Computers and Geotechnics 82 (2017) 134–143

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Numerical modelling of fluid-induced soil erosion in granular filters using a coupled bonded particle lattice Boltzmann method

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ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form 5 October 2016
Accepted 10 October 2016

Keywords:
Internal erosion
Bonded particle method
Lattice Boltzmann method
Granular filter
Immersed moving boundary
Fluid-solid coupling

ABSTRACT

This paper presents a three-dimensional coupled bonded particle and lattice Boltzmann method (BPLBM) with an immersed moving boundary scheme for the fluid-solid interaction. It is then applied to investigate the erosion process of soil particles in granular filters placed within earth dams. The microscopic migration of soil particles can be clearly visualised as the movement of particles can be directly recorded. Three granular filters with different representative size ratios are simulated and the numerical results are seen to match the empirical criteria. In addition, the effect of the representative size ratio of granular filters, hydraulic loading and erosion time are discussed.

1. Introduction

Internal erosion of soil particles induced by the hydraulic forces in a dam and its foundations is one of the most common causes of failure of levees, slopes and earth dams. The onset of soil erosion remains un-noticed within an earth structure until it has progressed enough to be detected during periodic field inspections. Providing a granular filter at an appropriate location is one of the effective ways to eliminate this risk of seepage induced erosion occurring in dams and embankments. It has been adopted in engineering practice for hundred years. However, the performance of granular filters is still not well understood and the designing of granular filters are mainly made according to the empirical criteria derived from experiments.

There has been much progress in the field of physical modelling of the transport of fines in granular filters [32,36,1,42,27]. It should be acknowledged the physical experiment is the principal method even now in this research field. The widespread filter design criteria are based on the statistical correlations of experimental observations [32]. These criteria are empirical and constantly revised as long as new experimental data becomes available [13,18,10]. Due to the complexity of soil erosion, emerging at the microscopic pore/grain level, the experimental methods have limitations in understanding such a complicated issue from the macroscopic viewpoint.

To overcome the problems aforementioned, a few numerical techniques were proposed or applied to the investigation of internal erosion from time to time. Zou et al. [44] first applied the coupled discrete element method and computational fluid dynamics (DEMCFD) [34,43,40] technique to simulate the transient transport of eroded base-soil particles into a filter. The distributions of the eroded base-soil particles in different filters were traced and analysed. It was found that the eroded mass and intruding depth of the base-soil particles into the filter are related to the representative particle size ratio of the base soil to the filter, hydraulic gradient and erosion time. Then, the migration mechanism of the base soil through granular filters was studied by the same method [17]. The total eroded base soil mass, the distribution of the eroded particles within the filter and the porosity were observed.

Cui et al. [7] introduced a two-dimensional coupled discrete element method and lattice Boltzmann method (DEMLBM) [14,6] to the study of soil erosion induced by local leakage from a buried pipe. The influence factors including flow rates and initial bed heights were considered, and the excess pore pressure distribution and the soil transport due to a localised leak were compared with existing experimental findings. This coupled two-dimensional technique was also applied to particle detachment and transport

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http://dx.doi.org/10.1016/j.compgeo.2016.10.006
0266-352X/

in piping erosion [30]. Numerical experiments showed that the erosion rate is linearly related to the hydraulic shear stress and the erosion threshold depends on the cohesion of the granular assembly.

Although the DEMLBM has been proven to be promising for internal erosion issues, two potential problems lie in the two-dimensional simulation of fluid-particle systems. First, it is hard to obtain the realistic flow channels in two-dimensional modelling, because the flow paths of fluid are always blocked up by contacted spheres. Attempts to resolve this problem can be seen in Ref. [2]. The other is that the cohesive force in geomaterials may be considered by the Johnson-Kendall-Roberts (JKR) model [21] or Derjaguin-Muller-Toporov (DMT) model [12] in discrete element method (DEM). It should be noticed that these adhesion models are mainly proposed to account for the influence of adhesion, like Van der Waals forces, between fine particles with very small size and low stiffness. To deal with the cohesion forces in a general way in DEMLBM, a two-dimensional bonded particle and lattice Boltzmann method (BPLBM) was proposed [38,39] and its feasibility was well demonstrated.

The main objective of this study is to develop a three-dimensional bonded particle and lattice Boltzmann method and use it to investigate the internal erosion process of soil particles in granular filters. This coupled method can directly deal with the fluid-particle interaction using an immersed moving boundary (IMB) method. Furthermore, the three-dimensional modelling of the migration of soil particles within the skeleton of granular filters by BPLBM gives insights into the microscopic erosion process. For the sake of consistency, a brief description of the coupled BPLBM is given in Section 2. However, for further details of theory and computational aspects, readers should refer to [38,39]. In Section 3, a numerical example of transport of finer particles into a layer of coarser filter is presented. Influence of various parameters such as hydraulic gradient and the representative size ratio are presented. Section 4 gives conclusions and recommendations for future work.

2. Computational methodology

2.1. Bonded particle method

The bonded particle method (BPM), an extension of DEM, is a combination of discrete element method and lattice method [29]. In BPM, the treatment of interactions between particles is similar to that in the discrete element method [8,9] in which particle-particle interactions are treated as a transient problem where an equilibrium state is reached when the internal forces are balanced. Newton's second law is utilised to determine the translation and rotation of each particle arising from the contact forces, e.g., externally applied forces and body forces as well as cohesive forces, whilst the force-displacement law is used to update the contact forces that keep changing due to the relative motion of particles at each contact.

The Newton's second law governing the motion of a particle is given by

$$m\boldsymbol{a} + c\boldsymbol{v} = \boldsymbol{F_c} + \boldsymbol{F_f} + m\boldsymbol{g} \tag{1}$$

$$\boldsymbol{I}\ddot{\theta} = \boldsymbol{T_c} + \boldsymbol{T_f} \tag{2}$$

where m and I are respectively the mass and the moment of inertia of particles, c is a damping coefficient, a and $\ddot{\theta}$ are acceleration and angular acceleration, $\boldsymbol{F_c}$ and $\boldsymbol{T_c}$ are, respectively, contact forces and corresponding torques, $\boldsymbol{F_f}$ and $\boldsymbol{T_f}$ are hydrodynamic forces and corresponding torques. It should be emphasized that $\boldsymbol{F_c}$ can be either particle-particle contact forces for granular particles or cohesion forces $\boldsymbol{F_b}$ existing between bonded particles.

2.1.1. The particle-particle contact model

The particle-particle contact force $\boldsymbol{F_c}$ has two components, the normal contact force and the tangential contact force, and they are, respectively, given by

Normal interaction laws:

$$F_n = K_n\delta^m \tag{3}$$

Coulomb friction model:

$$F_t = -\frac{\dot{\delta}_t}{|\dot{\delta}_t|}\begin{cases} K_t|\delta_t|; & |K_t\delta_t| \leqslant \mu F_n \\ \mu F_n; & |K_t\delta_t| > \mu F_n \end{cases} \tag{4}$$

where K_n and K_t are normal stiffness and tangential stiffness, δ_t and $\dot{\boldsymbol{\delta}}_t$ correspond to accumulated tangential sliding and sliding velocity, δ is the overlap of two particles. The coefficient m can be 1 and 3/2, the former is for the linear contact and the latter is for the Hertz contact model [26]. The normal stiffness in Hertz contact model is defined as

$$K_n = \frac{4E^*\sqrt{R^*}}{3} \tag{5}$$

$$\frac{1}{\mathrm{R}^*} = \frac{1}{\mathrm{R}_{[A]}} + \frac{1}{\mathrm{R}_{[B]}}, \quad \frac{1}{\mathrm{E}^*} = \frac{1-\upsilon_{[A]}^2}{\mathrm{E}_{[A]}} + \frac{1-\upsilon_{[B]}^2}{\mathrm{E_B}} \tag{6}$$

where $\upsilon_{[A]}$, $\upsilon_{[B]}$ are, respectively the Poisson's ratios of particle A and B. $R_{[A]}$, $E_{[A]}$, $R_{[B]}$ and $E_{[B]}$ are the radii and Young's moduli of particle A and B.

An alternative of the Coulomb friction model is the commonly used Mindlin-Deresiewicz model [33,26,35]. In this model, the tangential force is dependent on both loading history and the magnitude of the normal force.

2.1.2. Bond models

The initial bond model proposed is referred to as the 'contact bond model' [19,28]. It approximates the physical behaviour of a vanishingly small cemented-like substance joining the two bonded particles. It can be envisioned as a pair of elastic springs (or a point of glue) with constant and shear stiffness acting at the contact point. These two springs have specified shear and tensile strengths. The existence of a contact bond precludes the possibility of slip.

2.1.2.1. Contact bond model. The two components of the contact bond model can be described as follows:

Normal component:

$$F_n^b = \begin{cases} \mathrm{K}_n^b\delta; & F_n^b \leqslant F_{bn} \\ 0; & F_n^b > F_{bn} \end{cases} \tag{7}$$

Tangential component:

$$F_t^b = \begin{cases} \mathrm{K}_t^b|\delta_t|; & F_t^b \leqslant F_{bt} \\ 0; & F_t^b > F_{bt} \end{cases} \tag{8}$$

where K_n^b and K_t^b are the normal stiffness and tangential stiffness for the cement, F_{bn} is the critical tensile force and F_{bt} is the critical shear strength.

When the tensile contact force equals or exceeds the normal contact bond strength, the bond breaks. Both normal and shear bond forces are set to be zero. In contrast to this, when the shear contact force is equal or greater than the shear contact bond strength, the bond breaks, but only tangential bond force becomes zero.