaction analysis, identified each pore and considered the movement of particles that lead to pore volume changes. The relative volume change of the pores was used to calculate the excess pore pressure. The pores were considered to be connected to each other as a pipe network and due to differential pressures water could flow through the pores and the flow equations were solved by means of Darcy’s law. [13]. An alternative approach, was developed by Nakasa et al [14]. It avoided the difficulty in identifying each pore in the method adopted by Hakuno and Tarumi[10]. In this approach, the total volume change was carried out in a square cell which consists of many particles. And the pore pressure estimation was carried out as described by Hakuno and Tarumi [10]. Both finite volume and finite difference techniques can be used to characterize the fluid domain.

When finite difference scheme is adopted to model the fluid phase, pore pressures are assumed to be constant throughout the cell and are calculated at the centre of each cell [4]. Tsuji et al [11] and Kawaguchi et al [12], Shamy and Zeghal [15] used averaged Navier Stokes equations while Bonilla [16] used Hagen Poiseuille equation to model the fluid flow; and discrete element method, to model the solid phase.

Coupling Scheme

The term ‘coupled process’ is usually referred to the process that influences the initiation and development of other process. To solve the coupled model, solid and fluid phases are to be solved simultaneously. The soil mass porosity and hydraulic conductivity are assumed to be constant throughout the calculations. Drag forces are calculated for each cell based on the porosity and are applied proportionally to their volumes. Appropriate boundary conditions and initial conditions are also applied. Displacements of the particles subjected to drag forces, external loads and contact forces are then calculated. Fig.2 [3] shows an algorithm for the coupling for solid and fluid phases (averaged Navier Stokes equation is used for fluid flow modelling here).

APPLICATIONS OF FLUID COUPLED DEM MODELS

The fluid coupled DEM models have been used widely and effectively to study the behaviour of saturated soil mass at the particle level. Many researchers, e.g. [3][4][15], have used coupled models for the modelling of undrained behaviour of granular media.
Coupled Methods for Liquefaction Studies
Sand liquefaction analysis was the first simulation modelled by coupled methods. This was done by Hakuno and Tarumi [10] in 1988. The models have captured the mechanisms and have revealed the intricate nature of soil liquefaction. Simulations using coupled flow have showed the complex response patterns during the onset of quicksand conditions and have provided valuable informations about the associated mechanisms [15]. The results obtained during numerical simulations are found to be matching well with the observed laboratory results. Micro mechanical investigation of the dynamic response of saturated granular soils [3] and the liquefaction of loose and cemented granular soils [18] were also done by Zeghal and Shamy. Undrained triaxial behaviour was simulated by Okada and Ochiai [19] and pore pressure changes in liquefaction were numerically reproduced. Characterization of energy dissipation mechanisms in seismically loaded soils was done by Shamy and Denissen [20].

Coupled Methods for Hydrofracturing
Hydraulic fracturing in granular media was modelled by Sitharam in 1991 [13]. The fundamental mechanisms of fracture initiation and grain scale level propagation are investigated by using the coupled DEM method. The non linear behaviour around the bore hole and bore hole break outs are also well simulated, tackling the anisotropy and heterogeneity issues from a fundamental approach. Shimizu et al [21] modelled the hydro fracturing in hard rock with coupled DEM.

Coupled Methods for Seepage Problems
Soil flow and piping were simulated using coupled flow method by Xiao and Yuan [22]. The numerical experiments were used to study the phenomenon of seepage failure, and the numerical results were found to be consistent with the published experimental results. 1D upward seepage of fluid through a bed of particles at velocities approaching the critical gradient was modelled by Chen et al [23]. Transient pore water pressure distribution and the displacement of the uppermost particle of the system were modelled by Chen et al [24]. Bierwaski and Maeno [25] simulated the movements inside the granular assembly under the influence of pore water pressure gradients.

Coupled Methods for Consolidation Problems
Fluid pressure dissipation problems were simulated and compared with Terzaghi’s one dimensional consolidation theory by Bonilla [16]. Time rate of consolidation problems and the development / dissipation of excess pore water pressure distribution were simulated by Chen et al [24].

Coupled Methods for Jointed Rock Problems
A coupled discrete- continuum approach was used by Wei and Hudson [26] for modelling hydro mechanical behaviour of jointed rocks. Application of the simulation to a dam simulation problem was also demonstrated. A study of coupled hydraulic, thermal, mechanical phenomena in fractured rock mass was done by Millard et al. [27]

CONCLUSIONS
An overview of the fluid coupling methods with DEM is presented in this paper. Fluid coupling technique is very effective and powerful. It allows us to conduct the study of microscopic behaviour of particles during fluid interaction. Coupled methods have wide range of applications in geotechnical engineering as well as in other fields.

REFERENCES
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