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Modeling granular soils liquefaction using coupled lattice Boltzmann method and discrete element method

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ABSTRACT

In this paper, a novel coupled pore-scale model of pore-fluid interacting with discrete particles is presented for modeling liquefaction of saturated granular soil. A microscale idealization of the solid phase is achieved using the discrete element method (DEM) while the fluid phase is modeled at a pore-scale using the lattice Boltzmann method (LBM). The fluid forces applied on the particles are calculated based on the momentum exchange between the fluid and particles. The presented model is based on a first principles formulation in which pore-pressure develops due to actual changes in pore space as particles' rearrangement occurs during shaking. The proposed approach is used to model the response of a saturated soil deposit subjected to low and large amplitude seismic excitations. Results of conducted simulations show that at low amplitude shaking, the input motion propagates following the theory of wave propagation in elastic solids. The deposit response to the strong input motion indicates that liquefaction took place and it was due to reduction in void space during shaking that led to buildup in pore-fluid pressure. Soil liquefaction was associated with soil stiffness degradation and significant loss of interparticle contacts. Simulation results also indicate that the level of shaking-induced shear strains and associated volumetric strains play a major role in the onset of liquefaction and the rate of pore-pressure buildup.

1. Introduction

Earthquake excitations are induced by a fault rupture at large depths which generates seismic waves with elaborate patterns of frequency content and amplitude. Near the ground surface, saturated loose granular deposits experience a decrease in void space and a rise in pore-fluid pressure during dynamic excitations which leads to a degradation in soil stiffness and strength properties and ultimately liquefaction. Liquefaction is an instability phenomenon that is generally associated with a site loss of bearing capacity and flow failure along with lateral displacements and excessive settlements.

The coupled (solid–fluid) response of saturated granular soils is commonly modeled using continuum formulations derived based on phenomenological considerations (e.g., the mixture or the Biot theories) (e.g., [1,2]) or homogenization of the micromechanical equations of motion [3]. These formulations require a constitutive model to describe the relationship between effective stresses and strains of the solid phase. For liquefaction problems, several constitutive models based on the plasticity theory have been introduced that include the cap models [4,5], the multiyield plasticity model [6,7], the bounding surface plasticity models [8], and the fuzzy-set plasticity models [9], among others (e.g., [10–15]). Most of these models have been calibrated based on the undrained cyclic triaxial test or simple shear test results. The finite element method is typically used to discretize the field equations (e.g., [1,2,16–19]).

An alternative over a fully continuum description of the saturated granular medium is to adopt a multiscale model that accounts for the discontinuous nature of the granular soil by modeling it at a microscale while keeping the fluid at a continuum scale (e.g., [20–23]). In this technique, the fluid–particle interaction term that idealizes momentum transfer is calculated using semiempirical relations that rely on averaged solid phase quantities (e.g., porosity and effective diameter). While a continuum description of the fluid appears to be satisfactory, averaging of the solid phase properties may mask important pore-scale level phenomena and may misrepresent the actual interaction between the pore-fluid and the solid particles.

A fundamental idealization of saturated granular soils would combine a model that accounts for the discontinuous nature of granular soils, and a pore-scale representation of the fluid filling the void space between the solid particles. The discrete element method [24] has proven to be very efficient in modeling granular materials as a collection of discrete particles and thus accounting for intergrain discontinuity. There are several techniques that are

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capable of obtaining the fluid flow in the pores between particles. Patankar et al. [25,26] used a finite element technique based on moving unstructured grids to study the lift force on one particle and multiple particles. Zhu et al. [27] implemented the Smoothed Particle Hydrodynamics (SPH) method to investigate the flow through stationary porous media. SPH is a fully Lagrangian technique in which the solution is obtained without a grid (meshless). In this technique, the fluid velocity and pressure can be obtained in the pores. Potapov et al. [28] and Cleary et al. [29] combined SPH and DEM to simulate liquid–solid flows. The lattice Boltzmann method (LBM) is another pore-scale numerical technique to simulate fluid flow governed by Navier–Stokes equations. LBM is based on the microscopic kinetic equation for the fluid particle distribution function. The macroscopic quantities are then obtained through momentum integration of the distribution function. LBM models the fluid flow at a pore-scale and the fluid characteristics can be obtained at the soil pores. Moreover, the forces in LBM are calculated based on the stresses applied to the particles or the momentum the fluid exchanges with the particles through a nonslip boundary condition at the fluid–particle interface. LBM is especially useful for modeling complicated boundary conditions and multiphase interfaces (e.g., [30–32]).

In this paper, we introduce results of a novel model of soil liquefaction that couples a pore-scale idealization of pore-fluid with a discrete description of solid particles. That is, a microscale representation of the solid phase is achieved using DEM while the fluid phase is modeled at a pore-scale using LBM. The fluid forces applied on the particles are calculated based on the momentum exchange between the fluid and particles. The proposed approach is used to model the response of a saturated soil deposit subjected to seismic excitation. Results of conducted simulations suggest that liquefaction is due to reduction in void space during shaking that leads to buildup in pore-fluid pressure and is associated with soil stiffness degradation and significant loss of interparticle contacts.

2. Coupled fluid–particle model

A fully coupled model is presented herein to simulate a saturated granular deposit subjected to a dynamic base excitation. For the solid particles and fluid mixture, the fluid equations as well as the momentum equations for each particle are solved using an explicit time integration scheme. The fluid is idealized at pore-scale using the lattice Boltzmann method, and fluid variables such as velocity and pressure are obtained at fixed grid points. A nonslip fluid boundary condition is applied at the particle surface to maintain compatibility between the fluid phase and solid phase. The fluid hydromechanical forces are calculated based on the momentum exchange between the fluid and the particles. These forces are then applied on the particles and the equations of motion of each particle in the system are solved to provide new particle position. The following subsections provide details of model components.

2.1. Lattice Boltzmann formulation

In LBM, the fluid is modeled as packets of particles that move about a regular lattice or grid. This grid is defined by boundary and initial conditions. The fluid motion is solved over two phases for each time step. These phases are the streaming phase, where the fluid packets have a discrete set of velocities such that packets will move or stream from one lattice point to another, and the collision phase, where the fluid packets interact with each other. Collision and streaming of the fluid packets occur at the lattice points according to specific relationships that conserve mass and momentum in such a way that Navier–Stokes equations are recovered.

One of the problems in solving the Boltzmann equation is the complicated nature of the collision part. One practical way to overcome such difficulty is to use Bhatnager–Gross–Krook (BGK) approximation. The BGK method replaces the full collision term with the linearized BGK single time relaxation model [33]. The LBM–BGK equation can be written as

$$f_i(\mathbf{x}+\mathbf{e}_i t, t+\delta t) = f_i(\mathbf{x}, t) - \frac{\delta t}{\tau}(f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)) \tag{1}$$

where $f_i(\mathbf{x}, t)$ is the fluid particle density distribution function with velocity $\mathbf{e}_i$ at a lattice point located at position $\mathbf{x}$ for a given time t, τ is the relaxation time, and $f_i^{eq}(\mathbf{x}, t)$ is the equilibrium density distribution function for the fluid. Eq. (1) comprises a collision phase (the second term on the right-hand side), and a streaming phase that moves the distribution calculated on the right-hand side to the neighboring node indicated on the left, $\mathbf{x}+\mathbf{e}_i t, t+\delta t$. In this paper, the three-dimensional D3Q15 lattice cell shown in Fig. 1 is used to model the fluid. The velocity set of the D3Q15 lattice cell is presented in a matrix form as

$$\mathbf{e}_i = C\begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \end{bmatrix} \tag{2}$$

in which C is the lattice speed and is given by

$$C = \frac{\delta x}{\delta t} \tag{3}$$

where δx is the lattice spacing, and δt is the time step. The equilibrium density distribution function for the fluid is

$$f_i^{eq} = \rho w_i\left[1 + \frac{3}{C^2}\mathbf{e}_i \cdot \mathbf{u} + \frac{9}{2C^4}(e_i \cdot \mathbf{u})^2 - \frac{3}{2C^2}\mathbf{u} \cdot \mathbf{u}\right] \tag{4}$$

where w_i is a weighting factor, ρ is the fluid density, and $\mathbf{u}$ is the fluid velocity vector. The weighting factors for the (D3Q15) lattice cell are

$$w_i = \begin{cases} 2/9, & i = 0. \\ 1/9, & i = 1-6. \\ 1/72, & i = 7-14. \end{cases} \tag{5}$$

The macroscopic fluid variables at a lattice point, density ρ, velocity $\mathbf{u}$, and pressure p are obtained from

$$\rho = \sum_{i=0}^{14} f_i \tag{6}$$

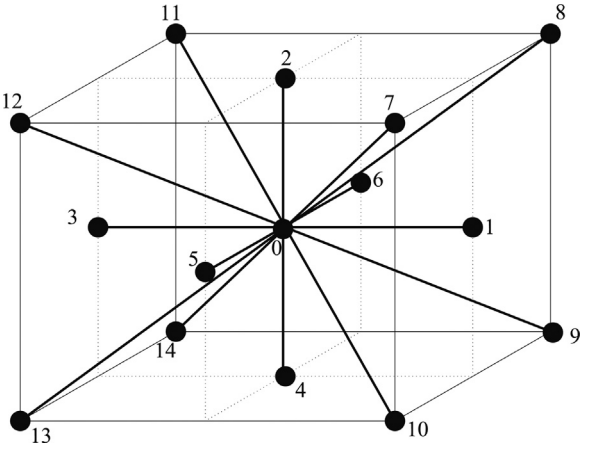

Fig. 1. Discrete velocity set of the three-dimensional 15 velocity D3Q15 model.