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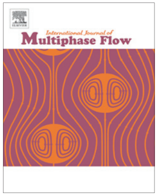

On the relevance of collision modeling for interface-resolving simulations of sediment transport in open channel flow

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ABSTRACT

This paper deals with the interface-resolving simulation of particle transport by a turbulent flow over a rough bed. It aims at clarifying the importance of the type of collision model employed for the computed particle transport and the resulting fluid motion. For this purpose, a collision model based on a repulsive potential often used in the literature and a more complex collision model, the Adaptive Collision Model [Kempe & Fröhlich, J. Fluid Mech. 709 (2012) 445–489] are applied in turbulent open channel flow with bed-load sediment transport. In a first step, the Adaptive Collision Model is validated for multiple simultaneous collisions. This is done using simple test cases where the fluid surrounding the particles is neglected, as well as the sedimentation of multiple particles towards a bed of fixed particles in a viscous fluid. Numerical experiments on sediment transport are undertaken with two different prototypical setups, a single mobile particle traveling over a fixed rough bed and a cloud of mobile particles. The results show significant differences in the statistical quantities of the fluid and the disperse phase for different collision models. Comparison with experimental observations indicate significant improvement of the results with the use of the more sophisticated collision model, which takes all governing physical and numerical effects into account. Beyond the modeling issue the paper presents relevant physical information in the transport of a single particle over a rough bed by means of numerous statistical data. The same is done for collective particle transport in the regime of small sediment supply.

1. Introduction

Near-bed transport of cohesionless sediment in a horizontal turbulent channel flow is of vital interest for many environmental and industrial applications such as the flow in river beds or hydraulic conveying in process industry, for example. The prediction of sediment entrainment and bed-load transport has been a subject of experimental research since the early 20th century (Buffington and Montgomery, 1997). Shields (Shields, 1936) was among the first, to propose a full description of particle entrainment thresholds for a wide range of particle Reynolds numbers, resulting in the classical Shields diagram. This study was later refined by numerous experiments. Bagnold (1966), for example, pointed out the non-linear effects of the coupling of the heterogeneous composition of the sediment bed with a turbulent boundary layer. These effects are averaged out by the considerations of Shields. Fenton and Abbott (1977) elaborated on the important aspect of particle exposure, which may locally affect the ability of a sediment bed to destabilize. The governing mechanisms that control bed load transport, however, are still far from being well understood, so that until now this topic is a field of active research (Campbell et al., 2002; Charru et al., 2004, 2007).

The investigation of bed-load transport by turbulent flow in channels raises the need for highly resolved data, as the relevant length scales rapidly decrease with increasing Reynolds number. Direct Numerical Simulations (DNS) have proven to be a powerful tool to provide such data (Balachandar and Eaton, 2010), but in cases when the particles are larger than the Kolmogorov scales, point-particle approaches cannot be used for the simulation of this type of flow without further modeling and the related uncertainties. The point particle approach particularly suffers from uncertainties in the empirical correlations for drag and lift if many particles are close together or if particles are colliding, for example. Aware of these drawbacks, such simulations have been performed by Moreno and Bombardelli (2012) with the focus on the importance of particle–particle collisions in sediment saltation. This is problematic since bed-load transport is characterized by high volume fractions of the disperse phase and very dense particle clusters close to the sediment bed (Forterre and Pouliquen, 2008). The flow of the bed load hence is dominated by collisions and frictional forces. This underlines the need for fully-resolved simulations with four-way coupling of the flow and the disperse phase (Balachandar and Eaton, 2010) and the necessity of an

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enhanced complexity of the numerical modeling of the collision process, a fact also supported by experiments (Nino and Garcia, 1998).

Three-dimensional simulations of moving particles in an open channel flow were conducted by Yergey et al. (2010), but the particles were modeled as mass points without spatial extension. Hence, empirical correlations are required for the computation of fluid forces acting on the particles, with the uncertainties mentioned above. Three-dimensional simulations of particle-laden flows with interface resolution were performed by Uhlmann and Fröhlich (2007), Uhlmann (2008), Chan-Braun et al. (2010), Shao et al. (2012), and recently by Kidanemariam et al. (2013). In all these studies, the simple collision model proposed by Glowinski et al. (1999) based on a repulsive force was used to prevent particles from overlapping. Friction was disregarded altogether.

Collision models accounting for friction have been derived in the framework of the Discrete Element Method (DEM). Such models were employed in simulations performed by Papista et al. (2011), Osanloo et al. (2008), Yergey et al. (2010) and Durán et al. (2012). In Papista et al. (2011), the shape of the particles was spatially resolved using a fictitious domain method. These authors, however, only considered two-dimensional configurations. Nevertheless, Papista et al. (2011) concluded from their results that the choice of the collision model does not drastically affect the particle as well as the fluid motion. This is in contrast to the results of Moreno and Bombardelli (2012) obtained with a point-particle approach. More sophisticated simulations were performed by Derksen (2011) who investigated the incipient motion of spherical particles in a laminar shear flow near the critical Shields number using a lattice-Boltzmann method. A hard-sphere collision model was employed in combination with an explicit lubrication force for under-resolved viscous forces during the approach and rebound of colliding particles. The relevance of the collision model on the physical results and their sensitivity, however, was not investigated.

The present paper fills this gap. The entire collision process can be decomposed into several phases dominated by different physical effects. The classical model by Glowinski et al. (1999) is of purely repulsive type, the recently proposed Adaptive Collision Model (ACM) (Kempe and Fröhlich, 2012a) unites several submodels together with a temporal stretching of the phase of direct surface contact which is crucial for efficiency. Switching on and off different sub-models in the ACM and repeating the same simulation, or replacing the ACM with the model of Glowinski et al. (1999) altogether, allows to access which elements have to be present in a collision model to warrant physical realism. The question addressed here is whether the classical approach is sufficient or whether higher sophistication is required.

The physical situation of bed-load transport in a three-dimensional turbulent open channel flow over a rough wall is considered here, with parameters chosen such that the sediment is close to incipient motion. The Shields number is varied together with other parameters to address the effect of different regimes on the particle behavior. All these cases involve turbulent flow, motivated by the observation of Yalin and Ferreira da Silva (2001) that sediment forming natural bed forms is related to turbulent conditions. On the other hand, the Reynolds number has to be moderate for reasons of feasibility of the simulations. Nevertheless, the data being generated provide valuable new and detailed information on collision modeling and the behavior of bed-load sediment. In Kempe and Fröhlich (2012a) the ACM was extensively validated for single collisions and proved to be very reliable in all cases considered. The classical regime diagram of Clift et al. (1978) features, at the upper end of the mass loading coordinate collision-dominated and contact-dominated flows. These in fact are the regimes covered by bed-load transport of sediment. Due to the high local mass loading, the collision model is required to work with multiple simultaneous collisions. This step is accomplished in the present paper by demonstrating that in fact the model can be used without modifications. Appropriate test cases involving multiple simultaneous collisions are employed to this end. Furthermore, the contact-dominated situation is addressed, highlighting the advantages of the ACM compared to the classical model.

The paper is structured as follows. Sections 2 and 3 present the numerical method for the continuous and the dispersed phase, respectively, including a detailed description of the collision models employed. In Section 4, a detailed validation for the Adaptive Collision Model in the case of multiple collision partners is performed. Sections 5 and 6 first present the specification of the physical configuration considered and then provide results for a single particle being transported over a rough bed. Here, only collisions between moving and fixed particles need to be modeled. The following Section 7 reports on simulations with many mobile particles, where collisions between mobile particles and between mobile and fixed particles occur.

2. Numerical method

2.1. Discretization of the continuous phase

The numerical method for the fluid and the particles was developed in a companion paper (Kempe and Fröhlich, 2012b) and is therefore only briefly described here. The equations to be solved are the unsteady three-dimensional Navier–Stokes equations for a Newtonian fluid of constant density

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = \frac{1}{\rho_f} \nabla \cdot \boldsymbol{\tau} + \mathbf{f} + \mathbf{f}_{IBM} \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

where $\boldsymbol{\tau}$ is the hydrodynamic stress tensor

$$\boldsymbol{\tau} = -p\,\mathbf{I} + \mu_f (\nabla \mathbf{u} + (\nabla \mathbf{u})^T). \tag{3}$$

The nomenclature is as usual, with $\mathbf{u} = (u, v, w)^T$ designating the velocity vector in Cartesian components, *i.e.* along the Cartesian coordinates x, y, z, while p is pressure, ρ_f fluid density, $\mathbf{f}$ the volume force driving the flow and $\mathbf{f}_{IBM}$ the forcing term introduced for the Immersed Boundary Method described below. Finally, $\mathbf{I}$ is the identity matrix, μ_f dynamic viscosity and t time, while the gradient operator is denoted by $\nabla(\cdot)$, the divergence operator is $\nabla \cdot (\cdot)$, and $\nabla^2(\cdot)$ the Laplace operator. The spatial discretization of (1) and (2) is performed by a second-order finite-volume scheme on a staggered grid (Harlow and Welch, 1965). The time-advancement is accomplished by an explicit third-order low-storage Runge–Kutta scheme for the convective terms and a Crank–Nicolson scheme for the viscous terms. The solution of a pressure Poisson equation and projection yields the divergence-free velocity field at the end of the Runge–Kutta step.

2.2. Discretization of the disperse phase

The dispersed solid particles are numerically represented by an Immersed Boundary Method (IBM). First variants of such a method for moving particles were presented in Kajishima et al. (2001) and Kajishima and Takiguchi (2002). The method used in the present paper is based on the scheme which was later developed by Uhlmann (2005). With an IBM the fluid usually is discretized on a fixed equidistant Cartesian grid. The fluid–solid interface is represented by discrete surface markers as sketched in Fig. 1. The coupling of the continuous and the disperse phase is realized by inserting additional volume forces in the vicinity of the interface. These virtual forces are computed such that they impose the