II -243

Euler-Lagrange Coupling of Two-Phase Flow Model for Bed-Load Transport at High Bed Shear Stress

Abbas Yeganeh, *Ph. D. candidate, Graduate School of Civil Engineering, Kyoto University*
Hitoshi Gotoh, *Assoc. Prof., Graduate School of Civil Engineering, Kyoto University*
Tetsuo Sakai, *Prof., Gaduate School of Civil Engineering, Kyoto University*

INTRODUCTION

A two-phase flow simulation is performed on the bed-load transport at high bed shear stress. The model is constructed based on the coupling of the Eulerian-Lagrangian form of the governing equations of fluid/sediment phase; the fluid/particle interaction term is explicitly introduced in the model. The fluid phase is described with the k–ε turbulence model in unidirectional flow. The sediment phase is numerically simulated by tracing the motion of irregular successive saltation of particles.

SIMULATION MODEL

Fluid phase model

Eulerian form of the governing equations of the fluid phase is implemented in the vertically two-dimension coordinates, as follows;

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=g\sin\theta-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(2\Gamma\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left\{\Gamma\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)\right\}+\frac{F_{dx}}{\rho(1-C)}$$

$$U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=g\cos\theta-\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left\{\Gamma\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)\right\}+\frac{\partial}{\partial y}\left(2\Gamma\frac{\partial V}{\partial y}\right)+\frac{F_{dy}}{\rho(1-C)}$$

$$U\frac{\partial k}{\partial x}+V\frac{\partial k}{\partial y}=\frac{\partial}{\partial x}\left\{\left(\nu+\frac{\nu_t}{\sigma_\kappa}\right)\frac{\partial k}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{\left(\nu+\frac{\nu_t}{\sigma_\kappa}\right)\frac{\partial k}{\partial y}\right\}+P_r+G-\varepsilon+\frac{\overline{uf_{dx}}+\overline{vf_{dy}}}{\rho(1-C)}$$

$$U\frac{\partial \varepsilon}{\partial x}+V\frac{\partial \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left\{\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right\}+\frac{\varepsilon}{k}\left(C_{1\varepsilon}P_r+C_{2\varepsilon}G-C_{3\varepsilon}\varepsilon\right)-\frac{\varepsilon}{k}\left(\frac{\overline{uf_{dx}}+\overline{vf_{dy}}}{\rho(1-C)}\right)$$

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \quad ; \quad P_r=\nu_t\left[2\left\{\left(\frac{\partial U}{\partial x}\right)^2+\left(\frac{\partial V}{\partial y}\right)^2+\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)^2\right\}\right]$$

$$\Gamma=\nu_t+\nu\, ; \quad ; \quad \nu_t=C_\mu\frac{k^2}{\varepsilon} \quad ; \quad G=\frac{\sigma-\rho}{\rho}g\frac{\nu_t}{S_c}\frac{\partial C}{\partial y}$$

in which U,V= mean flow velocity in x,y direction, respectively; θ= channel slope; P= pressure deviation from hydrostatic one; ρ= mass density of water; g= gravitational acceleration; ν= kinematic viscosity; ν_t= kinematic eddy viscosity; Γ= effective viscosity; k= turbulent energy; ε=energy dissipation; P_r= production of turbulent energy due to shear stress; G= boyant production of turbulent energy; σ= mass density of sediment; C= particle volumetric concentration; S_c= turbulent Schmit number; and (F_{dx}, F_{dy}), (f_{dx}, f_{dy})= mean value and fluctuating components of drag term caused by interaction between fluid and sediment per unit volume.

Fluid flow around sediment particle exerts a resultant force on the sediments, and as a consequence of the action and reaction, the sediments activate the same strength force, namely drag force, on the surrounding fluid in the opposite direction. Hence, the interaction terms in the mean flow equations are calculated by the spatial average of drag force for every computational grid cell. A correlation between the fluctuating drag force and the velocity fluctuating of the surrounding fluid of the particle is also included in the transport equation of turbulent energy, k. The transport equation of energy dissipation, ε, is originally derived by

Keywords: *two-phase flow, bed-load, saltation, Lagrangian model*
Address : Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan. ; Phone : 075-753-5099

assuming the analogy between k- and ε-equation, thus, the interaction term in ε-equation is defined similar to that of the k-equation with dimensional adjustment. To reproduce the time series of fluctuating velocity component (u,v) in the simulation, a simple Monte-Carlo model is used.

Sediment Phase model

A Lagrangian model of the irregular successive saltation is implemented for the sediment phase, in which the trajectory of a saltating particle is governed by the following equations:

$$\rho\left(\frac{\sigma}{\rho}+C_M\right)A_3 d^3\frac{du_p}{dt}=\frac{\rho}{2}C_D A_2 d^2\sqrt{\left(U-u_p\right)^2+\left(V-v_p\right)^2}\left(U-u_p\right)$$

$$\rho\left(\frac{\sigma}{\rho}+C_M\right)A_3 d^3\frac{dv_p}{dt}=\frac{\rho}{2}C_D A_2 d^2\sqrt{\left(U-u_p\right)^2+\left(V-v_p\right)^2}\left(V-v_p\right)-\rho\left(\frac{\sigma}{\rho}-1\right)gA_3 d^3$$

where, d= diameter of saltating particle; σ= mass density of sediment; A_2, A_3= two- and three-dimensional geometrical coefficients of sediment; C_M= added mass coefficient, C_D= drag coefficient; and u_p, v_p= velocity components of saltating particle in x,y direction, respectively.

DISCUSSION AND RESULTS

Fig.1 shows the simulation results of the mean velocity profile in comparison with the that of the experimental one, at the channel bottom inclination i_b= 3/100. The result of simulation shows a very good agreement with the experiment. As Fig.1 indicates, the mean velocity tends to have a two-layer type profile, corresponded to the saltation layer and the pure water layer. Two-layer type velocity profile is the characteristic feature of fluid/particle interaction dominant flow. Gotoh et al. (1994) based on a numerical study, and later Yeganeh (1997) in an experimental study on the sediment-laden flow, reported the presence of the same characteristics.

Yeganeh (1997) reveals that at higher bed shear stress, where the flow is capable to transport higher rate of sediments, the velocity profile transits to three-layer type one, corresponding to the hyper-concentrated layer, the saltation layer and the pure water layer. Moving sediments in the hyper-concentrated layer collide to each other frequently, hence the particle-particle interaction becomes the dominant mechanism in this region.

Fig. 2 depicts the mean velocity profile at the channel bottom inclination i_b=5/100. The simulation result shows a perfectly three-layer type velocity profile. In the hyper-concentrated layer, however, a clear discrepancy can be detected between the simulation results with the experimental one. The experimental velocity profile shows downward concave form, which may follow a power-law distribution as recommended by Sumer et al. (1996), whereas, the velocity profile resulted from the simulation is upward convex. This discrepancy in hyper-concentrated layer is due to the limitation of the simulation model in which the particle/particle interaction is neglected.

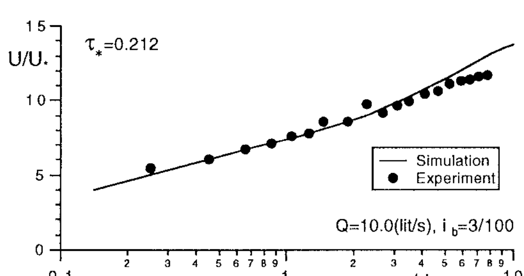

Fig. 1 Two-layer type velocity profile

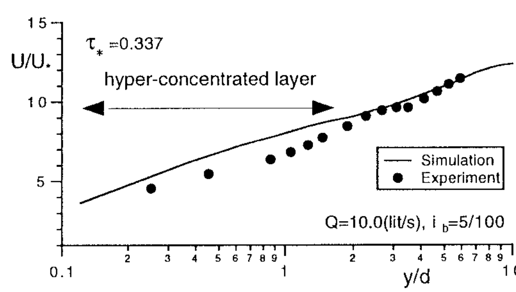

Fig. 2 Three-layer type velocity profile

References: Gotoh, H., T. Tsujimoto, and H. Nakagawa(1994), Proc. Hydraulic Eng., *JSCE*, Vol. 38, pp591-596. Sumer, B.M., A. Kozakiewicz, J. Fredsoe, and R. Deigaard(1996), Jour. Hydraulic Engrg., *ASCE*. Yeganeh, A.(1997), Proc. *XXVII IAHR Cong.*, San Francisco, USA, JFK- SP, pp. 1-6