Engineering Geology 193 (2015) 256–266

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Numerical simulation on undrained triaxial behavior of saturated soil by a fluid coupled-DEM model

Guang Liu [a], Guan Rong [a,b,*], Jun Peng [a], Chuangbing Zhou [a,c]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei 430072, China
[b] Key Laboratory of Rock Mechanics in Hydraulic Structural Engineering, Ministry of Education, Wuhan University, Wuhan, Hubei 430072, China
[c] School of Civil Engineering and Architecture, Nanchang University, Nanchang, Jiangxi 330031, China

ARTICLE INFO

Article history:
Received 13 September 2014
Received in revised form 7 March 2015
Accepted 26 April 2015
Available online 23 May 2015

Keywords:
Particle flow method
Fluid coupled-DEM model
Saturated soil
Undrained triaxial compression
Pore water pressure

ABSTRACT

A fluid coupled-DEM model is developed in this paper based on particle flow methods. In the model, soil grain is represented by using a sphere particle, and the motion of soil grain is depicted by Newton's laws of motion and the force–displacement law at contact point. The flow of fluid obeys Darcy's law and fluid–particle interactions are depicted by multi-physics coupled formulation. A numerical scheme for this model is developed to consider the mechanism for pore pressure generation and volume change induced by deformation. Undrained triaxial compression tests of saturated soil are simulated by using the coupled method. The calculated results are compared with that from constant volume methods and experiments of Beijing clayey silt. The results show that the deviatoric stress and pore pressure obtained by coupled method are comparable with that of constant volume methods and experiments. A series of drained and undrained triaxial compression tests for saturated soil under different confining pressures are also simulated. Deviatoric stress increases with the increase of confining pressure in both drained and undrained tests. The results of undrained test show that stress ratio decreases with increasing confining pressure. The decrease of pore pressure drives effective mean stress path to move right-upward. A loss of soil strength can be found in undrained test by comparing with the strength in drained test, and this may be caused by reduction of effective stress.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Saturated soil is two-phase mixtures of soil grains and fluid. It has been shown that interaction between soil grains and fluid is significant when saturated soil is suffering from stress or deformation. Contraction of soil skeleton often causes a rise of pore water pressure, and simultaneously, effective stress decreases due to increased pore water pressure acting on soil grains. Then the decrease of effective stress results in loss of soil shear strength, which even leads to soil liquefaction under certain conditions. Soil liquefaction has caused huge economic losses in previous earthquake disaster, for example the Niigata earthquakes in Japan (1964) (Liyanapathirana and Poulos, 2004). Undrained triaxial compression is an important experiment to understand mechanics properties of soil (Bahsan et al., 2014). Many researchers have studied liquefaction mechanism of soil by undrained triaxial compression (Seed and Lee, 1966; Seed, 1979; Ishihara et al., 1990; Zhang et al., 2013).

The numerical method for geomaterial has been greatly developed with the progress of modern computational mechanics (Rabczuk and Areias, 2006; Xu et al., 2013; Zhuang et al., 2014a, 2014b; Wu et al., 2014). The modeling approaches for undrained triaxial compression test of soil can be generally divided into two classes (Shafipour and Soroush, 2008): (1) Constant volume method. It is assumed that the solid grain and pore water in saturated medium are incompressible under undrained condition in constant volume method. Consequently, the sample volume keeps constant during loading processes to achieve undrained condition. This method is widely used to model the undrained behavior of soil (Dubujet and Dedecker, 1998; Ng and Dobry, 1994; Sitharam, 2003). By the biaxial tests of loose and dense sand under undrained condition with constant volume method, Liu et al. researched the meso-scopic mechanism of liquefaction (Liu et al., 2007a, 2007b). By ignoring the direct interactions of fluid and solid grains, the constant volume method is easy to achieve by controlling the volume deformation of sample during numerical tests. (2) Coupled methods. These couple methods consider fluid and the fluid–particle interactions directly based on a series of coupled models (Zhuang et al., 2014a). Since Cundall and Strack (1979) presented discrete element model for granular materials, discrete element method has been widely used to simulate behavior of granular materials. Tarumi et al. investigated the liquefaction of saturated soil with the effect of pore water based on Darcy's law in a discrete element model (Tarumi and Hakuno, 1988). Nakase et al. (1999) divided the calculation domain into square meshes

* Corresponding author at: State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei 430072, China.
E-mail address: rg_mail@163.com (G. Rong).

http://dx.doi.org/10.1016/j.enggeo.2015.04.019
0013-7952/© 2015 Elsevier B.V. All rights reserved.

and pore fluid pressure in every square grid is calculated by the change of void ratio. A two-dimensional numerical model to study the interaction of solid phase particles and pore fluid was presented by Hakuno (1995). Then Zeghal and El Shamy(2004) put forward an enhanced coupled method based on the previous research. This method introduced averaged Navier–Stokes equations to depict fluid flow, and a semi-empirical relationship was utilized to quantify the fluid–particle interactions. A method for treating fluid–structure interaction of fracturing structures under impulsive loads is put forward, and this method allows fluid to flow through openings between crack surfaces (Rabczuk et al., 2010).

Scientific research has shown that the results from coupled methods agree well with those obtained by constant volume method in undrained triaxial compression (Bonilla, 2004). However, given the interaction mechanism between fluid and solid particles, numerical methods using coupled model are more suitable for soil. And constant volume methods is only applicable to simulate undrained test, while coupled methods have more extensively applicable scope to deal with the problems in geotechnical engineering, such as soil liquefaction.

Three-dimensional particle flow code (PFC3D), as one modeling program based on the discrete element method (Itasca Consulting Group, 2008), has a distinct advantage in simulation of granular materials (Cundall, 2001; Itasca Consulting Group, 2008). On the base of simple assumptions and microscopic parameters, some issues like large deformation and discontinuous fracture can be treated in PFC3D effectively. The influence of pore fluid is considerably significant in undrained triaxial compression test. So far, there are mainly two algorithms relating to fluid flow in PFC3D, P. Cundall's (unpublished technical note, 2000) fluid flow algorithm and the fixed coarse-grid fluid flow algorithm. P. Cundall's fluid flow algorithm assumes that fluid stores in “domain” which is defined as a pore created by every four neighboring particles, and fluid flows in “pipe” which is defined as a flow channel between two adjacent domains (Itasca Consulting Group, 2008; Al-Busaidi et al., 2005). This algorithm generates the network of domains and pipes before computation starts. It requires that the boundary of the model remains unchanged as the locations of domains and pipes are hard to update in the process of fluid flow computation. The fixed coarse-grid fluid flow algorithm divides the model into fixed rectangular grid, and velocities and pressures in each grid are calculated by solving a generalized form of the Navier–Stokes equation. However, this algorithm has not yet settled the problem of variable boundary and it only can be applied to rectangular column model for the limitation of mesh generation. This method does not include a mechanism for generation of pore-pressure under strain (Itasca Consulting Group, 2008). In the process of undrained triaxial compression, the boundary of the model keeps changing as a result of compression of model under axial stress and confining pressure. The pore fluid pressure under strain is significant. Consequently, these two algorithms in PFC3D may not be applicable to study undrained behavior of soil.

This paper aims to develop a fluid coupled-DEM model including a mechanism for generation of pore-pressure under strain and for change of pore structure on the base of previous studies. Then a fluid coupled-DEM scheme is developed using FISH language embedded within PFC3D. In order to assess validity of the scheme, an undrained triaxial compression test for saturated soil is modeled by employing this code and results obtained from this fluid coupled-DEM model were comparable with results from experiment and constant volume method. Drained and undrained triaxial compression tests for saturated soil under different confining pressures are studied using coupled-DEM model after numerical calibration.

2. Fluid coupled-DEM model and numerical scheme

The soil grains in fluid coupled-DEM model are idealized as an assembly of spherical particles. Fluid coupled-DEM model in this paper mainly includes three components. The first component is motion equation and the force–displacement law of solid particle. The second component is pressure equation and flow equation of fluid. The pressure equation represents the change of pore fluid pressure due to the compression of pore, and the flow equation represents the fluid flow driven by pressure gradients in pore. The third component in this model is interaction of fluid and solid particle. In Okada's research regarding numerical triaxial compression tests under undrained conditions, basic framework about this model was first presented (Okada and Ochiai, 2007). Fluid coupled-DEM model in this paper introduces a concept of porosity into Okada's model in order to consider the compression of pore structure. And our model redefines the measurement sphere mentioned in Okada's model to optimize computational efficiency. Based on Okada's study (Okada and Ochiai, 2007), a fluid coupled-DEM algorithm capable of considering pore fluid pressure generated under strain was derived. A numerical scheme for this model was developed on the basis of PFC3D. The details of this model are as follows.

2.1. Solid phase

Soil grains are represented by spherical particles in this scheme, and mechanical behaviors of materials are simulated in terms of the movement of each particle and the inter-particle forces acting at each contact point. At each contact point, contact behaviors consist of stiffness, slip and bond (Itasca Consulting Group, 2008). The bond behavior can be envisioned as a kind of glue joining the two particles. In this paper, the contact bond model in PFC3D is employed. For this model, when the magnitude of the tensile normal contact force equals or exceeds the normal contact bond strength, the bond breaks, and both the normal and shear contact forces are set to zero. When the magnitude of the shear contact force equals or exceeds the shear contact bond strength, the bond also breaks. But, for the latter, the contact forces may not change after bonding break, provided that the shear force does not exceed the friction limit, and provided that the normal force is compressive (Itasca Consulting Group, 2008). The equation for particle translational motion can be written as:

$$\mathbf{F}_\mathrm{i} = \mathrm{m}(\mathbf{a}_\mathrm{i} - \mathbf{g}_\mathrm{i}) \tag{1}$$

in which $\mathbf{F}_\mathrm{i}$ is the resultant force acting upon particle i, m is the mass of particle, $\mathbf{a}_\mathrm{i}$ is the acceleration vector of particle i, and $\mathbf{g}_\mathrm{i}$ is the body force acceleration vector (e.g., gravity loading).

The equation for rotational motion is given by vector form below, where $\mathbf{M}_\mathrm{i}$ is the resultant moment acting on the particle, and $\mathbf{H}_\mathrm{i}$ is the angular momentum of the particle.

$$\mathbf{M}_\mathrm{i} = \dot{\mathbf{H}}_\mathrm{i} \tag{2}$$

In the contact normal direction, the stiffness behavior provides the relation among the contact normal force component $\mathbf{F}_\mathrm{i}^n$, the total normal displacements U^n and the contact normal stiffness K^n (unit: Pa/m). In the contact tangential direction, the stiffness behavior relates the increment of shear force $\Delta F_\mathrm{i}{}^s$, the tangent stiffness k^s (unit: Pa/m) the normal direction unit vector $\mathbf{n}_\mathrm{i}$ and the increment of shear displacement ΔU^s. The force–displacement law with stiffness behavior is given by:

$$\mathbf{F}_\mathrm{i}^n = K^n U^n \mathbf{n}_\mathrm{i} \tag{3}$$

$$\Delta F_\mathrm{i}{}^s = -k^s \Delta U^s. \tag{4}$$

The slip condition at each contact point is expressed as:

$$F^s_{\max} = \mu \left| F_\mathrm{i}{}^n \right| \tag{5}$$

in which μ is the friction coefficient, and $F^s_{\max}$ is maximum allowable shear contact force. When $|F^s_\mathrm{i}| > F^s_{\max}$, particles slip at contact point. In the next calculation cycle, the magnitude of F^s_i is set to $F^s_{\max}$.

Download English Version:

https://daneshyari.com/en/article/6447749

Download Persian Version:

https://daneshyari.com/article/6447749

Daneshyari.com