International Journal of Multiphase Flow 67 (2014) 174–188

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Interface-resolved direct numerical simulation of the erosion of a sediment bed sheared by laminar channel flow

Aman G. Kidanemariam, Markus Uhlmann [*]

Institute for Hydromechanics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 13 August 2014
Accepted 19 August 2014
Available online 16 September 2014

Keywords:
Plane channel flow
Bedload transport
Direct numerical simulation
Interface resolution
Discrete element model
Immersed boundary method

ABSTRACT

A numerical method based upon the immersed boundary technique for the fluid–solid coupling and on a soft-sphere approach for solid–solid contact is used to perform direct numerical simulation of the flow-induced motion of a thick bed of spherical particles in a horizontal plane channel. The collision model features a normal force component with a spring and a damper, as well as a damping tangential component, limited by a Coulomb friction law. The standard test case of a single particle colliding perpendicularly with a horizontal wall in a viscous fluid is simulated over a broad range of Stokes numbers, yielding values of the effective restitution coefficient in close agreement with experimental data. The case of bedload particle transport by laminar channel flow is simulated for 24 different parameter values covering a broad range of the Shields number. Comparison of the present results with reference data from the experiment of Aussillous et al. (2013) yields excellent agreement. It is confirmed that the particle flow rate varies with the third power of the Shields number once the known threshold value is exceeded. The present data suggests that the thickness of the mobile particle layer (normalized with the height of the clear fluid region) increases with the square of the normalized fluid flow rate.

1. Introduction

Subaqueous sediment transport is a dense particulate flow problem, which involves the erosion, entrainment, transport and deposition of sediment particles as a result of the net effect of hydrodynamic forces, gravity forces as well as forces arising from inter-particle contacts. Systems which are significantly affected by the sediment transport process involve many fields of engineering, in particular civil and environmental engineering (e.g. river morphology and dune formation). Therefore, an improved understanding of the mechanisms leading to fluid-induced transport of sediment and to its accurate prediction is highly desirable.

A considerable amount of experimental and theoretical studies have been carried out in the past, leading to a number of (semi-) empirical predictive models for engineering purposes. For instance, there exist several algebraic expressions for the particle flux as a function of the local bed shear stress both in the laminar and turbulent flow regimes (see e.g. García, 2008; Ouriemi et al., 2009). Critically assessing the validity of the proposed models is a challenging task due to the complex interaction between the flow and the mobile sediment bed, and due to the dependence on multiple parameters. For similar reasons, available experimental data is widely dispersed (Ouriemi et al., 2009).

In order to investigate the fundamental aspects of granular transport, the problem was simplified in some studies by considering the erosion of a sediment bed consisting of mono-dispersed spherical particles under laminar shear flows (see e.g. Charru et al., 2004; Loiseleux et al., 2005; Charru et al., 2007; Ouriemi et al., 2007; Lobkovsky et al., 2008; Mouilleron et al., 2009; Ouriemi et al., 2009; Aussillous et al., 2013). There is a general consensus that the onset of particle motion and bedload transport is controlled by the Shields number Θ, which is proportional to the wall shear stress times the cross-sectional area of a particle, divided by its apparent weight (Shields, 1936). Below a critical value $\Theta^{(c)}$, almost independent of the particle Reynolds number in the laminar regime, no erosion of sediment is observed. Ouriemi et al. (2007) have performed an experimental investigation of the cessation of motion (which indirectly yields the threshold for the onset of motion) of spherical beads in laminar pipe flow. They inferred that the critical Shields number has a value $\Theta^{(c)} = 0.12 \pm 0.03$. This value has also been reported by other authors (Charru et al., 2004; Loiseleux et al., 2005). Note that, $\Theta^{(c)}$ is different from and larger in value than another critical Shields number which corresponds to the initiation of the motion of individual particles in an initially loosely packed granular bed. Experiments show that particles, when they are initially set in

---

[*] Corresponding author. Tel.: +49 721 60844106; fax: +49 721 60842202.
E-mail address: markus.uhlmann@kit.edu (M. Uhlmann).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.08.008
0301-9322/© 2014 Elsevier Ltd. All rights reserved.

motion, move in an erratic manner by rolling over other particles, temporarily halting in troughs and then starting to move again, most of the time impacting other particles and possibly setting them in motion. After a sufficient duration, the particles rearrange and the sediment bed gets compacted. Charru et al. (2004) refer to this phenomenon as the 'armoring effect of the bed'; they explain the observed initiation of motion of particles at $\Theta \approx 0.04$ in an initially loosely packed sediment bed and describe the gradual increase of the critical shear number towards $\Theta^{(c)}$.

At super-critical values of the Shields number, the resulting sediment flux is usually expressed as a function of the local bed shear number (or the excess shear number $\Theta - \Theta^{(c)}$). Charru and Mouilleron-Arnould (2002), applying the viscous resuspension model of Leighton and Acrivos (1986), found that the particle flux varies cubically with the Shields number. Ouriemi et al. (2009), considering an alternative continuum description of bedload transport and assuming a frictional rheology of the mobile granular layer, proposed an expression for the dimensionless particle flux which likewise predicts a cubic variation with the Shields number for $\Theta \gg \Theta^{(c)}$.

In an attempt to complement experiments, a number of numerical simulations of the transport of particles as bedload have been performed in the granular flow community, albeit without properly resolving the near-field around the particles (see e.g. Schmeeckle and Nelson, 2003; Heald et al., 2004). These simulations are based on the discrete element model (DEM) by which the trajectory of all individual particles, which constitute the sediment bed, is accounted for. The main feature of DEM is the modelling of the inter-particle collisions. Various collision models have been proposed which are usually based either on the hard-sphere or the soft-sphere approach. In the hard-sphere approach particles are assumed to be rigid and to exchange momentum during instantaneous binary collision events (see e.g. Foerster et al., 1994). On the other hand, in the soft-sphere approach the deformation of particles during contact is indirectly considered by allowing them to overlap. The contact forces, which are assumed to be functions of the overlap thickness and/or the relative particle velocities, are computed based on mechanical models such as springs, dash-pots and sliders (Cundall and Strack, 1979).

Recently, a number of studies has emerged in which the fluid flow even in the near vicinity of individual grains is being fully resolved while at the same time a realistic contact model is employed (Yang and Hunt, 2008; Wachs, 2009; Li et al., 2011; Simeonov and Calantoni, 2012; Kempe and Fröhlich, 2012; Brändle de Motta et al., 2013). For the purpose of validation of the coupling between the fluid–solid solver and the contact model, most of these studies have considered benchmark cases where a single spherical particle collides with a plane wall or with another particle in a viscous fluid. Experimental studies of this configuration have shown that when a particle freely approaches and collides with another particle or a wall, in addition to energy dissipation from the solid–solid contact, it loses energy as a result of the work done to squeeze out the viscous fluid from the gap between the contacting edges, thereby decelerating it prior to contact (Joseph et al., 2001; Gondret et al., 2002; ten Cate et al., 2002; Joseph and Hunt, 2004; Yang and Hunt, 2006). Similarly, additional fluid-induced losses occur during the rebound phase. The effect of the viscous fluid on the bouncing behavior of the particle is classically characterized by an effective coefficient of restitution ε which is the ratio of the particle's pre- and post-collision normal velocities. Thus ε accounts for the total energy dissipation both from viscous fluid resistance as well as from the actual solid–solid contact, in contrast to the dry coefficient of restitution defined in the same way but for collisions happening in vacuum. It is well established that the Stokes number, defined as $St = (\rho_p/\rho_f)Re_p/9$ where Re_p is the particle's Reynolds number based on its diameter and its velocity before impact, is the relevant parameter which determines the degree of viscous influence on the bouncing behavior of a particle. At large values of the Stokes number (above $St = 1000$ say), the effect of the fluid on the collision becomes negligible and ε approaches the dry coefficient of restitution. On the other hand, at small values of the Stokes number ($St \lesssim 10$), viscous damping is so large that no rebound of the particle is observed. Various sets of experimental data are available for the bouncing sphere (see e.g. Joseph et al., 2001; Gondret et al., 2002) and it has become a standard benchmark for the validation of numerical approaches which model the collision dynamics of finite-size objects fully immersed in a viscous fluid.

One of the goals of the present work is to investigate the formation of patterns from an initially flat bed of erodible sediment particles. A precursor stage to this process is bedload transport, i.e. the featureless motion of sediment particles which involves multiple contacts, sliding, rolling and saltation of particles. For this latter case, detailed experimental data are available from the recent experiments of Aussillous et al. (2013). Using an index-matching technique these authors were able to determine the velocity profiles of both the fluid and the particulate phase in pressure driven flow through a rectangular duct. As will be shown in the present paper, the experimental conditions and the range of the main control parameter (the Shields number) covered therein is accessible to interface-resolved numerical simulation. For these reasons, the case of bedload transport in horizontal wall-bounded flow is an attractive benchmark configuration for the purpose of validation of numerical approaches to the transport of dense sediment.

In the present contribution we first present an extension of the immersed boundary method of Uhlmann (2005a) to include solid–solid contact forces by means of a soft-sphere model similar to the approach of Wachs (2009). This coupled DNS–DEM technique is then validated in Section 3 through simulations of the standard test case of a single sphere colliding with a plane wall. In Section 4 we present simulation results of bedload transport in laminar plane channel flow over a broad range of parameters, comparing them to data from the reference experiment. This second test serves to validate the coupled DNS–DEM approach in a case with many particles simultaneously interacting. As such it provides an important step towards the simulation of sediment pattern formation. Furthermore, the present results contribute new data to the ongoing discussion of scaling laws in bedload transport. The paper closes with conclusions in Section 5.

2. Numerical method

2.1. Immersed boundary method

The numerical method employed is a variant of the immersed boundary method as proposed by Uhlmann (2005a). The incompressible Navier–Stokes equations are solved throughout the entire computational domain Ω comprising the fluid domain Ω_f and the space occupied by the suspended particles Ω_s. For this purpose a force term is added to the right-hand side of the momentum equation which serves to impose the no-slip condition at the fluid–solid interfaces. The direct numerical simulation (DNS) code has been validated on a whole range of benchmark problems (Uhlmann, 2004, 2005a,b, 2006; Uhlmann and Dušek, 2014), and has been previously employed for the simulation of various particulate flow configurations (Uhlmann, 2008; Chan-Braun et al., 2011; García-Villalba et al., 2012; Kidanemariam et al., 2013).

2.2. Inter-particle collision model

In direct numerical simulations of systems with a low solid volume fraction the particle–particle or particle–wall encounters are