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Influence of particle shape on the erodibility of non-cohesive soil: Insights from coupled CFD–DEM simulations

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A B S T R A C T

Soil erosion is a critical process that is being studied in soil science, hydraulic engineering, and geotechnical engineering. Among many societal and environmental impacts, soil erosion is a major cause for the failures of bridges. The erodibility of soil is determined by its physical and geochemical properties and is also affected by surrounding biological activities. In most of the current models for soil erosion, erodibility of non-cohesive soil is characterized by its median grain size (D_{50}), density, and porosity. The contribution to erodibility of the irregular shape of soil grains, which plays an important role in the mechanical and hydraulic properties of coarse-grained soils, is generally ignored. In this paper, a coupled computational fluid dynamics and discrete element method model is developed to analyze the influence of the shape of sand grain on soil erodibility. A numerical model for the drag force on spherical and non-spherical particles is verified by using the results from physical free settling experiments. Erosion of sand grains of different shapes is simulated in a virtual erosion function apparatus, a laboratory device used to measure soil erodibility. The simulation results indicate that the grain shape has major effects on erodibility. Spherical particles do not show a critical velocity because of their low rolling resistance, but a critical velocity does exist for angular particles owing to grain interlocking. The erosion rate is proportional to the flow velocity for both spherical and non-spherical particles. The simulation result for angular particle erosion is fairly consistent with the experimental observations, implying that grain shape is an important factor affecting the erodibility of non-cohesive soils.

Introduction

Soil erosion is a process with important engineering implications in fields including soil science and hydraulic and geotechnical engineering. Bridge scour, the erosion of sediments around bridge foundations, is the cause for over 60% of total number of bridge failures in the United States (Briaud, 2015a; Briaud et al., 2001; Sumer, 2007). Erosion is determined by the erodibility of soils as well as by the surrounding water flow conditions. Soil erodibility, the resistance of soil material to erosion induced by fluid flow, is commonly described by critical states of erosion and transport rates (Grabowski, Droppo, & Wharton, 2011). Some of the properties affecting soil erodibility are the soil's porosity and grain size distribution (Stevens, Wheatcroft, & Wiberg, 2007), organic matter content (Adams, Xiao, & Wright, 2013), freeze–thaw cycles (Wynn, Henderson, & Vaughan, 2008), cation exchange capacity (Tejada & Gonzalez, 2006), and vegetation cover (Pan, Li, Amini, & Kuang, 2015). For cohesive soil, the erodibility is mainly controlled by its physical and geochemical properties as well as associated biological activities (Grabowski et al., 2011). The microscale interaction forces of clay particles, including van der Waals attraction, electrostatic repulsion, and hydration forces (Lu, Anderson, Likos, & Mustoe, 2008), may dominate the macroscale resistance of soils to erosion. The erodibility of non-cohesive soil can be described with relatively simple formulations where the critical shear stress and erosion rate are related to soil density, porosity, and grain size (Briaud, 2015b; Sharif, Elkholy, Hanif Chaudhry, & Imran, 2015; Wei, Brethour, Grünzner, & Burnham, 2014). The erosion rate is also influenced by the flow conditions, i.e. laminar or turbulent flow.

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Soil erosion predictions require accurate models for the behavior of the liquid and the soil particles as well as proper consideration of the soil–fluid interactions. A number of approaches have been developed for the mathematical modeling of fluid–particle systems. Volume-averaged concepts were first introduced to describe fluid flow in a particle–fluid system (Anderson & Jackson, 1967, 1969). With this concept, locally averaged velocity and pressure fields are treated as continuous and solved by the Navier–Stokes equations regardless of the volume occupied by the solid particles. Similar transport equations can be used for the solid phase based upon its volume fraction. During the calculations, fluid and solid phases exchange momentum through a drag force model. This Eulerian–Eulerian model is widely used in the study of particle transport under fluid drag in chemical and mechanical engineering (Bouillard, Lyczkowski, & Gidaspow, 1989; Nguyen, Guillou, Chauchat, & Barbry, 2009; Shah, Ritvanen, Hyppänen, & Kallio, 2013). A limitation of this model is that it fails to predict the trajectories of the solid particles (Chen & Wang, 2014). The discrete element method (DEM) is a powerful tool for analyzing granular material flows (Cundall & Strack, 1979). This Lagrangian method monitors the motion of discrete particles and calculates the contact forces generated among particles. A coupled computational fluid dynamics (CFD) and DEM model combines the advantages of the high computational efficiency of the Eulerian approach with the capability of the DEM approach to predict particle trajectories (Tsuji, Tanaka, & Ishida, 1992). The coupled CFD–DEM approach has been applied to understand the performance of fluidized beds (Atsonios et al., 2011; Limtrakul et al., 2003; Saidi, Tabrizi, Grace, & Lim, 2015; Tsuji, Kawaguchi, & Tanaka, 1993; Xu & Yu, 1997), powder mixing (Jovanović, Pezo, Pezo, & Lević, 2014), seepage flow in porous materials (Chen, Drumm, & Guiochon, 2011; Zhao, Houlsby, & Utili, 2014; Zou, Chen, Chen, & Cui, 2013), the impact of granular flow on water (Shan & Zhao, 2014), and the efficacy of drilling fluid (Akhshik, Behzad, & Rajabi, 2016). It can be an effective tool for advancing the microscale understanding of soil erosion mechanism.

Simulating the erosion of cohesive soils is challenging because of the complicated particle interaction forces and the computational demands associated with the platy geometry of the particles. For that reason, the work described in this paper primarily focuses on developing a CFD–DEM model to simulate and understand the erosion of non-cohesive soils, particularly the influence of the angularity of the soil particles on their erodibility. For non-cohesive soils, an increase in particle angularity leads to an increase in maximum and minimum void ratios as well as a higher friction angle (Cho, Dodds, & Santamarina, 2006). Angular particles tend to have a higher coordination number and may suffer a tensile stress under compression (McDowell, Bolton, & Robertson, 1996). Laboratory experiments on glass beads, crushed glass beads, and natural sand have demonstrated the great influence of particle shape on shear resistance; the influence of particle shape on shear resistance may be greater than the influence of the particle's surface roughness (Cavarretta, Coop, & O'Sullivan, 2010; Yang & Luo, 2015). A jet test conducted on glass beads and crushed glass beads showed the particle shape significantly influences the formation of craters under fluid flow: non-spherical particles tend to have a smaller but deeper crater than spherical particles (LaMarche & Curtis, 2015).

Spherical particles are widely used in the modeling of granular material flows in part because there is an efficient contact detecting scheme (Bayesteh & Mirghasemi, 2013; Cundall, 1988). For particles with a complex shape, one common approach using the DEM method is the multi-sphere approximation; the irregular shaped particles are approximated by amalgamating multiple spherical elements (Elskamp, Kruggel-Emden, Hennig, & Teipel, 2015; Parteli & Pöschel, 2016; Thomas & Bray, 1999; Yu, Cheng, Xu, & Soga, 2016; Zhao, Dai, Xu, Liu, & Xu, 2015).

This research aims to develop and implement a coupled CFD–DEM model to simulate the erosion of non-cohesive soils taking different grain shapes into consideration. Ellipsoidal sand particles are approximated using the multi-sphere method with a scaled drag force model according to the particle's actual volume. The magnitude of the drag force is first verified by free settling experiments using 3D printed particles. Soil erosion simulation is conducted with geometric dimensions similar to the erosion function apparatus (EFA) designed by Briaud et al. (2001). Results of the EFA simulation indicate that the grain shape is an important factor for the erodibility of non-cohesive soils; the simulated erosion is consistent with that described for the empirical model currently used in the practice, that is, particle angularity contributes to a critical shear stress above which the erosion rate is linearly dependent upon the flow velocity.

Description of mathematical models

The coupled CFD–DEM model is implemented through a custom-built framework developed under the Matlab environment (MathWorks, Natick, MA, USA). The coupled model links the simulations of two general software packages; the solution of locally averaged Navier–Stokes equations with COMSOL (COMSOL Inc., Burlington, MA, USA) by using its weak form module, and the solution for particle flows with the general DEM code in PFC3D (Itasca Consulting Group, Minneapolis, MN, USA). During each coupled time step, particle velocities and coordinates are extracted from the PFC3D model while fluid velocity and pressure are extracted from the COMSOL fluid model. Porosity and interaction forces are calculated under the Matlab environment. Information on particle porosity and interaction force is transferred into the COMSOL model. The opposing interaction force from the fluid to the solid is transferred to the particles in the PFC3D model. A sensitivity study on the coupling time steps was conducted to determine the appropriate time range for data exchange. The result indicated that a time step of 10^{-3} s (1 μs) provided sufficiently accurate simulation results as well as efficient computational performance for the following simulation cases. The time step of the COMSOL model was set to be 10^{-4} s and the time step of the PFC3D model was around 10^{-6} s.

Fluid phase

The mass and momentum conservation principles for the fluid phase with particles are given in Eqs. (1) and (2) (Anderson & Jackson, 1967). The properties of the fluid field have been averaged by the volume fraction (or porosity). The body force term describing fluid–solid interactions is included in the momentum equation (Eq. (2)), which is defined to be the total drag force divided by the volume of the mesh element. The momentum equation adopted in this paper is based on the assumption that the fluid pressure drop is shared by the fluid phase and the solid phase. Different mathematical forms exist based on different physical assumptions (Guo & Yu, 2017). The mass and momentum equations are:

$$\frac{\partial n\rho}{\partial t} + (\nabla \cdot n\rho\mathbf{u}) = 0, \tag{1}$$

$$\frac{\partial n\rho\mathbf{u}}{\partial t} + (\nabla \cdot n\rho\mathbf{u}\mathbf{u}) = -n\nabla p + \nabla \cdot n\mathbf{K} + n\rho\mathbf{g} + \mathbf{f}^{\mathrm{p}}, \tag{2}$$

where n is porosity of the solid particles; t is the simulation time, $\mathbf{u}$ is the fluid velocity vector, ρ is the density of fluid, p is fluid pressure, $\mathbf{K}$ is the stress tensor for the fluid where $\mathbf{K} = \mu\left(\nabla \mathrm{u} + (\nabla \mathrm{u})^{\mathrm{T}}\right)$, μ is the fluid dynamic viscosity, g is gravitational acceleration, F^{p} is the volumetric fluid–particle interaction force.

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