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CFD–DEM simulations of current-induced dune formation and morphological evolution

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ABSTRACT

Understanding the fundamental mechanisms of sediment transport, particularly those during the formation and evolution of bedforms, is of critical scientific importance and has engineering relevance. Traditional approaches of sediment transport simulations heavily rely on empirical models, which are not able to capture the physics-rich, regime-dependent behaviors of the process. With the increase of available computational resources in the past decade, CFD–DEM (computational fluid dynamics–discrete element method) has emerged as a viable high-fidelity method for the study of sediment transport. However, a comprehensive, quantitative study of the generation and migration of different sediment bed patterns using CFD–DEM is still lacking. In this work, current-induced sediment transport problems in a wide range of regimes are simulated, including 'flat bed in motion', 'small dune', 'vortex dune' and suspended transport. Simulations are performed by using *SediFoam*, an open-source, massively parallel CFD–DEM solver developed by the authors. This is a general-purpose solver for particle-laden flows tailed for particle transport problems. Validation tests are performed to demonstrate the capability of CFD–DEM in the full range of sediment transport regimes. Comparison of simulation results with experimental and numerical benchmark data demonstrates the merits of CFD–DEM approach. In addition, the improvements of the present simulations over existing studies using CFD–DEM are presented. The present solver gives more accurate prediction of sediment transport rate by properly accounting for the influence of particle volume fraction on the fluid flow. In summary, this work demonstrates that CFD–DEM is a promising particle-resolving approach for probing the physics of current-induced sediment transport.

1. Introduction

The perpetual motion of water carves the surface of the earth by entraining and carrying sediment from one location to another, leading to changes of morphology in the ocean and particularly along the coastline. Scientists rely on fundamental understanding of sediment transport to explain and predict the dynamic evolution of the seabed and coastal bathymetry at various spatial and temporal scales; engineers utilize the understanding of the sediment transport mechanisms to design better civil defense infrastructure, which mitigates the impact of coastal hazards such as storm surges and tsunamis on the coastal communities. However, the understanding and prediction of sediment transport are hindered by the complex dynamics and numerous regimes. Traditional hydro- and morphodynamic models (Delft Hydraulics, 1999; Lesser et al., 2000; Warren and Bach, 1992; Xiao et al., 2010) for sediment transport simulations heavily relied on phenomenological models and empirical correlations to describe sediment erosion and deposition fluxes (Meyer-Peter and Müller, 1948; van Rijn, 1984), which lack universal applicability across different regimes and can lead to large discrepancies in predictions.

With the rapid growth of available computational resources in the past decades, many high-fidelity models have been proposed, including two-fluid models (Hsu et al., 2004; Yu et al., 2012), particle-resolving models (Calantoni et al., 2004; Drake and Calantoni, 2001; Jiang, 1995; Schmeeckle, 2014), and interface-resolving models (Kempe and Fröhlich, 2012; Kempe et al., 2014; Kidanemariam and Uhlmann, 2014a, 2014b). Two-fluid models describe the particle phase as a continuum and thus need constitutive relations to account for the particle–particle collisions and fluid–particle interactions. Particle-resolving models explicitly track the movements of all particles and their collisions, which are thus much more expensive than two-fluid models. Empirical models are still used to compute the fluid–particle interaction forces. In interface-resolving models, not only individual particles but also the detailed flows fields around particle surfaces

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are fully resolved. Consequently, they are more expensive than particle-resolving models but require even less empirical modeling.

Particle-resolving models can accurately predict particle phase dynamics such as vertical and horizontal sorting due to densities, sizes, shapes, which are important phenomena in nearshore sediment transport. Possibly constrained by computational resources at the time, early particle-resolving models used highly simplified assumptions for the fluid phase by modeling the fluid as two-dimensional layers (Drake and Calantoni, 2001; Jiang, 1995). The number of particles was also limited to a few thousand particles, and thus the computational domain covers only a few centimeters or less for particle diameters typical for coastal sediments. As a result, these methods were limited to featureless bed under specific flow conditions (e.g., intense sheet flow conditions, where the layer fluid assumption is valid).

1.1. Simulation of sediment transport with modern CFD–DEM methodology

In the past few years, researchers started to use modern, general-purpose particle-resolving solvers based on Computational Fluid Dynamics–Discrete Element Method (CFD–DEM) to study sediment transport. In CFD–DEM, Reynolds Averaged Navier–Stokes (RANS) equations or Large Eddy Simulations (LES) are used to model the fluid flows, which are coupled with the discrete element method for the particles. CFD–DEM has been used extensively in the past two decades in the chemical and pharmaceutical industry on a wide range of applications such as fluidized beds, cyclone separator, and pneumatic conveying (Ebrahimi, 2014; Han et al., 2003). On the other hand, special-purpose codes have been used to study specific regimes of sediment transport, where solvers are developed based on and valid for only the sediment transport regime to be studied, e.g., bedload transport under two-dimensional, laminar flow conditions (Durán et al., 2012). However, the use of modern, general-purpose CFD–DEM solvers as those used in chemical engineering applications to simulate sediment transport is only a recent development in the past few years. In his pioneering work, Schmeeckle (2014) used an open-source CFD–DEM solver (Goniva et al., 2009; Kloss et al., 2012) to study suspended sediment transport. The merits and significance of Schmeecle's pioneering work are summarized as follows: (1) It is the first work done by using modern CFD–DEM solver in the simulation of sediment transport, especially in the suspended sediment transport regime; (2) Rich data sets are obtained by the CFD–DEM solver that are very difficult to obtain in the field or the laboratory; (3) Several questions of the mechanics of sediment transport are answered, including the mechanisms of saltation and entrainment; (4) Interesting and insightful phenomena are observed, including the increase of bed friction at the transition of suspension. However, a theoretical limitation of his work is that the influence of particle volume fraction on the fluid flow is not considered, since the volume fraction does not appear in the fluid continuity equation (see Eq. (1) in Schmeeckle (2014)). This choice was likely made to avoid the destabilizing effects of the volume fraction on the LES equations. Moreover, the fluid–particle drag law adopted in his work does not explicitly account for the volume fraction. Consequently, the drag law he used is not able to represent the varying shielding effects of particles under different particle loading conditions. This effect is important in particle-laden flows where the flow field has disparate distributions of particle loadings from very dilute to very dense, which is the consensus of the CFD–DEM community (Feng and Yu, 2007; Kafui et al., 2002; Tsuji et al., 1993) in simulating industrial particle-laden flows. Finally, the study by Schmeeckle (2014) focused on suspended sediment on featureless beds with comparison of sediment transport rates to empirical formulas in the literature. Many other regimes of sediment transport such as bedload transport as well as more complex patterns such as the formation and evolution of bedforms are still yet to be studied. Arolla and Desjardins (2015) studied the transport of cuttings particles in a pipe with CFD–DEM, where a volume-filtered LES approach is used to model the fluid flow (Capecelatro and Desjardins, 2013). The emergence of small dunes and sinusoidal dunes from an initially flat particle bed under different flow velocity are observed, demonstrating the capability of CFD–DEM in predicting the stability characteristics of sediment beds. However, quantitative comparisons with experimental data are limited to a few integral quantities such as holding rate, and a more detailed validation with experimental or numerical benchmark data were not performed. In summary, while a few researchers have made attempts in using CFD–DEM to study sediment transport and have obtained qualitatively reasonable predictions, a rigorous, comprehensive study of sediment transport in a wide range of regimes with detailed quantitative comparisons with benchmark data is still lacking. This study aims to bridge this gap by tackling the unique challenges for the CFD–DEM posed by the physical characteristics of sediment transport problems, which are detailed below.

1.2. Unique challenges of sediment transport with CFD–DEM

Given the decades of experiences of using CFD–DEM in chemical engineering applications, one may expect that all these experiences should be straightforwardly transferable to simulations of sediment transport. Unfortunately, this is not the case. First, most of the critical phenomena such as incipient motion, entrainment, suspension, and mixing of suspended sediments with water occur in a boundary layer near the interface of the fluid and the sediment bed. Adequately resolving the flow features within the boundary layer such as the mean velocity gradient, shear stress, and turbulent coherent structures is essential for capturing the overall dynamics of fluid and particle flows. In contrast, in fluidized bed applications, the dynamics of the fluids and particles in the entire bed are of equal importance. Accurately resolving the boundary layer features poses both theoretical and practical challenges for CFD–DEM. This is because the characteristic length scales of the flow can be comparable to or smaller than the particle diameters, but the CFD–DEM describes the fluid flows with *locally averaged* Navier–Stokes equations, which are only valid at scales much larger than the particle size (Anderson and Jackson, 1967). Moreover, since the carrier phase (water) and the dispersed phase (particles) have comparable densities in sediment transport, many effects that are negligible in gas–solid flows such as added mass effects and lubrication are important sediment transport. In comparison, the density of the carrier phase (air or other gases) in gas–solid flows is two orders of magnitude smaller than that of the particles. Consequently, the fluid–particle interactions are dominated by the drag forces, while the other forces mentioned above are of secondary importance and can be neglected (Zhou et al., 2011).

In this work, we demonstrate that CFD–DEM is able to capture the essential features of sediment transport in various regimes with a small fraction of the computational cost of interface-resolved models. On the other hand, detailed features in the bed dynamics in the turbulent flows are reproduced correctly, which is beyond the reach of lower fidelity models such as two-fluid models or phenomenological model based morphodynamic simulations. Furthermore, we demonstrate that improved results can be obtained by properly accounting for the effects of particle volume fraction on the fluid dynamics and the fluid–particle interaction forces. Therefore, when properly used, CFD–DEM can be a powerful and practical tool to probe the fundamental dynamics of sediment transport across a wide range of regimes.