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Eddy interaction model for turbulent suspension in Reynolds-averaged Euler–Lagrange simulations of steady sheet flow

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ABSTRACT

A Reynolds-averaged Euler–Lagrange sediment transport model (CFDEM-EIM) was developed for steady sheet flow, where the inter-granular interactions were resolved and the flow turbulence was modeled with a low Reynolds number corrected $k-\omega$ turbulence closure modified for two-phase flows. To model the effect of turbulence on the sediment suspension, the interaction between the turbulent eddies and particles was simulated with an eddy interaction model (EIM). The EIM was first calibrated with measurements from dilute suspension experiments. We demonstrated that the eddy-interaction model was able to reproduce the well-known Rouse profile for suspended sediment concentration. The model results were found to be sensitive to the choice of the coefficient, C_0, associated with the turbulence-sediment interaction time. A value $C_0 = 3$ was suggested to match the measured concentration in the dilute suspension. The calibrated CFDEM-EIM was used to model a steady sheet flow experiment of lightweight coarse particles and yielded reasonable agreements with measured velocity, concentration and turbulence kinetic energy profiles. Further numerical experiments for sheet flow suggested that when C_0 was decreased to $C_0 < 3$, the simulation under-predicted the amount of suspended sediment in the dilute region and the Schmidt number is over-predicted ($Sc > 1.0$). Additional simulations for a range of Shields parameters between 0.3 and 1.2 confirmed that CFDEM-EIM was capable of predicting sediment transport rates similar to empirical formulations. Based on the analysis of sediment transport rate and transport layer thickness, the EIM and the resulting suspended load were shown to be important when the fall parameter is less than 1.25.

1. Introduction

Studying sediment transport in rivers and coastal regions is critical to understand the fluvial geomorphology, loss of wetland, and beach erosion. For example, significant engineering efforts were devoted to control the river discharge and sediment budget to reduce the loss of Louisiana wetland (Allison et al., 2012; Mossa, 1996). In the Indian River inlet, significant erosion of the north beach is mitigated through proper beach nourishment that interacts with littoral drift (Keshtpoor et al., 2013). The characteristics of sediment transport vary significantly with sediment properties and flow conditions, and it is widely believed that sheet flow plays a dominant role in nearshore beach erosion and riverine sediment delivery, especially during storm and flood conditions, respectively.

Sheet flow is an intense sediment transport mode, in which a thick layer of concentrated sediment is mobilized above the quasi-static bed. The conventional single-phase-based sediment transport models assume the dynamics of transport can be subjectively separated into bedload and suspended load (*e.g.*, van Rijn, 1984a; 1984b). While the suspended load are directly resolved, the bedload are parameterized by empirical formulations. Several laboratory measurements of sheet flow with the full profile of sediment transport flux and net transport rate indicated that the split of bedload and suspended load may be too simple because sediment entrainment/deposition is a continuous and highly dynamic process near the mobile bed (*e.g.*, O'Donoghue and Wright, 2004; Revil-Baudard et al., 2015). In sheet flow, the two prevailing mechanisms driving the sediment transport are inter-granular interactions and turbulent suspension (Jenkins and Hanes, 1998; Revil-Baudard et al., 2015). In order to model the full profile of sediment transport, both mechanisms must be taken into account. In the past decade, many Eulerian two-phase flow models have been developed for sheet flow transport in steady (Jenkins and Hanes, 1998; Longo, 2005; Revil-

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Baudard and Chauchat, 2013) and oscillatory flows (Dong and Zhang, 2002; Hsu et al., 2004), Amoudry et al., (Chen et al., 2011; Cheng et al., 2017a; Liu and Sato, 2006). By solving the mass and momentum equations of fluid phase and sediment phase with appropriate closures for interphase momentum transfer, turbulence, and intergranular stresses, these models are able to resolve the entire profiles of sediment transport without the assumption of bedload and suspended load.

In the continuum description of the sediment phase, the assumption of uniform particle properties and spherical particle shapes are usually adopted. To better capture the polydisperse nature of sediment transport and irregular particle shapes, the Lagrangian approach for the particle phase, namely the Discrete Element Method (DEM, Cundall and Strack, 1979; Maurin et al., 2015; Sun and Xiao, 2016a) is superior to the Eulerian approach because individual particle properties may be uniquely specified (Calantoni et al., 2004; Fukuoka et al., 2014; Harada and Gotoh, 2008). One of the main challenges in modeling sheet flow arise from the various length scales involved in inter-granular interactions and sediment-turbulence interactions. To resolve the flow turbulence and turbulence-sediment interactions in sheet flow, the computational domain needs to be sufficiently large to resolve the largest eddies, while the grid resolution should be small enough to resolve the energy containing turbulent eddies. This constrain becomes even more challenging in the Euler–Lagrange modeling framework. Large domains require both a large number of grid points to resolve a sufficient amount of turbulence energy cascade (*i.e.*, large-eddy simulation) and a large number of particles in a given simulation (*e.g.*, Finn et al., 2016). It is well-established that in sheet flow, the transport layer thickness scales with the grain size and the Shields parameter (Wilson, 1987), suggesting that a common sheet flow layer thickness must be about several tens of grain diameters. To simulate the largest eddies and their subsequent cascade, the domain lengths in the two horizontal directions must be proportional to the boundary layer thickness, which is usually about several tens of centimeters. For a bed layer thickness of 50 grains with a typical grain diameter of 0.2 mm, sheet flow simulations may require at least several tens of millions of particles. Therefore, to efficiently model sediment transport for many scenarios in sheet flow, a turbulence-averaged approach for the carrier phase may be necessary. In a turbulence-averaged formulation, turbulent eddies are not resolved and their effects on the averaged flow field are often parameterized via eddy viscosity. In this case, the domain lengths in the two horizontal directions are solely determined by the largest length scale of inter-granular interaction, which is usually captured within 50 grain diameters (Maurin et al., 2015). Consequently, the number of particles needed for each sheet flow simulation is limited to no more than a few hundred thousand.

With a goal to develop a robust open-source coupled Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) for sheet flow applications, we adopt a turbulence-averaged approach in this study. Existing Reynolds-averaged CFD-DEM models have the capability to model bedload transport (Durán et al., 2012; Maurin et al., 2015) and sheet flow for coarse sand (Drake and Calantoni, 2001), where the inter-granular interactions are dominant, and the turbulent suspension is of minor importance. The previous studies made significant progresses in understanding the sediment dynamics due to intergranular collisions and interactions with the mean flow, and the key characteristics such as sediment transport rate and transport layer thickness close to the empirical formulations were obtained. In more energetic sheet flows with medium to fine sand particles, the role of turbulence-induced suspension can become important, where substantial sediment suspension occurs above the bedload layer (Bagnold, 1966; Sumer et al., 1996). In such condition, a more complete closure models for turbulent suspension and turbulence modulation by particles are needed. The natural way of describing the diffusion and dispersion of dispersed particles is to sample the turbulent velocity statistics along their trajectories in a stochastic manner (Taylor, 1922), and this idea lays the foundation of modeling the turbulent motions of particles with a Lagrangian approach.

In the stochastic Lagrange model for particle dispersion, the turbulent agitation to the sediment particles are considered either through a random-walk model (RWM) or an eddy interaction model (EIM). In the RWM framework, the strength of particle velocity fluctuations are typically assumed to be similar to the fluid turbulence, and a series of random velocity fluctuations are directly added to the particle velocities. While the Lagrange model with RWM is successful in studying the particle dispersion in mixing layer (Coimbra et al., 1998) and dilute suspension (Shi and Yu, 2015), the assumption of estimating the particle velocity fluctuations based on the fluid turbulence is crucial, and many researchers found that the correlation between the particle and fluid fluctuations are highly dependent on the particle Stokes number, $St = t_p/t_l$ (Balachandar and Eaton, 2010), where t_p is the particle response time, and t_l is the characteristic time scale of energetic eddies. For the particles with very small inertia ($St \ll 1$), they can closely follow the eddy motion. However, if $St \gg 1$, the particle trajectory is hardly affected by the fluid eddy motion. Due to the particle inertia effect, it was found that the fluid turbulent intensity needs to be enhanced for medium to coarse particles (Shi and Yu, 2015). This problem can be largely remedied by the EIM (Matida et al., 2004), where the fluid velocity fluctuations associated with the fluid turbulence are added through the particle-sediment interaction force, *i.e.*, the drag force. This approach incorporates the particle inertia effect naturally and it is applicable for a wide range of sediment properties. Graham (1996) found that the dispersion of inertial particles may be correctly represented with a suitable choice of maximum interaction time and length scales with the eddies. This model was later improved by using a randomly sampled eddy interaction time, in which more realistic turbulent scales become possible, and the enhanced dispersion of high-inertia particles are captured. In the previous studies of particle dispersion (*e.g.*, Shi and Yu, 2015), the turbulent intensity is either prescribed from the empirical formula, or modeled using clear fluid turbulence closure without considering turbulence modulation by the presence of particles. In sheet flow, it is well-known that the sediment-turbulence interaction is important in attenuating the flow turbulence, thus the presence of sediment can dissipate/enhance flow turbulence through drag/density stratification.

In this paper, we present an application of the eddy interaction model (EIM) in a Reynolds-averaged Euler–Lagrange formulation to study sheet flow. The eddy interaction model is implemented into an open source coupled CFD-DEM scheme called CFDEM (Goniva et al., 2012), and the new solver is called CFDEM-EIM. The fluid phase is modeled in a similar way as the Eulerian two-phase flow model SedFOAM (Cheng et al., 2017a), and the particles are modeled with the discrete particle model, LIGGGHTS (Kloss et al., 2012). The paper is organized in the following manner. The model formulation is described in Section 2. The model calibration with dilute suspension experiments is presented in Section 3.1, followed by model validation of steady sheet flow (Section 3.2) using a comprehensive dataset (Revil-Baudard et al., 2015; 2016). Section 4 discusses the model sensitivity of the resulting sediment diffusivity and Schmidt number to model coefficients in the eddy interaction scheme, and effects of the EIM on the modeled sediment transport rate and transport layer thickness are also evaluated. Finally, a practical regime for the EIM to be important is proposed based on the fall parameter. Concluding remarks are given in Section 5.

2. Model formulations

2.1. Discrete particle model

In the framework of the discrete element method (Cundall and Strack, 1979), the position of each particle is tracked by integrating the particle equation of motion,