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An effective Euler–Lagrange model for suspended sediment transport by open channel flows

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ABSTRACT

An Euler–Lagrange two-phase flow model is developed to study suspended sediment transport by open-channel flows with an Eddy Interaction Model (EIM) applied to consider the effect of fluid turbulence on sediment diffusion. For the continuous phase, the mean fluid velocity, the turbulent kinetic energy and its dissipation rate are directly estimated by well-established empirical formulas. For the dispersed phase, sediment particles are tracked by solving the equation of motion. The EIM is applied to compute the particle fluctuation velocity. Neglecting the effect of particles on flow turbulence as usually suggested for dilute cases in the literature, the Euler–Lagrange model is applied to simulate suspended sediment transport in open channels. Although the numerical results agree well with those by the well-known random walk particle tracking model (RWM) and with the laboratory data for fine sediment cases, it is clearly shown that such an Euler–Lagrange model underestimates the sediment concentration for the medium-sized and coarse sediment cases. To improve the model, a formula is proposed to consider the local fluid turbulence enhancement around a particle due to vortex shedding in the wake. Numerical results of the modified model then agree very well with laboratory data for not only the fine but also the coarse sediment cases.

1. Introduction

The mechanics of sediment transport is a classical and important subject of river and coastal engineering and has been extensively studied in the last century. A large number of laboratory experiments have been performed to explore sediment transport under both unidirectional and oscillatory flow conditions (Vanoni, 1946; Dibajnia & Watanabe, 1998; Chien & Wan, 1999; Dohmen-Janssen & Hanes, 2002; Noguchi & Nezu, 2009; Van der et al., 2010). Many numerical models have also been developed (Elghobashi, 1994; Hsu et al., 2003; Jha & Bombardelli, 2009; Chen et al., 2011). However, the complex mechanisms of sediment motion in a moving fluid are still far from clearly understood.

A sediment-laden flow can naturally be treated as a two-phase flow (Elghobashi, 1994; Dong & Zhang, 1999; Liu & Sato, 2006; Jha & Bombardelli, 2011). The existing two-phase flow models can be categorized into the Euler–Euler and the Euler–Lagrange type according to their different ways to deal with the sediment phase. An Euler–Euler model describes sediment as a continuous phase and cares about statistical properties of the sediment cloud, while an Euler–Lagrange model treats the sediment as a dispersed phase and tracks the motion of each sediment particle. Both of the models describe the water as a continuous phase, satisfying the conservation laws for the mass and momentum. In a practical problem, the Euler–Euler model requires significantly less computational effort than the Euler–Lagrange one, and as a result, there have been much more studies employing the Euler–Euler model for sediment transport in the last decades (Elghobashi & Abou-Arab, 1983; Dong & Zhang, 2002; Jha & Bombardelli, 2009; Chen et al., 2011). With the rapid growth of computer capacity, application of the Euler–Lagrange model in sediment-laden flow has received more and more attention in recent years, especially in the study of bed-load transport (Sekine & Kikkawa, 1992; Lee & Hsu, 1994; Nino & Garcia, 1994; Drake & Calantoni, 2001; Schmeeckle & Nelson, 2003; Yeganeh-Bakhtiary et al., 2009; Ji et al., 2013). In the present paper, an Euler–Lagrange model is developed to deal with the suspended sediment transport.

Vinkovic et al. (2011) developed an Euler–Lagrange model, with a direct numerical simulation (DNS) for the continuous phase, to

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study the characteristics of ejections that surround sediment particles in dilute turbulent channel flows, which are important to the movement of sediment near the bed. Jaszczur (2011) applied large eddy simulation (LES) to turbulent flow in its Euler–Lagrange model. Ong et al. (2012) studied the sediment movement downstream of a circular cylinder with the Reynolds Averaged Navier–Stokes (RANS) equations and the standard k–ε model for the flow field.

The Euler–Lagrange model based on the RANS method is advantageous when compared with DNS and LES because relatively less computational effort is required. However, this approach requires an additional stochastic model for the fluctuating velocities of the fluid. The Eddy Interaction Model (EIM) used in Oliveira et al. (2002) is an effective method. Following the study of Hutchinson et al. (1971), the EIM has been intensively developed (e.g., Yuu et al., 1978; Gosman & Ioannides, 1981; Shuen et al. 1983; MacInnes & Bracco, 1992). In this model, the fluid fluctuation velocity is randomly sampled from a Gaussian distribution with zero mean and with the turbulence intensity as the standard deviation. Graham and James (1996) studied the EIM theoretically and improved it to describe the turbulent diffusion of particles with different inertia. It has been shown that the EIM performs well in simulating the turbulent diffusion of particles under various conditions (Chen & Pereira, 2000; Matida et al., 2004; Dehbi, 2008).

The effect of the particles on fluid turbulence is an important problem in the mechanics of sediment suspension, though it is frequently assumed to be negligible in dilute flows (Elghobashi, 1994). A great many researchers have studied this problem (Gore & Crowe, 1989; Yarin & Hetsroni, 1994; Crowe, 2000; Lain & Sommerfeld, 2003). Hetsroni (1989) found that particles with particle Reynolds number (Re_p) larger than 400 tend to intensify the fluid turbulence, while particles with Re_p smaller than 400 tend to attenuate it. On the other hand, Noguchi and Nezu (2009) pointed out that particles smaller than the Kolmogorov microscale suppress the turbulence, whereas those larger enhance it.

In the present paper, an Euler–Lagrange two-phase flow model coupled with the EIM is applied to study the suspended load in dilute sediment-laden open-channel flows. The equations of motion for sediment particles and the EIM are described in detail in Section 2. Typical experimental results of sediment transport in open-channel flow are described in Section 3 for the purpose of verification of the developed numerical model. The Random Walk particle tracking Method (RWM) is also applied for comparison. A formula is suggested to describe the turbulence enhancement due to particles. Conclusions are summarized in Section 4.

2. Numerical model

2.1. Continuous phase

Consider the classical problem of suspended load in a two-dimensional steady and uniform channel flow. In general, an Euler–Lagrange model may have to solve the RANS equations in conjunction with the standard k–ε turbulence model for Reynolds-averaged variables of the continuous phase. However, the steady turbulent open-channel flow has been extensively studied, and empirical formulas that accurately describe the mean flow as well as the turbulence statistics have been well established. For simplicity, the carefully verified empirical formulas are used for the carrier flow in the present study. In addition, this paper focuses on the suspended load in dilute flow, and as a first step, the effect of sediment particles on the flow is neglected.

For a two-dimensional steady flow, the vertical mean fluid velocity, v, vanishes and the horizontal mean velocity, u, can be evaluated according to the formula of Dou (1987),

$$\frac{u}{u_*} = 2.5\log\left(1+\frac{y^+}{5}\right) + 7.05\left(\frac{y^+}{5+y^+}\right)^2 + 2.5\frac{y^+}{5+y^+} + 0.5\left[1-\cos\left(2\pi\frac{y}{h}\right)\right] \tag{1}$$

in which, u_* is the friction velocity; $y^+ = yu_*/\nu_f$; ν_f is the kinematic viscosity of the fluid; h is the water depth. The turbulent kinetic energy, k, and its rate of dissipation, ε, are expressed by the formulas of Nezu and Nakagawa (1993),

$$\frac{k}{u_*^2} = 4.78\exp(-2\xi) \tag{2}$$

$$\frac{\varepsilon h}{u_*^3} = 9.8\xi^{-1/2}\exp(-3\xi) \tag{3}$$

where $\xi = y/h$. According to Nezu (2005), the fluid turbulence can be treated as isotropic.

2.2. Dispersed phase

Particle–particle collisions are omitted in this study since a dilute flow is under consideration. The trajectory of a sediment particle, $\mathbf{x}_p(t)$, is, thus, determined by

$$\frac{d\mathbf{x}_p(t)}{dt} = \mathbf{u}_p(t) + \mathbf{u}_p' \tag{4}$$

where $\mathbf{u}_p(t)$ is the Reynolds averaged particle velocity, and $\mathbf{u}_p'$ is the velocity fluctuation. $\mathbf{u}_p(t)$ is governed by the equation of motion:

$$\frac{d\mathbf{u}_p(t)}{dt} = \frac{3}{4}\frac{C_D}{d_p}\frac{\rho_f}{\rho_p}|\mathbf{u}-\mathbf{u}_p|(\mathbf{u}-\mathbf{u}_p) + \mathbf{g} - \frac{\rho_f}{\rho_p}\mathbf{g} + \frac{9.69}{\pi}\frac{\rho_f}{\rho_p}\frac{\nu_f^{1/2}}{d_p}|\boldsymbol{\Omega}|^{-1/2}(\mathbf{u}-\mathbf{u}_p)\times\boldsymbol{\Omega} \tag{5}$$

where ρ_f and ρ_p are densities of the water and the sediment, respectively; d_p is the diameter of the particle; $\mathbf{u}$ is the Reynolds averaged velocity of the fluid phase; $\boldsymbol{\Omega} = \nabla\times\mathbf{u}$ is the vorticity of the mean fluid flow; $\mathbf{g}$ is the gravitational acceleration; and C_D is the drag coefficient, given by the well-known Schiller and Naumann (1935) formula,

$$C_D = \begin{cases} \frac{24}{Re_p}(1+0.15Re_p^{0.687}) & \text{if } Re_p \le 1000 \\ 0.44 & \text{if } Re_p > 1000 \end{cases} \tag{6}$$

where $Re_p = |\mathbf{u}-\mathbf{u}_p|d_p/\nu_f$ is the particle Reynolds number. The four terms on the right hand side of Eq. (5) represent, respectively, the drag force, gravity force, buoyancy, and lift acting on the particle. Compared with these four terms, the inertia force and Basset force are negligible and do not appear in Eq. (5).

2.3. Eddy Interaction Model (EIM)

The particle fluctuation velocity must be determined when integrating Eq. (4), and the EIM is here applied for this purpose. According to MacInnes and Bracco (1992), if the turbulence intensity of the particles is assumed to be identical to that of the carrier fluid, the particle fluctuation velocity, u_{pi}', can then be expressed by

$$u_{pi}' = \sqrt{\frac{2}{3}k}\varphi_i \tag{7}$$

where φ_i (i=1, 2) are two independent random numbers in the horizontal and vertical directions respectively, with zero mean and unit variance. Note that k is the local value of the turbulent kinetic