Feasibility study on coupled CFD-DEM modeling of fluid-driven soil erosion at the particle scale

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ABSTRACT

Understanding and modeling of the fluid-particle interaction is important in modeling soil erosion processes. However, computation of particle-level forces applied by fluid flows and thus modeling of erosion behaviors at a particle level have been daunting tasks. Therefore, this study presents a numerical approach to model the fluid-driven erosion of non-cohesive sands by coupling computational fluid dynamics (CFD) and discrete element method (DEM). Here, we modeled the erosion function apparatus (EFA) test which is frequently used to estimate soil erodibility or soil erosion resistance in the laboratory. DEM was used to model the particle motions by solving Newton's laws of motion and CFD was employed to simulate the fluid flows by solving the volume-averaged Navier-Stokes equations. In addition, the k-ω turbulence model was implemented into the fluid phase to describe turbulent flow behaviors. The particle-level forces, including drag force, buoyancy force, pressure-gradient force, and viscous force, were computed and taken into account for the fluid-particle interactions during the fluid-driven erosion process. The simulation results were discussed in comparison to the experimental EFA test results. This work shows that the coupled CFD-DEM can be a useful and promising tool to model and analyze the soil erosion behavior at the particle scale.

Keywords: Numerical simulation; CFD-DEM; soil erosion; computational fluid dynamics; discrete element method

1 INTRODUCTION

Scour can cause severe structural damage to underwater foundations or embankments (de Falco and Mele 2002; Briaud et al. 1999). As such, identification of the erosion characteristics of soil is important to predict soil scour for the design of underwater structures. Understanding the fluid-particle interaction and quantifying the effects of influencing variables are required as the key mechanism to model soil erosion processes. Soil erosion can be investigated via a numerical approach based on continuum-based models (Papamichos and Malmanger 2001; Chin and Ramos 2002) and discrete element methods (Li et al. 2006; Cook et al. 2004).

This study presents a numerical model coupling computational fluid dynamics (CFD) and the discrete element method (DEM) to study soil erosion mechanisms at the particle scale by modeling the interactions between the fluid and soil particles. In particular, we modeled the erosion process occurring in the laboratory experiment referred to as the erosion function apparatus (EFA) test, which is widely used in the laboratory (Briaud et al. 2001; Ham et al. 2016). This test measures the erosion resistance of the soil subjected to water flows. A soil protrusion of 1 mm thick is exposed to water flows, and the rate of erosion is measured by monitoring the change in the protrusion length with time. The relation between the shear stress induced by water flow and the erosion rate defines the erodibility of soils. The simulations were performed to describe the effect of the fluid velocities on erosion behaviors. These simulation results were compared with the experimental EFA test results (Ham et al., 2016). The feasibility of the proposed simulation method was further discussed.

2 NUMERICAL SIMULATION

2.1 Coupled CFD-DEM

Coupled CFD-DEM method is based on the combined approach of CFD and DEM. The CFD is employed to simulate the fluid flow by solving the volume-averaged Navier-Stokes equations, and the DEM is used to model the particle motion by solving the Newton's laws of motion (Zhou et al. 2010). The closed-form equations were formulated to compute interaction forces that are applied to particles. The parallel CFD-DEM coupling algorithm initiates from CFD analysis. The fluid flow data which is the result of the first step of CFD analysis is used for the DEM analysis. Then, the updated particle information is used for the next CFD step. This process is continued during the simulation.

Different forces including pressure gradient, drag force, virtual mass force, lifting force, capillary force may play dominant roles in different situations as a fluid-particle interaction force. For the fully saturated particles, only the buoyancy force and drag force have been considered because the other forces are too small and can be neglected. The expression of drag force (F_d) is as follows (Di Felice 1994):

$$F_d = \frac{1}{8} C_d \rho d^2 (u-v)|u-v| \varepsilon^{1-\chi} \quad (1)$$

where ρ is the fluid density, d is the diameter of the particle, u is the fluid velocity, v is the particle velocity, $\varepsilon^{1-\chi}$ is a corrective function to account for the presence of other particles, and C_d is the particle-fluid drag coefficient determined by:

$$C_d = \left(0.63 + \frac{4.8\sqrt{\mu}}{\sqrt{\varepsilon \rho d |u-v|}} \right)^2 \quad (2)$$

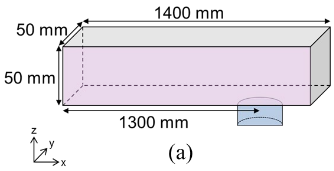
where μ is the viscosity of the fluid. These formulations were implemented to account for the fluid-particle interactions during the erosion process.

2.2 Defined Model Problem

We generated the model to simulate the EFA test; the model dimensions were determined following the actual EFA test setup (Briaud et al. 2001). The rectangular flow channel of which the geometry was 1400 × 50 × 50 mm for length (x-direction), width (y-direction), and height (z-direction), respectively, served as the flow domain for the CFD model. Figure 1 shows the schematic drawing for CFD set-up. Herein, half of the section was modeled using the symmetry. The water comes in and goes out through inlet and outlet of this flow channel, and the flow was solved with k-ω turbulence flow model. The inlet velocities varied as 0.1, 0.16, 0.234, and 0.34 m/s to study the effect of the fluid flow, and the fluid velocity at the wall boundary was set to be zero. For the pressure field, the inlet and walls were set to be zero gradient, and zero pressure value was assigned to the outlet boundary.

For DEM setting, the diameter of the soil specimen was 5 mm, and half of the circular section was modeled, in which the spherical particles with the radius of 0.32 mm were generated. The particle has a density of 2.65 g/cm3, and the other properties are summarized in Table 1. The packed soil specimen was located 1300 mm in x-direction from the inlet.

Then, the coupled CFD-DEM analysis was performed to simulate the EFA test. The DEM and CFD time steps were set as 10^{-6} s and 10^{-4} s and the total simulation time was 2 s. The Di Felice drag force (Di Felice 1994), pressure gradient force, viscous force,



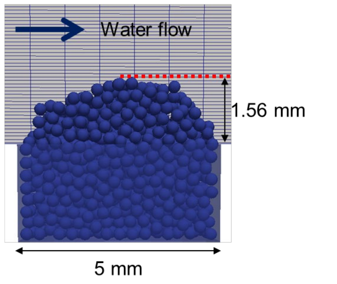


Fig. 1. The set-up of (a) the coupled CFD-DEM analysis for EFA test (schematic drawing) and (b) soil specimen.

and buoyancy force were considered as the particle-fluid interaction forces. Figure 1b shows the initial set-up of the soil specimen for the simulation. The soil particles were positioned at the soil specimen tube with 1.5 mm thickness. A total of four cases were run for the different water velocities.

3 RESULTS AND DISCUSSION

3.1 EFA simulation result

In the simulation, soil particles were eroded due to the shear stress applied by the water flow. The simulated evolution of the erosion process for the water velocity of 0.34 m/s are shown in Figure 2. The coupled CFD-DEM analysis was conducted by examining the interaction between the soil particles and the water flow, as the soil particles moved along the path of the flow and water velocity changed near the soil specimen (Figure 2). Soil erosion continued until the force induced by the water flow was insufficient to erode the particles. At a low water velocity, the resulting interaction force that was applied to the particles was small because the interaction force is the function of the water velocity (e.g. Di Felice drag force; Di Felice 1994). As the fluid velocity at the wall boundary was set to be zero, the fluid velocity near the bottom wall was too low to erode the particles. For this reason, part of the total soil protrusion was eroded.

Table 1. Input parameters of the coupled CFD-DEM analysis for EFA test

Properties	Value
Fluid density (kg/m3)	1000
Inlet flow velocity (m/s)	0.1, 0.16, 0.234, 0.34
Thickness of soil particles (mm)	1.56
Radius of soil particle (mm)	0.32
Specific gravity	2.65
Coefficient of restitution	0.06
Coefficient of friction	0.5
Coefficient of rolling	0.5

3.2 Estimation of the erosion rate

Figure 3a shows the change in the soil depth at four different water velocities, estimated by the particle locations during the EFA simulation. The soil specimen was divided into three sections along the flow direction.

The maximum z-location at each section was picked, and then the averaged z-location was used to plot the change in soil depth curve (Figure 3a). The initial height of the soil protrusion was 1.56 mm (Figure 1). As the soil particles were gradually removed, the height became 1.48, 1.07, 0.67, and 0.29 mm for the fluid velocity of 0.1, 0.16, 0.234, and 0.34 m/s, respectively. At the slow flow velocity of 0.1 m/s, the change in soil depth was less than 0.2 mm, which meant only minimal erosion occurred. Whereas, at the high flow velocity of 0.34 m/s, the soil was eroded by more than 1.3 mm in 0.4 s. In particular, it is interesting to note that the soil erosion became more significant and faster as the water velocity increased.

Figure 3b shows the erosion rate versus shear stress for all the simulated cases. The soil erosion rate was calculated by dividing the eroded soil depth with the time taken to erode the corresponding depth. For example, at a water velocity of 0.34 m/s, the total 1.3 mm of soil was eroded in 0.4 s, and then the erosion rate would be the 3.25 mm/s. The shear stress (τ) was calculated in the matter as in the EFA method as:

$$\tau = \frac{1}{8} f \rho v^2 \qquad (3)$$

where f is the friction factor that can be obtained from Moody's chart (Moody 1944), ρ is the density of water, and v is the mean flow velocity. The erosion curve from Ham et al. (2016) was plotted in Figure 3b to compare the CFD-DEM simulation results with the experiment results. Consequently, it was found that the critical shear stress values that cause erosion from the simulation and the experiment are fairly well matched. This implies that the suggested CFD-DEM modeling can effectively capture the critical shear stress.

However, the erosion curve from the simulation was higher than those from the experiment. This was attributed to many possible reasons which include the size of the specimen, the particle shape, the particle size, and the pre-consolidation process. For instance, a soil specimen with 71 mm diameter was used in the experiment (Ham et al. 2016), while that with 5 mm was used in the simulation for the computational effort. As the longer distance required for particles to move for complete erosion, the greater erosion rate was observed in the simulation, due to the small specimen diameter.

Furthermore, the shear stress that is theoretically estimated by using a theory may differ with the actual shear stress that the particles are subject to in the simulation. This may have contributed to the observed difference in erosion rate, as can be seen in Figure 3b.

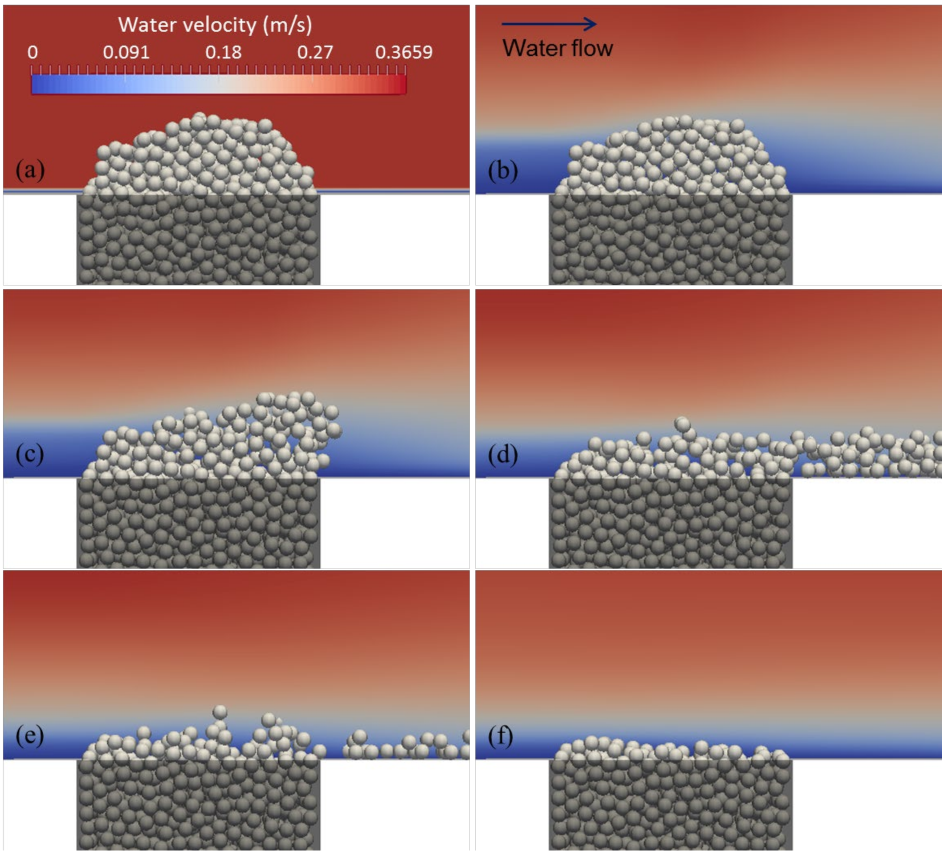


Fig. 2. The water velocity and particle behavior at water velocity of 0.34 m/s: (a) initial condition, (b) after steady-state fluid flow, (c) at 0.01 s, (d) at 0.05 s, (e) at 0.1 s, and (f) 1 s.

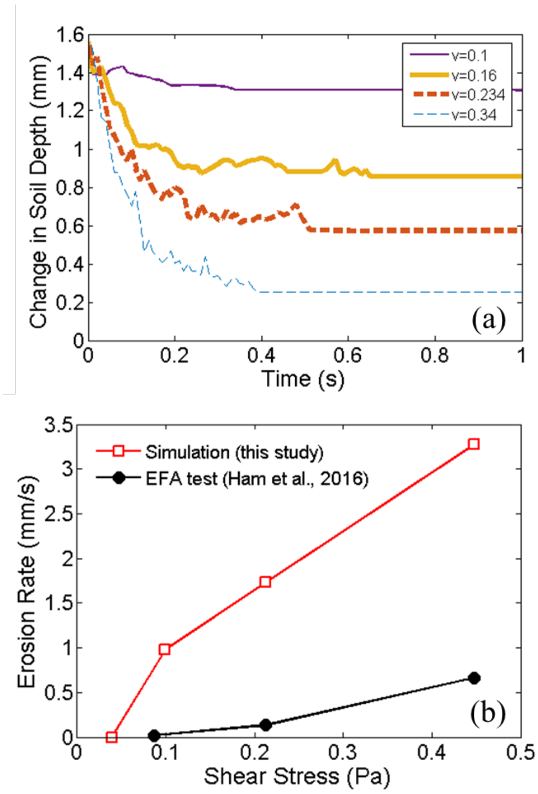


Fig. 3. (a) Change in soil depth at various water velocities and (b) erosion curve obtained from the simulation and the experiment.

4 CONCLUSION

The feasibility of using the coupled CFD-DEM simulation to describe the erosion process was investigated. The simulation of the EFA test was performed and then compared with the experimental results. The coupled CFD-DEM method was found to be applicable. The erosion was well described with the simulation and the exact erosion rate was obtained by analyzing the particle location. Particularly, the critical shear stress value from the simulation is fairly in concordance with that from the experiment. The difference in shear stress calculated with the theoretical model and the actual shear stress may have contributed to the observed difference in erosion rate. There were several advantages of using the simulation, which includes the interaction between flow and the particles, accurate particle location, and velocity profile that can be used for the future study. This work shows that the coupled CFD-DEM is a useful and promising tool to analyze the soil erosion behavior for sand at the particle scale.

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