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An Eulerian two-phase model for steady sheet flow using large-eddy simulation methodology

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ABSTRACT

A three-dimensional Eulerian two-phase flow model for sediment transport in sheet flow conditions is presented. To resolve turbulence and turbulence-sediment interactions, the large-eddy simulation approach is adopted. Specifically, a dynamic Smagorinsky closure is used for the subgrid fluid and sediment stresses, while the subgrid contribution to the drag force is included using a drift velocity model with a similar dynamic procedure. The contribution of sediment stresses due to intergranular interactions is modeled by the kinetic theory of granular flow at low to intermediate sediment concentration, while at high sediment concentration of enduring contact, a phenomenological closure for particle pressure and frictional viscosity is used. The model is validated with a comprehensive high-resolution dataset of unidirectional steady sheet flow (Revil-Baudard et al., 2015, Journal of Fluid Mechanics, 767, 1–30). At a particle Stokes number of about 10, simulation results indicate a reduced von Kármán coefficient of $\kappa \approx 0.215$ obtained from the fluid velocity profile. A fluid turbulence kinetic energy budget analysis further indicates that the drag-induced turbulence dissipation rate is significant in the sheet flow layer, while in the dilute transport layer, the pressure work plays a similar role as the buoyancy dissipation, which is typically used in the single-phase stratified flow formulation. The present model also reproduces the sheet layer thickness and mobile bed roughness similar to measured data. However, the resulting mobile bed roughness is more than two times larger than that predicted by the empirical formulae. Further analysis suggests that through intermittent turbulent motions near the bed, the resolved sediment Reynolds stress plays a major role in the enhancement of mobile bed roughness. Our analysis on near-bed intermittency also suggests that the turbulent ejection motions are highly correlated with the upward sediment suspension flux, while the turbulent sweep events are mostly associated with the downward sediment deposition flux.

1. Introduction

Understanding the mechanisms driving the mobilization, suspension, transport and deposition of sediments is fundamental to the prediction of the earth surface evolution. Sheet flow represents an intense sediment transport mode, in which a thick layer of concentrated sediment is mobilized above the quasi-static bed. However, modeling sheet flow remains challenging due to the tightly coupled fluid-particle and inter-particle interactions covering a full range of particle concentration, namely, from the volumetric concentration of about 0.6 in the bed (near random-close packing) to the dilute transport of concentration less than 10^{-4}. The mechanisms associated with this nearly five orders of magnitude of concentration are also diverse. In moderate to high concentration, transport is dominated by inter-particle interactions ranging from intermittent collisions to enduring contacts (Armanini et al., 2005; Berzi and Fraccarollo, 2015). In this sediment concentration range, rheological closures are required for the contributions from both particle inertia and interstitial fluid viscosity (e.g., Jenkins and Berzi, 2010; Boyer et al., 2011). When sediment concentration decreases, the transport becomes increasingly dominated by turbulent eddies, while the turbulent eddies are also affected by the presence of particles. A specific challenge is the vast range of cascading turbulent eddy sizes (from $\mathcal{O}(10^{-1})$ to $\mathcal{O}(10^{-4})$ m) and their interactions with different grain sizes (from $\mathcal{O}(10^{-3})$ to $\mathcal{O}(10^{-6})$ m).

The conventional modeling approach for sediment transport is essentially a single-phase model, which splits the transport into bedload and suspended load layers. Due to its simplicity and numerical efficiency, the single phase model has been integrated into meso/large scale models (e.g., Lesser et al., 2004; Hu et al., 2009). Due to the dilute assumption in the single-phase flow formulation, the bedload layer

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cannot be resolved but must rely on semi-empirical parameterizations of transport rate (e.g., Meyer-Peter and Muller, 1948; Ribberink, 1998). In addition, a semi-empirical suspension flux boundary condition has to be applied to the suspended load (van Rijn, 1984a). Although the single-phase-based sediment transport models have clearly made progresses in predicting some aspects of sediment transport (e.g., Zedler and Street, 2006; Liu and Garcia, 2008), laboratory measurements of sheet flow with the full profile of sediment transport flux (Revil-Baudard et al., 2015) and net transport rate (O'Donoghue and Wright, 2004) clearly indicated that these assumptions are too simple and cannot explain many observed sediment transport dynamics. For example, important mechanisms such as turbulent entrainment and intermittent burst events cannot be resolved (e.g., Revil-Baudard et al., 2015; Kiger and Pan, 2002). In addition, the particle velocities are often approximated by the fluid velocity and the particle settling velocity. Balachandar and Eaton (2010) and Balachandar (2009) reviewed the applicability of such approximation, and revealed that this method is only plausible when the particle Stokes number (the ratio of particle relaxation time to Kolmogorov time scale) is small (< 0.2), for which the particles respond to the turbulent eddies rapidly. For typical sand transport in aquatic environments, the relevant particle Stokes number often exceeds 0.2, thus single-phase-based model becomes questionable even for fine sand (Finn and Li, 2016).

For larger particle Stokes number, more sophisticated methods to model sediment transport have been developed using the Euler-Lagrange approach. In Euler–Lagrange models, the sediment particles are tracked as point-particle (e.g., Drake and Calantoni, 2001; Schmeeckle, 2014; Sun and Xiao, 2016b; Finn et al., 2016) or with the interstitial fluid resolved (Fukuoka et al., 2014; Uhlmann, 2008). The position and velocity of each particle are directly tracked using the Newton's second law, and individual particle collision is directly modeled. In the point-particle approach, the fluid phase is solved as a continuum phase, and it is coupled with particles through a series of averaged momentum transfer terms, such as drag force, buoyancy force, lift force and added mass. Euler–Lagrange models are shown to be promising in modeling grain size sorting (Harada et al., 2015) and non-spherical particle shapes (Calantoni et al., 2004; Fukuoka et al., 2014; Sun et al., 2017). Schmeeckle (2014) and Liu et al. (2016) applied large eddy simulation to model bedload transport of coarse sand and identified the role of turbulent ejection/sweep on sediment entrainment. Sun and Xiao (2016a) further carried out 3D simulation of dune evolution for coarse sand. Recently, Finn et al. (2016) used a point-particle method to study medium sand transport in wave boundary layer, where the sediment trapping due to ripple vortexes was successfully captured. In the Lagrangian description of particle transport, a major challenge remains to be the high computational cost as the number of particles increases. Though the computation technology is advancing rapidly, the largest achievable number of particles in the literature was on the order of $\mathscr{O}(10)$ million at this moment. Therefore, it is not practical to apply Euler-Lagrange approach to study transport of fine to medium sand.

Alternatively, the particle phase can be treated as a continuum and a classical Eulerian–Eulerian two-phase flow approach can be used (e.g., Jenkins and Hanes, 1998; Dong and Zhang, 1999; Hsu et al., 2004; Bakhtyar et al., 2009; Revil-Baudard and Chauchat, 2013; Cheng et al., 2017). 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 two-phase flow models are able to resolve the entire profiles of sediment transport without the assumptions of bedload and suspended load. Hsu et al. (2004) incorporated an empirical sediment stress closure in the enduring contact layer, and adopted kinetic theory for inter-granular stress in the collisional sediment transport regimes. The $k-\epsilon$ equations were modified to account for the turbulence-sediment interactions for large particle Stokes number. Later, Amoudry et al. (2008), Kranenburg et al. (2014), and Cheng et al. (2017) further improved the turbulence-sediment interaction parameterization, and extended the turbulence closure to a wider range of particle Stokes number. Recently, new particle stress closure were adopted using phenomenological laws for dense granular flow rheology (Revil-Baudard and Chauchat, 2013) and it was demonstrated that granular rheology can produce similar predictions of sediment transport as other models using the kinetic theory for granular flow.

With the progress made in Eulerian two-phase modeling of sediment transport, several advancements are warranted. Firstly, nearly all these Eulerian two-phase sediment transport models are developed in the turbulence-averaged formulation, and the turbulence closures rely on eddy viscosity calculated ranging from a mixing length model to two-equation models. Aside from their empirical treatment on turbulence-sediment interaction, as reported by several studies (e.g., Amoudry et al., 2008; Kranenburg et al., 2014; Cheng et al., 2017), the model results are sensitive to the coefficients in the turbulence closure. It is likely that the existing closures for turbulence-sediment interaction in turbulence-averaged sediment transport models need to be further improved. To better understand the effect of sediments on modulating turbulence and conversely, the mixing and transport of sediments by turbulent eddies, a turbulence-resolving two-phase flow modeling approach is necessary. For many sediment transport applications that involve sand transport at high Reynolds number, the Stokes number is greater than unity and grain-scale process is usually larger than the Kolmogorov length scale. Hence, a turbulence-resolving approach based on large-eddy simulation (LES) methodology can be adopted to solve the Eulerian two-phase flow formulation (Balachandar, 2009; Finn and Li, 2016). The purpose of this study is to develop a turbulence-resolving numerical modeling framework and begin to tackle the challenge of modeling turbulence-sediment interactions for the full range of concentration in sediment transport.

Recently, an open-source multi-dimensional Eulerian two-phase flow model for sediment transport, SedFoam (Cheng et al., 2017), is developed using the CFD toolbox OpenFOAM. Although the numerical model is created for full three-dimensions (3D), existing SedFoam solver has only been used for two-dimensional turbulence-averaged sediment transport modeling. In this study, we extend the SedFoam solver to a 3D large-eddy simulation model, in which a substantial amount of turbulent motions and turbulence-sediment interactions are resolved, and the effects of small eddies and sediment dispersion are modeled with subgrid closures. Model formulations are described in Section 2, and model setup and validation for the steady unidirectional sheet flow experiment of Revil-Baudard et al. (2015) are presented in Section 3. Section 4 is devoted to discuss several insights of turbulence-sediment interactions in sheet flow revealed by the resolved fields. Concluding remarks are given in Section 5.

2. Model formulation

2.1. Filtered Eulerian two-phase flow equations

In this study, we adopt the Eulerian two-phase flow formulation for a particulate system (Ding and Gidaspow, 1990; Drew, 1983) to model sediment transport (Cheng, 2016). To better resolve turbulence-sediment interactions, a large-eddy simulation (LES) methodology is utilized. Turbulent motions (eddies) involve a wide range of length scales. In LES, the large-scale motions are directly resolved, and the effects of the small-scale motions are modeled with subgrid closures. To achieve the separation of scales, a filter operation is applied to the Eulerian two-phase flow equations. Similar to the previous studies using the two-phase flow approach for compressible flows (e.g., Vreman et al., 1995), a Favre filtering concept is used, i.e., $\mathbb{F}(\phi f) = \widehat{\phi}\widehat{f}$, where '$\mathbb{F}$' denotes the Favre filter operation, ' $\wedge$ ' denotes the Favre filtered variables, and ϕ is the volumetric concentration of quantity f. It shall be noted that although the Favre filter operation does not commute with the partial