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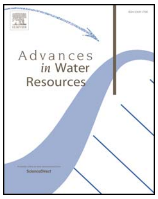

Investigating the settling dynamics of cohesive silt particles with particle-resolving simulations

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ABSTRACT

The settling of cohesive sediment is ubiquitous in aquatic environments, and the study of the settling process is important for both engineering and environmental reasons. In the settling process, the silt particles show behaviors that are different from non-cohesive particles due to the influence of inter-particle cohesive force. For instance, the flocs formed in the settling process of cohesive silt can loosen the packing, and thus the structural densities of cohesive silt beds are much smaller than that of non-cohesive sand beds. While there is a consensus that cohesive behaviors depend on the characteristics of sediment particles (e.g., Bond number, particle size distribution), little is known about the exact influence of these characteristics on the cohesive behaviors. In addition, since the cohesive behaviors of the silt are caused by the inter-particle cohesive forces, the motions of and the contacts among silt particles should be resolved to study these cohesive behaviors in the settling process. However, studies of the cohesive behaviors of silt particles in the settling process based on particle-resolving approach are still lacking. In the present work, three-dimensional settling process is investigated numerically by using CFD–DEM (Computational Fluid Dynamics–Discrete Element Method). The inter-particle collision force, the van der Waals force, and the fluid–particle interaction forces are considered. The numerical model is used to simulate the hindered settling process of silt based on the experimental setup in the literature. The results obtained in the simulations, including the structural densities of the beds, the characteristic lines, and the particle terminal velocity, are in good agreement with the experimental observations in the literature. To the authors' knowledge, this is the first time that the influences of non-dimensional Bond number and particle polydispersity on the structural densities of silt beds have been investigated separately. The results demonstrate that the cohesive behavior of silt in the settling process is attributed to both the cohesion among silt particles themselves and the particle polydispersity. To guide to the macro-scale modeling of cohesive silt sedimentation, the collision frequency functions obtained in the numerical simulations are also presented based on the micromechanics of particles. The results obtained by using CFD–DEM indicate that the binary collision theory overestimated the particle collision frequency in the flocculation process at high solid volume fraction.

1. Introduction

1.1. Background in hindered settling of cohesive silt

The settling process occurs ubiquitously in the natural environment, and during the settling process, lake floor or river floor to form a loose sediment layer (Zhao et al., 2014). The settling of sediment particles can have negative impacts on the environment. For example, excess sedimentation in waterways can make them too shallow for navigation; sediment deposition can bury the aquatic habitats and it is detrimental to aquatic life. On the other hand, diminished sedimentation can cause the losses of valuable wetlands (McAnally and Mehta, 2000). Therefore, the understanding of the settling process is important in the calculation of sediment budget for engineering, economic and environmental reasons. In addition, the sedimentation process is found in chemical, mining, pharmaceutical and other industries due to its importance in the understanding of fluid–solid separation (Bürger and Wendland, 2001; Dong et al., 2009; Shih et al., 1987; Zhao et al., 2014).

Since silt is the prevailing sediment fraction in many river systems, the modeling and assessment of sediment dynamics in these rivers require proper knowledge of the behaviors of silt (te Slaa et al., 2015). The size of silt is larger than clay but smaller than sand (Krumbein and Aberdeen, 1937). Compared with non-cohesive sand, silt demonstrates some behaviors that are unique to cohesive particles. Specifically, these

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behaviors include: (1) the structural densities (solid volume fractions) of silt beds are smaller than those of sand beds (te Slaa et al., 2015; Winterwerp and van Kesteren, 2004); (2) the trajectories of silt particles are deflected when the flocs form (Mazzolani et al., 1998; Stolzenbach and Elimelech, 1994; Zhang and Zhang, 2011); (3) the critical shear stress to initiate silt bed motion is larger than that of sand bed (Lick et al., 2004; Roberts et al., 1998). These behaviors are collectively referred to as "cohesive behaviors" hereafter following the literature (te Slaa et al., 2015). These cohesive behaviors could be caused by the cohesion of silt particle itself or the inter-mixture of silt particles of different sizes (te Slaa et al., 2015). It is believed that the variation of the characteristics of the sediment particles (e.g., Bond number, particle size distribution) can significantly influence the cohesive behaviors (Dong et al., 2006; 2009). However, little is known about how exactly the variation in these characteristics can influence the sedimentation of silt particles.

1.2. Overview of modeling silt settling

The modeling of the silt settling process is hindered by the complex dynamics of the particles and the challenges in predicting the fluid–-particle interaction and inter-particle contact. The traditional empirical approaches based on experimental measurements (Richardson and Zaki, 1954; te Slaa et al., 2015; Winterwerp and van Kesteren, 2004) are used to predict the settling velocity, which is among the most important quantities of interest for the fluid–solid mixture (Batchelor and Green, 1972; Hinch, 1977; Zhao et al., 2014). At higher particle concentrations, the influence of return flow and wake formation, the inter-particle collision, and the increased buoyancy effects are considered in the settling process (Winterwerp, 2002). The influence of flocculation on cohesive sediment in differential settling process can be also considered by using collision frequency function to describe inter-particle contact (Krishnappan, 1990; Winterwerp, 2002). The traditional approaches are able to predict the settling velocity and the sediment concentration in the regime where calibration data were obtained, but they heavily rely on empirical correlations to describe the influence of return flow and inter-particle contact. Therefore, these models may lead to large discrepancies in the predictions of the cohesive behavior of silt particles when outside these regimes because the empirical correlations are not derived directly from first principles.

With the growth of available computational resources in the past few decades, the Discrete Element Method (DEM) has gained popularity (Capecelatro and Desjardins, 2013; Chen et al., 2011; Drake and Calantoni, 2001; Jiang and Haff, 1993; Schmeeckle, 2014). The DEM uses Newton's law of motion to predict individual particle motion, and the detailed packing arrangement of individual particles in the sediment bed can be captured. Consequently, the DEM has been used to predict the distribution of poly-dispersed sediment particle in the aggregates after sedimentation (Bravo et al., 2015). Moreover, the DEM explicitly resolves the interaction among the sediment particles, and thus the influence of the inter-particle cohesive force on the particle trajectory can be captured (Dyachenko and Dueck, 2012). When the influence of fluid flow (e.g., return flow, wake formation, pressure) is significant in the sedimentation problems, the fluid flow is usually resolved using the CFD and the coupled CFD–DEM approach is used. In CFD–DEM approach, the locally-averaged Navier–Stokes equations are solved for the fluid flow, and the fluid–particle interaction forces are considered. This coupled approach is not only successful in predicting the excess pore pressure in the sand bed during the sedimentation process (Zhao and Shan, 2013; Zhao et al., 2014), but can also capture the reduction of the structural densities in the packed beds of cohesive particles in chemical and mineral engineering applications (Dong et al., 2006; 2009). However, the study of cohesive silt settling and the cohesive behaviors based on CFD–DEM approach is still lacking.

It has recently been demonstrated that *SediFoam*, a hybrid CFD–DEM solver for particle-laden flows, is capable of modeling the subaqueous sediment motion in extensive validation tests. For example, satisfactory predictive performances were observed in the modeling of the current-induced suspended sediment transport, the generation and migration of sand dune, and the sediment transport in oscillatory flows (Sun and Xiao, 2016a; 2016b; 2016c). In this study, we use *SediFoam* to study the settling process of cohesive silt particles. Compared with the previous study on sand particle settling using CFD–DEM (Zhao et al., 2014), the size of silt is smaller and inter-particle cohesion is more significant. The objectives of the present study are to (1) demonstrate the capability of CFD–DEM to predict the cohesive behaviors (e.g., decrease of structural densities) in the settling of poly-dispersed cohesive silt, (2) investigate the influence of the particle characteristics (e.g., Bond number, particle polydispersity) on the structural densities of the silt beds after sedimentation, and (3) examine the accuracy of the empirical formulas in the prediction of collision frequency function in the macro-scale modeling of cohesive silt sedimentation. While this work focuses on the sedimentation of cohesive silt, the proposed approach also opens the possibility for first-principle-based simulations of the flocculation and erosion of cohesive silt.

1.3. Novelty of present work

Earlier works (e.g., Higashitani et al., 2001; Dong et al., 2006; 2009; Zhang and Zhang, 2011) have used particle-resolving simulations to study the settling of cohesive particles. However, the investigation of the settling of cohesive sediment silt particles still needs further improvements. The advantages and novelties of the present work are summarized below:

1. Compared with the studies using mono-dispersed cohesive particles in the literature, we investigated the settling process of poly-dispersed cohesive silt. The cohesive behaviors of the poly-dispersed silt particles observed in the experimental studies are captured in the present simulations. We investigated the influence of the polydispersity in the cohesive behaviors, including the decrease of the structural densities of the beds, the decrease in the separation between characteristic lines, and the variation of particle terminal velocity in the settling process. These cohesive behaviors obtained by using particle-resolving simulations are validated against the experimental observations in the literature.
2. To the authors' knowledge, this is the first time that the influences of non-dimensional Bond number and particle polydispersity on the structural densities of silt beds have been investigated separately. The results demonstrate that the cohesive behavior of silt in the settling process is attributed to both the cohesion among silt particles themselves and the particle polydispersity.
3. To guide the macro-scale modeling of cohesive silt sedimentation, the collision frequency functions obtained in the numerical simulations are also presented based on the micromechanics of particles. The results obtained by using particle-resolving simulations indicate that the binary collision theory over-estimated the particle collision frequency in the flocculation process at high solid volume fraction. This over-estimation of the collision frequency may lead to the over-estimation of the flocculation rate and thus over-estimate the settling velocity of the flocs in the literature (Van and Van Bang, 2013).

The rest of the paper is organized as follows. Section 2 introduces the methodology of the present model, including the mathematical formulation of fluid equations, the particle motion equations, the fluid–particle interactions, and the modeling of cohesion. The implementation details of the code and the numerical methods used in the simulations are described in Section 3. In Section 4, the results obtained in the numerical simulations are presented. Section 5 discusses the insights gained from the present results for macro-scale modeling. Finally, Section 6 concludes the paper.