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Discrete particle model of aeolian sand transport: Comparison of 2D and 2.5D simulations

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ABSTRACT

A discrete particle model is applied to describe aeolian sand transport. In this model, the inter-particle collisions and the fluid–particle coupling interactions are considered, the fluid turbulence is treated with a mixing length theory, and the motion of each particle is directly tracked. The 2.5D model includes the 2D flow for gas and the 3D motion for sand particles. The differences between 2D and 2.5D simulations are compared. The results show that the 2.5D simulation can produce the non-uniform distribution of particle in the spanwise direction. In the 2D simulation, the particle motion is limited only to a vertical plane, so the number density or concentration of particle in the 2D simulation is artificially increased. The particle concentration in the 2.5D simulation is less than that in the 2D simulation. Both the mean horizontal velocity of particles and the wind velocity in the 2.5D simulation are more than those obtained in the 2D simulation. The decay rate of sand mass flux with increasing height in the 2.5D simulation is larger than that in the 2D simulation. In the saltation layer, the particle shear stress in the 2.5D simulation is less than that in the 2D simulation, while the fluid shear stress in the 2.5D simulation is larger than that in the 2D simulation. The 2.5D model can consider the particle motion in all the three coordinate directions and improve the simulated results of the 2D model, and thus acquire better results.

1. Introduction

The movement of sand particles by wind has received much attention as it is an important geomorphological process for landform change. The blowing particles generally have three different modes: creep, saltation and suspension, of which saltation is the dominant mode accounting for about 75% of the total sand flux (Bagnold, 1941). The saltating particles are also an active geomorphological agent causing erosion on Earth and other planets such as Mars, Venus and Titan (Greeley and Iversen, 1985). Hence, many methods are applied to study windblown sand movement, in which the theoretical model plays an important role. In this paper, a discrete particle model is used to study the aeolian sand transport.

Developing a reliable model is very important to predict blowing sand movement. Since the 1980s, many numerical models of aeolian sand transport have been developed. The typical numerical model generally includes several different sub-processes: aerodynamic entrainment, grain trajectories, grain-bed impacts, and wind field modification (Ungar and Haff, 1987; Anderson and Haff, 1988, 1991; McEwan and Willetts, 1991, 1993; Spies and McEwan, 2000; Spies et al., 2000). By linking these sub-processes, the saltation equilibrium state can be reached. In these typical numerical models, the grain-bed collision is generally treated in an empirical way, i.e., a splash function (Ungar and Haff, 1987; Anderson and Haff, 1988, 1991) or a set of the experimental data (McEwan and Willetts, 1991, 1993) is used to specify the initial or launch velocity distribution of saltating particles. However, the splash function is deduced under the no-wind condition (Anderson and Haff, 1991).

In recent years, some other models of saltation have been also developed (Andreotti, 2004; Ji et al., 2004; Almeida et al., 2006; Creyssels et al., 2009; Kok and Renno, 2009). Ji et al. (2004) reported a convection–diffusion CFD model for aeolian particle transport, in which the motion of fluid mixture is modeled by the multiphase model with the algebraic-slip approximation, and the slip of the dispersed phase is modeled by an algebraic model. A two-species model of aeolian sand transport is developed by Andreotti (2004), in which there is coexistence of saltation and reptation grains. In the model of Almeida et al. (2006), the Reynolds-averaged Navier–Stokes equations with the standard $k-\varepsilon$ model are used to describe wind turbulence, the particle trajectory is calculated by the motion equation with the drag and gravity acting on the particles, and the particle stream is rebounded with a given energy fraction and a given angle. Kok and Renno (2009) developed a comprehensive numerical model of steady state saltation, in which three processes are included to form a feedback loop, i.e., the motion of saltating particles, the modification of wind profile, and the collision of particles with the

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soil surface. These above models improved our understanding for windblown sand movement. However, many efforts are still needed to develop a reliable and available model. In these above models, the inter-particle collisions are not considered during particle motion in air. Further study is therefore needed.

In the last ten years, inter-particle collisions have been considered in the simulation of windblown sand movement. In the model of Sun and Wang (2001), the simple hard sphere impact model is applied in the calculation of windblown sand movement, then a reasonable sand bed-form and saltation trajectory are obtained. Huang et al. (2008) introduced the mid-air collision probability in the saltation model, and the result showed that the mid-air collision has a significant effect on the sand mass flux. Hence, inter-particle collisions have an important role in simulation of aeolian sand transport.

Aeolian sand transport is a special case of gas–solid two phase flow, in which the ground sand particles are driven by the shear wind. During aeolian sand transport, the particle flow can be classified as three types, i.e., contact-dominated, collision-dominated and collision-free flows. On the sand bed, the particles almost contact each other, so the particle flow is contact-dominated. Above the sand bed surface, the descending particle will impact the sand bed and release the energy by collision to make many other particles eject into air, then the collision-dominated flow is formed. With the increase of the height, the particle number density will decrease, and the flow will become the collision-free flow. The three flow patterns coexist in the windblown sand movement. Obviously, it is difficult to simulate the three flow patterns at the same time.

In order to simulate the three flow patterns, the discrete particle model was developed for aeolian sand transport (Kang and Guo, 2006; Kang and Liu, 2010; Kang and Zou, 2011). The discrete particle model can consider the inter-particle collisions and the fluid–particle coupling interactions, and obtain detailed information of particle motion at the individual particle level. With the discrete particle model, the macroscopic parameters such as sand velocity profile, sand mass flux and wind velocity profile have been analyzed by Kang and Guo (2006), the particle velocity distribution acquired by Kang and Liu (2010), and the vertical distributions of drag force, Magnus and Saffman forces in aeolian sand transport are reported by Kang and Zou (2011). However, in the discrete particle simulations of Kang and Guo (2006), Kang and Liu (2010) and Kang and Zou (2011), only the two-dimensional simulation is performed.

In this paper, in order to improve the discrete particle model and make to improve prediction of the experimental data in field or laboratory, the 2.5D discrete particle simulation of aeolian sand transport is carried out. Then, the 2D and 2.5D simulations of windblown sand movement are compared to further study the distinctions between the 2D and 2.5D discrete particle models, and the relative performance of the two models is considered. The main reasons for the differences between the 2D and 2.5D models are also discussed.

2. Discrete particle model

The present model is based on the model of Kang and Liu (2010) and Kang and Zou (2011). Here, the brief description for this model with some modifications is given below.

According to the study of Kang and Zou (2011), the Magnus and Saffman forces have no important influence on the macroscopic statistical parameters such as wind velocity, mean particle horizontal velocity and sand mass flux. Hence, in this paper, the Magnus and Saffman forces are neglected, only the drag force is considered for fluid–particle interaction.

The continuity and momentum equations of gas are expressed as:

$$\frac{\partial}{\partial t}\left(\alpha_f\rho_f\right)+\nabla\cdot\left(\alpha_f\rho_f\mathbf{u}_f\right)=0 \tag{1}$$

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_f\rho_f\mathbf{u}_f\right)+\nabla\cdot\left(\alpha_f\rho_f\mathbf{u}_f\mathbf{u}_f\right)\\&=-\alpha_f\nabla p+\nabla\cdot\left(\alpha_f\boldsymbol{\tau}_f\right)+\alpha_f\rho_f\mathbf{g}-\mathbf{f}_{drag}\end{aligned} \tag{2}$$

where α_f is the volume fraction of fluid; ρ_f, $\mathbf{u}_f$ and p are the fluid density, velocity and pressure, respectively; and $\mathbf{g}$ is acceleration due to gravity.

$\boldsymbol{\tau}_f$ is the fluid shear stress, shown as:

$$\boldsymbol{\tau}_f=-\frac{2}{3}\left(\mu_{eff}\nabla\cdot\mathbf{u}_f\right)\boldsymbol{\delta}_k+\mu_{eff}\left[\nabla\mathbf{u}_f+\left(\nabla\mathbf{u}_f\right)^T\right] \tag{3}$$

where $\boldsymbol{\delta}_k$ is the Kronecker delta; μ_{eff} is the fluid effective viscosity, $\mu_{eff}=\mu_f+\mu_{ft}$, where μ_f and μ_{ft} are the fluid dynamic viscosity and turbulent viscosity, respectively.

$\mathbf{f}_{drag}$ is the volumetric drag force, expressed by:

$$\mathbf{f}_{drag}=\frac{1}{\Delta V}\sum_{i=1}^{n}\mathbf{F}_{drag,i} \tag{4}$$

where ΔV is the volume of a computational cell, and n is the number of particles in the cell.

$\mathbf{F}_{drag}$ is the fluid drag force on one individual particle, following the model of Di Felice (1994), the detailed expression of which is shown in Kang and Liu (2010).

In the present paper, the fluid turbulence is treated with a mixing length theory. In the windblown sand movement, the gas flow is a shear flow in the macroscopic scale, hence the turbulent viscosity can be expressed as:

$$\mu_{ft}=\rho_f\kappa^2y^2\left|\frac{du_f}{dy}\right| \tag{5}$$

where κ is the von Karman's constant, $\kappa=0.4$; y is the height above the sand bed surface; and u_f is the wind velocity in the horizontal direction.

The equations of particle motion are described as:

$$m_p\frac{d\mathbf{u}_p}{dt}=m_p\mathbf{g}+\mathbf{F}_{drag}+\sum_{j=1}^{n_c}\left(\mathbf{f}_{n,ij}+\mathbf{f}_{t,ij}\right) \tag{6}$$

$$I_p\frac{d\boldsymbol{\omega}_p}{dt}=\sum_{j=1}^{n_c}\mathbf{T}_{ij}+\mathbf{T}_f \tag{7}$$

where m_p, $\mathbf{u}_p$ and $\boldsymbol{\omega}_p$ are the mass, translational and angular velocity of particle i, respectively; $\mathbf{f}_{n,ij}$ and $\mathbf{f}_{t,ij}$ are the normal and tangential forces between particle i and j due to particle collision, respectively; n_c is the number of the particles in contact with particle i; I_p is the moment of inertia of particle; $\mathbf{T}_{ij}$ is the torque between particle i and j due to particle collision; $\mathbf{T}_f$ is the flow torque acting on the particle i in a fluid due to the shear stress distribution on the particle surface.

The linear spring-damping model is used to calculate the inter-particle forces (Kang and Liu, 2010).

3. Computational method and boundary conditions

The detailed numerical method, parameter selection and some boundary conditions are explained in Kang and Liu (2010). Here, a brief description and some modifications are expressed.

The equations of gas phase are solved by the conventional SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations – Consistent) method. The equations of discrete particles are solved by the explicit time integration method. After the equations of gas phase are solved, the inter-particle forces and the particle motion equations are calculated.