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Case study

Sediment micromechanics in sheet flows induced by asymmetric waves: A CFD–DEM study

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ABSTRACT

Understanding the sediment transport in oscillatory flows is essential to the investigation of the overall sediment budget for coastal regions. This overall budget is crucial for the prediction of the morphological change of the coastline in engineering applications. Since the sediment transport in oscillatory flows is dense particle-laden flow, appropriate modeling the particle interaction is critical. Although traditional two-fluid approaches have been applied to the study of sediment transport in oscillatory flows, the approaches do not capture the interaction of the particles. The study of the motion of individual sediment particles and their micromechanics (e.g., packing and contact force) in oscillatory flows is still lacking. In this work, a parallel CFD–DEM solver *SediFoam* that can model the inter-particle collision is applied to study the granular micromechanics of sediment particles in oscillatory flows. The results obtained from the CFD–DEM solver are validated by using the experimental data of coarse and medium sands. The comparison with experimental results suggests that the flow velocity, the sediment flux and the net sediment transport rate predicted by *SediFoam* are satisfactory. Moreover, the micromechanic quantities of the sediment bed are presented in detail, including the Voronoi concentration, the coordination number, and the particle interaction force. It is demonstrated that the variation of these micromechanic quantities at different phases in the oscillatory cycle is significant, which is due to different responses of the sediment bed. To investigate the structural properties of the sediment bed, the correlation of the Voronoi volume fraction and coordination number is compared to the results from the fluidized bed simulations. The consistency in the comparison indicates the structural micromechanics of sediment transport and fluidized bed are similar despite the differences in flow patterns. From the prediction of the CFD–DEM model, we observed that the coordination number in rapid sheet flow layer is larger than one, which indicates that a typical particle in the sediment layer is in contact with more than one particles, and thus the binary collision model commonly used in two-fluid approaches may underestimate the contact between the particles.

1. Introduction

Oscillatory sheet-flow sediment transport is important in coastal and geotechnical engineering because it carries significant amount of sand and has a considerable impact on the overall sediment budget (Malarkey et al., 2009). Since the inter-particle collision plays an important role in oscillatory sheet-flow sediment transport, understanding the mechanics at the particle scale can provide physical insights of this problem. The microscopic information can describe the properties of the sediment bed, such as packing, mixing, and permeability (Yi et al., 2011). In addition, the structural strength of the seabed, without which the sediment particles will behave as fluid (Scholtès et al., 2015), can be also evaluated by using micromechanic variables. There is also an increasing interest to seek for the constitutive laws for dense granular flows in the macroscopic modeling of sediment transport problems based on the microscopic information, including the understanding of the anisotropic nature of the soil, the response of the sediment bed under stress, and the relationship between particle-scale response and material response (O'Sullivan, 2011).

1.1. Sediment transport in oscillatory sheet-flow

The wave orbital motion is dominant in cross-shore sediment transport (Ribberink, 1998). The wave-induced oscillatory flow may lead to onshore or offshore sediment transport, and thus is important in the prediction of beach-profile changes. Although some researchers performed experimental studies of the sediment transport in oscillatory flows, the measurement of the concentration and velocity of sediment particles are still considered

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very difficult (Flores and Sleath, 1998; O'Donoghue and Wright, 2004a,b). For example, O'Donoghue and Wright (2004b) used both conductivity concentration measurement (CCM) probes and suction samplers to measure the sediment concentration. Conductivity concentration probes are used to measure the sediment concentration in the region of high concentration in the sheet flow layer, whereas suction samplers are used in the low concentration region in the suspension layer. The samplers are located at approximately one centimeter above the sediment bed to avoid the possible interaction of suction sampler and sediment bed. Therefore, the regions with medium concentration cannot be measured and there is a gap above the sediment bed in the experimental measurement data. Because of the difficulties in the experimental measurements, numerical simulations have been a cost-effective approach to study the sediment transport in oscillatory flows.

A traditional numerical simulation approach is the two-fluid model (Hanes and Bowen, 1985; Jenkins and Hanes, 1998; Hsu et al., 2004; Malarkey et al., 2009; Cheng and Hsu, 2014), in which both the fluid and particle phases are described as inter-penetrating continuum. This approach does not capture the motion of individual sediment particle but solves the concentration field of the particles. To model the inter-particle collision, constitutive relations based on binary collision assumptions are used (Cheng and Hsu, 2014). The two-fluid model is satisfactory in capturing the sediment concentration and sediment flux compared to the experimental results (Malarkey et al., 2009; Cheng and Hsu, 2014). However, since two-fluid models rely on constitutive relations of the particle phase based on binary collisions, it is only valid in relatively dilute flows. In dense flows, the particles have endured contact, and thus the binary collisions may not be applicable (O'Sullivan, 2011; Hou et al., 2012).

CFD–DEM (Computational Fluid Dynamics–Discrete Element Method) is another numerical approach that has been applied to study sediment transport in sheet flows. In contrast to the two-fluid model, CFD–DEM models the motion of sediment particles explicitly, and accounts for the collision of sediment particles. However, due to the limitation of the computational costs, the study of sediment transport in oscillatory flows using CFD–DEM was simplified in the early studies (Drake and Calantoni, 2001; Calantoni et al., 2004). The oscillatory flow was modeled as two-dimensional layers and only a few thousand particles were used. In addition, the early studies did not resolve the instantaneous turbulent flow and only investigated the mechanics of very coarse sediment particles in oscillatory sheet-flow. With the growth of available computational resources, this approach has gained more popularity in solving sediment transport problems. In the recent works (Schmeeckle, 2014; Sun and Xiao, 2016a), the motion of medium or coarse sand particles in turbulent flows is captured.

1.2. Granular micromechanics

The granular micromechanics of particle-laden flow are critical in the physical understanding of granular microscopic structures, especially for chemical and pharmaceutical engineering problems (Kuang and Yu, 2011; Hou et al., 2012). The micromechanic variables, including Voronoi volume fraction, coordination number, contact force and others quantities, are obtained based on the packing of the particles. Since such micromechanic variables are much easier to produce from DEM than measuring from experiment, DEM has been extensively used to investigate the granular micromechanics in the past decade (Yi et al., 2011).

DEM has been widely applied to investigate the granular micromechanics in engineering applications, for example, hopper, rotating drum, and sand piles (Langston et al., 1995; Yang et al., 2003; Zhao and Shan, 2013). Micromechanic variables are investigated to understand the heat conduction, particle agglomeration and structural stability. CFD–DEM simulations of pneumatic convey and fluidized bed problems are also performed to study the variation of micromechanic variables in different flow regimes (Kuang and Yu, 2011; Hou et al., 2012). Moreover, the constitutive models are proposed according to the micromechanics of the granular materials (Sun and Sundaresan, 2011), which contributes to macroscopic modeling. Previous studies of granular micromechanics have demonstrated that the CFD–DEM approach has good potential for the granular micromechanics in geotechnical engineering, for example, the modeling of arbitrary-shaped particles (O'Sullivan, 2011). However, the study in granular micromechanics of sediment transport is still lacking.

Although recent studies prove that CFD–DEM is capable of predicting sediment transport in unidirectional turbulent flow (Kidanemariam and Uhlmann, 2014; Schmeeckle, 2014; Sun and Xiao, 2016a), the capability of this approach in predicting the motion of coarse and medium sand in oscillatory flow is still not demonstrated. The present work aims at (1) demonstrating that CFD–DEM is capable of predicting the instantaneous motion of sediment particles in oscillatory sheet-flow, and (2) investigating the granular micromechanics in sediment transport process. Coarse and medium sands are used in the present numerical simulations. The instantaneous turbulent flow field within the boundary layer is resolved.

The rest of the paper is organized as follows. The methodology of the present model is introduced in Section 2, including the mathematical formulation of fluid equations, the particle motion equations, the fluid–particle interactions, and diffusion-based averaging procedure. The implementation of the code and the numerical methods used in the simulations are detailed in Section 3. In Section 4, the results obtained in the simulations are discussed. Finally, Section 5 concludes the paper.

2. Methodology

2.1. Mathematical model of particle motion

In *SediFoam*, the translational and rotational motions of each particle are calculated based on Newton's second law as the following equations (Cundall and Strack, 1979; Ball and Melrose, 1997):

$$m\frac{d\mathbf{u}}{dt} = \mathbf{f}^{col} + \mathbf{f}^{fp} + m\mathbf{g}, \tag{1a}$$

$$I\frac{d\mathbf{\Psi}}{dt} = \mathbf{T}^{col} + \mathbf{T}^{fp}, \tag{1b}$$

where $\mathbf{u}$ is the velocity of the particle; t is time; m is particle mass; $\mathbf{f}^{col}$ represents the contact forces due to particle–particle or particle–wall collisions; $\mathbf{f}^{fp}$ denotes fluid–particle interaction forces; $\mathbf{g}$ is body force. I and $\mathbf{\Psi}$ are angular moment of inertia and angular velocity of the particle; $\mathbf{T}^{col}$ and $\mathbf{T}^{fp}$ are the torques due to contact forces and fluid–particle interactions, respectively. To compute the collision forces and torques, the particles are modeled as soft spheres with inter-particle contact represented by an elastic spring and a viscous dashpot. Further details can be found in the study by Tsuji et al. (1993).

2.2. Locally-averaged Navier–Stokes equations for fluids

The fluid flow is described by the locally-averaged incompressible Navier–Stokes equations. Assuming constant fluid density ρ_f, the governing equations for the fluid are (Anderson and