Euler-Lagrange simulations of debris flow experiments

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The applicability of an Euler-Lagrange simulation for debris flows is discussed in the paper. The simulation model was applied to debris flow laboratory experiments conducted by Egashira et.al [1]. Experimental cases of sediment concentration of 0.196 and 0.444 were simulated with particles of spheres and gravels. The results demonstrated that the simulation model was able to reproduce discharge rates of water and particles and vertical distributions of particle velocities. Moreover the simulation showed that effects of particle shapes arose greatly in highly concentrated debris flows because particle shear stresses became dominant.

Key Words: *Euler-Lagrange simulation, particle shape, debris flow, particle velocity, concentration ,internal friction angle*

1. Introduction

Three-dimensional numerical simulations based on the Euler-Lagrange approach have been developed and become powerful tool for investigations of fluid-particle interaction mechanism in two-phase flows. However, simulations for highly concentrated sediment transport have not been validated yet. We have developed a numerical simulation model based on the Euler-Lagrange approach to investigate fluid–particle interactions (Fukuoka et al. [2]). The present study applies our numerical model to the laboratory experiments on debris flows conducted by Egashira et al. [1]. Simulated motions of particles and water in highly concentrated debris flows are validated by comparing with the experimental data. Moreover, shapes of particles play an important role in gravel transport in flows [2]. Differences between simulated motions of sphere and gravel particles are discussed in relation with the variations of sediment concentrations.

2. Debris flow experiment

Egashira et al.[1] conducted the experiments of debris flow over rigid bed in a rectangular open channel (12 m long, 0.1 m wide and bed slope of 19 deg.) as follows; uniform debris flows with different sediment concentrations c_f (0.141 - 0.444) were created in the channel. The water was supplied at a constant rate from upstream and the gravel (d_{50} = 2.18 mm) was fed at 6 m section from the end. The water and the sediment discharge were measured by sampling water-sediment mixture at the downstream end. Vertical distributions of particle velocities were photographed by video cameras from the side of the channel and measured by the image analysis. Vertical distributions of gravel concentrations were also measured by using a sampler which had several inlets at different levels.

	Gravel used for the experiments	Sphere		Gravel	
ϕ_μ : Internal friction angle	38.7˚	29.7 ˚		38.9 ˚	
c*: Stationary deposited concentration	0.512	0.60		0.62	

Fig. 1. Particle conditions of the experiment and the simulation.

Table 1. Parameters used in the simulation.

$\Delta x, \Delta y, \Delta z$: Fluid computational grid size	0.545	mm	μ_w: Kinematic viscosity	8.9×10^{-4}	Pa·s
ρ_w : Water density	1,000	kg/m^3	C_S : Smagorinsky constant	0.173	
ρ_s : Particle density	2,620	kg/m^3	ϕ_s : Friction angle of particle surface	26.6	˚
			d : Diameter	2.18	mm

3. Simulation method

The numerical method is able to simulate detailed flows around particles by using smaller computational grid than particles, see [2]. In the simulation of flow motion, particles are dealt as a liquid with a different density. All domains of water and particles are computed by the governing equations of one fluid model for incompressible solid-liquid multiphase flow based on the computation method (Ushijima et al. [3]). Smagorinsky model is employed for a turbulence model.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{Du_i}{Dt} = g_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{2\left(\nu + \nu_t\right)S_{ij}\right\} \tag{2}$$

$$\nu_t = \left(C_s \Delta\right)^2 \sqrt{2 S_{ij} S_{ij}} \tag{3}$$

where u_i is i-th component of weight average velocity including particles, ρ is volume average density, p is sum of pressure and isotropic component of SGS stresses, S_{ij} is strain rate tensor, ν is kinematic viscosity, C_s is Smagorinsky constant and Δ is computational grid size. Fluid forces on particles are computed by integration of forces on particle-domain in the multiphase flow.

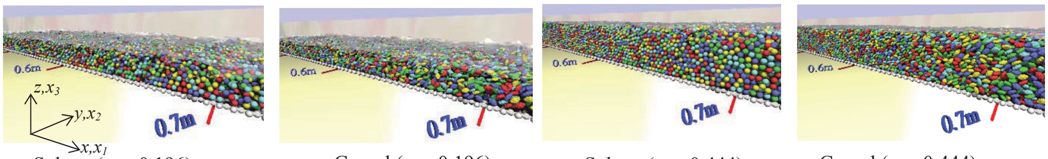
The Discrete Element Method is used for particle motions. Combined tetrahedron models (CTM) and superposed sphere models (SSM) are often used for nonspherical particles. CTM is also suitable for reproducing shapes of particles [4], but it needs many elements to reproduce particles like gravels. This study has implemented simulations of motions of a number of gravel particles (about two hundred thousand) by employing SSM that can reproduce gravel shapes with a few small spheres.

4. Simulation conditions

The simulation model was applied to two cases of the debris flow experiments (Case1: sediment discharge concentrations c_f = 0.196, depth 0.0139 m, Case2: c_f =0.444, depth 0.0259 m) by using spheres and gravel particles, see Fig.1. The length of numerical channel was 1 m. The width was 0.1 m and bed slope was 19 degrees as with the experiment. Uniform flows were simulated by applying periodic conditions in the streamwise direction. Numerical results of channel length 1.0 m were not different from those with 6.0 m channel length for the case of c_f = 0.196. Parameter used in the simulation are shown in Table 1.

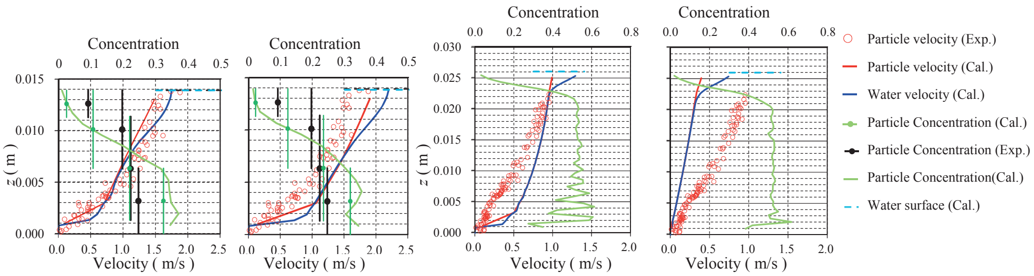
5. Validation of the numerical simulations with the debris flow experiments

Simulation results were compared with the data measured in the experiment. Fig.2 shows simulation results of motions of gravel and sphere particles and water. Gravel particles had long axis directed the streamwise direction in the manner of the imbrication structure. Gravel motions were strongly affected by their shapes. Vertical distributions of particle velocities and concentrations were compared in Fig.3. In the case of sediment discharge concentration 0.196, simulated vertical velocity distributions of sphere were a little smaller than measured ones and those of gravel particles were a little greater than experimental ones. However, both particle velocity distributions were close to the experimental ones. Vertical distributions of particle volume concentrations of spheres and gravel particles roughly reproduced the experimental ones. The stationary deposited concentration c_* measured in the experiment was 0.512 and rather small compared to 0.60 and 0.62 used in the simulations. This means that experimental gravel particles were thought to have jagged shapes. The particle model requires many



Sphere (c_f = 0.196) Gravel (c_f = 0.196) Sphere (c_f = 0.444) Gravel (c_f = 0.444)

Fig. 2. Simulated particles and water surfaces.



Sphere (c_f = 0.196) Gravel (c_f = 0.196) Sphere (c_f = 0.444) Gravel (c_f = 0.444)

Fig. 3. Vertical distributions of particle and water velocities and concentrations.

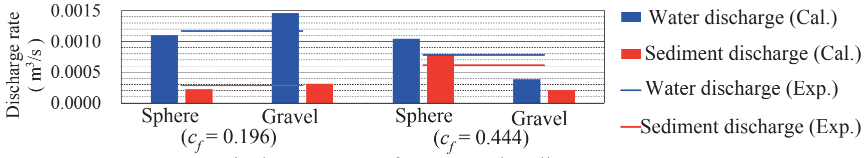


Fig. 4. Discharge rates of water and sediment.

small spheres to imitate gravel particles of jagged shapes. This brings difficulties in simulations due to high computation load. Therefore, simulations of gravel particles could not imitate properly the stationary deposited concentration of experimental particles. This seems to the cause of difference in concentrations distributions between the experiment and the simulation.

In the experiment case of c_f = 0.444, vertical distributions of particle volume concentrations could not be measured because of the sediment sampler clogging. Only vertical particle velocities were compared between simulated and experimental ones. Simulated gravel velocities were smaller than experimental ones, on the other hand, simulated sphere velocities were greater than experimental ones. Fig.4 shows discharge rates of water and particles. Experimental values of water and sediment discharge rates and particle velocities were nearly intermediate between simulated values of spheres and gravels for both cases of c_f = 0.196 and 0.444. It can be concluded that the present Euler-Lagrange simulation is able to reproduce the distributions of particle velocities and discharge rates of water and particles in various concentrations by selecting suitable particle shapes.

6. Stresses of water and particles in two phase flows

It is important to clarify the difference in stresses between sphere-water flows and gravel-water flows. Here, stresses of water, spheres and gravels were predicted from the Euler-Lagrange simulation results. Stresses of water and particles in uniform flows are able to be estimated by Eqs. (4) and (5)

$$\sigma_{33}^{\beta} = \int_{x_3}^{x_3^s} \left(\rho^{\beta}\alpha^{\beta}g_3 + f_3^{\beta}\right)dx_3 \tag{4}$$

$$\sigma_{31}^{\beta} = \int_{x_3}^{x_3^s} \left(\rho^{\beta}\alpha^{\beta}g_1 + f_1^{\beta}\right)dx_3 \tag{5}$$

where the superscript β denotes the values of water "w" and particles "p" respectively. σ is the stress and α is a volume fraction of water or particles. f is fluid force represented by the relationship of $f_i^p = -f_i^w$. Superscript s denotes the value of the water surface. The coordinate systems are presented in Fig. 2.

The predicted vertical distributions of stresses and apparent particle friction angles, θ_f = arctan($\sigma_{31}/(-\sigma_{33})$) are indicated in Fig.5. Apparent particle friction angles θ_f^p of c_f = 0.1 96 were greater than those of 0.444. The turbulence could bring greater apparent friction angles for c_f = 0.196. Apparent particle friction angles θ_f^p of c_f = 0.444 were about 30˚ for spheres and about 40˚ for gravels. Those angles

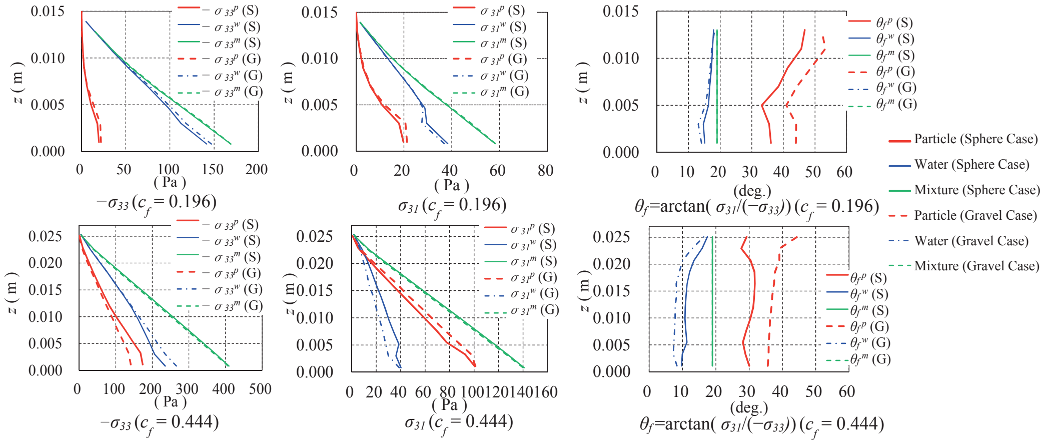


Fig. 5. Vertical distributions of stresses and apparent friction angles.

nearly coincided with the simulated internal particle friction angles ϕ_μ measured by the direct shear test simulations (see Fig.1). 2D DEM simulations of the biaxial compression test [5] proved that circular cylinders had difficulty restraining particle rotations by just only increasing friction angles of particle-surfaces ϕ_s and reproducing internal friction angles ϕ_μ greater than about 30˚. In other words, although apparent friction angles $\theta_f^{\,p}$ is equivalent to the internal friction angles ϕ_μ in highly concentrated debris flows, spheres could not produce large internal friction angles 40˚ as gravels. It was concluded that the use of spheres was hard to reproduce debris flows of gravels. In high concentration c_f = 0.444, particle shear stress $\sigma_{31}{}^{p}$ was dominant, while water shear stress $\sigma_{31}{}^{w}$ was dominant in the debris flow of c_f = 0.196. Therefore, main resistances of highly concentrated debris flows were caused by particles and strongly affected by apparent friction angles of particles. Then, in highly concentrated flows of c_f = 0.444, considerably smaller sediment discharge rate of gravels than that of spheres (see Fig.4) was brought by the difference of friction angles of spheres and gravels.

7. Conclusions

The results of debris flow experiments of sediment discharge concentration of c_f = 0.196 and 0.444 were examined using materials of spheres and gravels by the Euler-Lagrange approach. The comparisons of the results of simulation and experiments brought that the present Euler-Lagrange simulation was able to reproduce vertical distributions of particle velocities and discharge rates of water and particles of various concentrations only if suitable particle shapes were selected for the debris flow simulations. The difference of friction angles between spheres and gravel caused considerable effects on the reproducibility of highly concentrated debris flows such as c_f = 0.444 where particle shear stress was dominant.

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