ARTICLE IN PRESS

Advances in Water Resources xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Advances in Water Resources

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

Effects of sizes and shapes of gravel particles on sediment transports and bed variations in a numerical movable-bed channel

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Numerical movable-bed channel
Three-dimensional computation
Sediment transport
Gravel shape
Hydrodynamic force
Channel-bed configuration

ABSTRACT

The paper presents a numerical movable-bed channel capable of simulating three-dimensional motions of flows and gravel particles in different shapes. At first, the numerical channel was tested against results of fixed-bed channel experiments in which gravel particles were transported. Simulated particle motions were validated in comparison with those in the laboratory experiment. Next, numerical movable-bed experiments with sphere particles and gravel particles were conducted. The results of these experiments clearly elucidated the difference in motion between the large and the small particles, effects of shapes of gravel particles on sediment-transport rates, and hydrodynamic forces and contact forces at incipient motion and at settling.

1. Introduction

Natural gravel-bed rivers display a large variety of particles sizes and shapes which often include cobbles. Although the sediment-transport rate in gravel-bed rivers has been discussed [1–8], the effect of sizes and shapes of gravel particles on sediment transport and river-bed variation have not been clarified sufficiently. The sediment-transport process in gravel-bed rivers during floods is explained that, at first small particles on the bed surface move, and next large gravel particles are exposed, resisting hydrodynamic forces primarily [1]. Exposed large particles do not move easily in large floods, but roll intermittently. However, studies on sediment transport for mixed-size sediment [3,9] in the laboratory experiments have been conducted primarily without large particles, such as cobbles. Such sediment-transport mechanism seems to differ from that of gravel-bed rivers. The bed-variation analysis using sediment-discharge formulas for mixed-size sediment [9] cannot explain adequately the variations of the bed levels and grain size distributions on the bed surface in gravel-bed rivers because the sediment-discharge formulas cannot evaluate the sheltering effect of large particles on small particles and hydrodynamic forces on projecting large particles [4,5]. Bed-surface patches caused by formation of large-particle clusters affect sediment transport in gravel-bed rivers [6–8]. Hendrick et al. [6] made field observations of formation of large-particle clusters on a gravel bed in several flow events. They demonstrated that large-particle clusters were formed adjacent to riffles related to river-bed topographies. Piedra et al. [7] made experiments with mixed-size movable-bed, and investigated the relationship between tractive forces and ratio of large-gravel cluster occupying area to the bed surfaces. However, laboratory experiments and field observations have difficulty in investigating details of gravel-transport mechanism and arrangements of gravel particles on the bed due to the hydrodynamic forces.

In recent years, the progress in computing performances has made possible to analyze the transport mechanism of individual particle motions by a Lagrangian method [10–12]. In most of these analyses, hydrodynamic forces on particles are calculated using drag coefficient [11,12]; therefore, evaluations of hydrodynamic forces remain inaccurate. A numerical method for solid–liquid multiphase flow has been developed in which hydrodynamic forces are calculated directly by calculating three-dimensional fluid motion around a solid object using finer computational cells than the object size [13,14]. Harada et al. [15] conducted large eddy simulation of solid–liquid multi-phase flow for drifting particles on a movable-bed of spheres in three different sizes and investigated vertical sorting processes in oscillatory flows. However, characteristic structural arrangements of particles in gravel-bed rivers, such as imbrications [16], indicate that motions of particles near the bed surface are strongly affected by the sizes and the shapes of particles. This natural image suggests that the investigation of particle motions in gravel-bed rivers should take irregular particle shapes into consideration.

This paper presents numerical movable-bed channel composing different particle sizes and shapes where three-dimensional fluid

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http://dx.doi.org/10.1016/j.advwatres.2014.05.013
0309-1708/

motion was simulated in an Eulerian computational method for solid–liquid multiphase flow and gravel particles motion by a Lagrangian method. We use gravel particles with different sizes and shapes made of 8–10 small spheres superposed, as shown in Fig. 1 [17].

Eulerian descriptions of particle motions [18–20], especially descriptions of depth-integrated sediment transport [18,19], are practical for simulating sediment transport over a large area. However, the Eulerian description for the motion of particles of various sizes and shapes requires clear understanding of interactions among particle and particles themselves, flow and particles and the bed composition. We believe that flow and sediment-particle interaction dynamics of the Eulerian approach remains unsolved. This paper attempts to evaluate the dynamic interactions of particles themselves and particle–fluid which consider the effect of particle-size distributions, shapes of particles, and the bed structures. At first, the developed numerical channel was applied to the results of a fixed-bed channel experiment (hereinafter referred to as the real-scale experiment) in which motions of real-scale gravel particles in streams were measured [21]. Simulated particle motions were validated by comparing with those in the physical experiment. Next, two numerical experiments were conducted using the numerical movable-bed channel where mixed-size sphere particles and modeled gravel particles were used as the bed materials. The flow and particle motion and hydrodynamic forces on particles were predicted and visualized. The effects of size and shape of particles on motion of gravel particles, sorting mechanism of particles on the bed surface and flow structures near the bed were analyzed.

2. Numerical model

In the present numerical model, fluid motions were simulated with the Eulerian method [14] and gravel motions were simulated with the Lagrangian method. To take into account the effect of solid phase on liquid phase, fluid motions were simulated by the governing equations of multiphase flows, as illustrated in Fig. 2. Fluid dynamic forces on particles were evaluated directly by integrating the forces on a particle region in the multiphase flow. Gravel particles with various shapes are made by the superposition of several small spheres, as shown in Fig. 1 [17]. Motions of the particles were simulated as rigid bodies.

2.1. Governing equations of the fluid motion

The fluid motion was simulated by one-fluid model for the solid–liquid multiphase flow using the Smagorinsky model as the subgrid turbulence model:

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

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = g_i - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\{2(\nu + \nu_t)S_{ij}\} \tag{2}$$

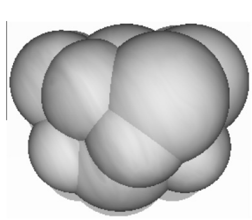

Fig. 1. A model gravel particle constructed with multiple spheres.

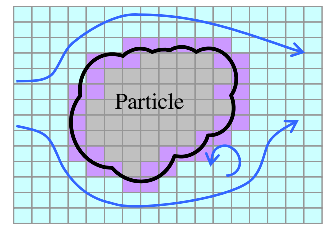

Fig. 2. Concept of fluid motion analysis.

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

$$\nu = \mu/\rho \tag{4}$$

$$\nu_t = (C_S\Delta)^2\sqrt{2S_{ij}S_{ij}} \tag{5}$$

where u_i: ith component of averaged velocity given by the weight of the mass within a fluid cell, P: sum of the pressure and isotropic component of SGS stress, ρ: density, μ: dynamic viscosity, g_i: gravitational acceleration, ν_t: SGS turbulent viscosity, C_S: Smagorinsky constant, Δ: computational grid size.

Physical property ϕ (density ρ, dynamic viscosity μ) and averaged velocity u_i were calculated as volume-averaged values and mass-averaged values, respectively, as follows:

$$\phi = \alpha\phi_s + (1-\alpha)\phi_f, \quad \phi_f = f\phi_l + (1-f)\phi_g \tag{6}$$

$$u_i = \{\alpha\rho_s u_{si} + (1-\alpha)\rho_f u_{fi}\}/\rho \tag{7}$$

where f: fluid volume fraction in fluid calculation cell, α: solid volume fraction in fluid calculation cell, suffixes l, s and g denotes liquid phase, solid phase, and gas phase, respectively. u_f is fluid velocity, and u_s is solid velocity. Continuity equation and momentum equation were solved by the SMAC scheme with staggered grids.

2.2. Evaluation of solid rigidity in fluid calculation

The solid rigidity was evaluated by simulating particle motion as rigid body and setting average density ρ and average velocity u_i with Eqs. (6) and (7). Solid velocity u_{si} in Eq. (7) was calculated by the following equation:

$$\boldsymbol{u}_s = \dot{\boldsymbol{r}}_G + \boldsymbol{\omega} \times \boldsymbol{r}_f \tag{8}$$

where $\boldsymbol{r}_G$: position vector of the center of gravity of the particle, $\boldsymbol{\omega}$: angular velocity vector of particle, $\boldsymbol{r}_f$: position vector measured from particle's center of gravity to the calculation point of $\boldsymbol{u}_s$. Dot notation denotes the time derivative. The solid volume fraction in fluid calculation cell α in Eqs. (6) and (7) was calculated by dividing a fluid calculation cell into sub-cells and counting the number of

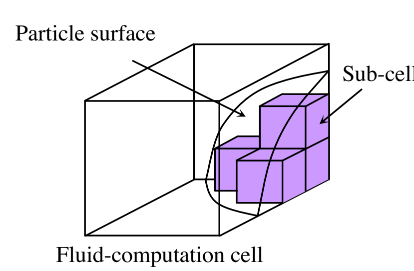

Fig. 3. Evaluation of particle volume with sub-cells.

Please cite this article in press as: Fukuoka S et al. Effects of sizes and shapes of gravel particles on sediment transports and bed variations in a numerical movable-bed channel. Adv Water Resour (2014), http://dx.doi.org/10.1016/j.advwatres.2014.05.013