Prediction of three-dimensional movement of gravel particles in a movable-bed numerical channel

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We have developed a movable-bed numerical channel which simulates three-dimensional movement of streams and various shape gravel particles. Using the numerical channel we performed numerical channel experiments with graded gravel particles and demonstrated motion of streams and particles which has been difficult to measure in experiments and fields. Characteristic motion of gravel particles, sorting mechanism of particles at the bed surface and velocity distributions near the bed are predicted from the numerical investigations of the motion of streams and particles.

Key words

Movable-bed numerical channel, three-dimensional motion, gravel bed river, shape of particle, large particle cluster, vertical velocity distribution, sediment transport rate.

I INTRODUCTION

Gravel-bed rivers consisting of large bed materials are generally seen in natural world. Many researchers have attempted to demonstrate the movement of streams and gravel particles by field experiments and numerical computation method. However, the prediction method of sediment discharge and bed variation in rivers with large range of particle sizes have not been established. The reason is because sediment transport mechanism in gravel-bed rivers is more complicated than that of sand-gravel bed rivers and measurements in gravel bed rivers are very difficult.
A computational method for solid-liquid multi-phase flow have been developed recently, in which fluid motion around objects are calculated precisely with fine computational cells smaller than particles and solid objects are evaluated by considering as a liquid with the different density.
In this paper, we developed a movable-bed numerical channel with different particle sizes and shapes which simulated three-dimensional motions of streams and gravel particles by calculating fluid motion in the Eulerian computational method for solid-liquid multiphase flow and calculating gravel particles motion in the Lagrangian method. We made gravel particles with different sizes and shapes by superimposing 8 to 10 small spheres. We conducted movable-bed experiments using the numerical channel and clarify the motion of streams and gravel particles and hydrodynamic forces acting on particles, which are difficult to measure in the experiments and fields.

II OUT LINE OF NUMERICAL METHOD

In the calculation of fluid motion, fluid and solid are calculated as an incompressible multiphase flow by the equations described below , where the region of gravel particles are considered as a different density fluid.

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

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

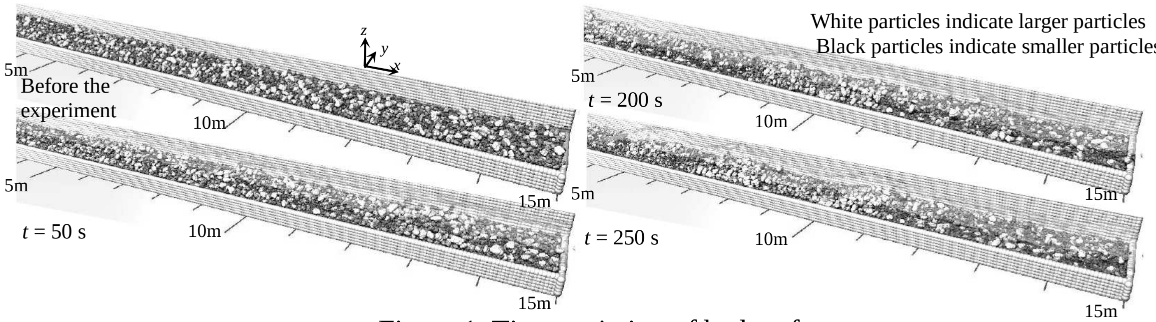


Figure 1. Time variation of bed surface.

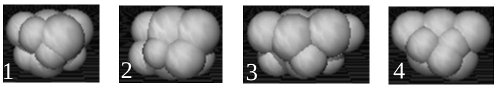


Figure 2. Gravel particle model.

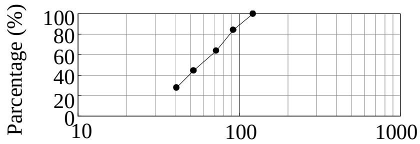


Figure 3. Grain size distributions.

$$\nu_t = (C_S \Delta)^2 \sqrt{2 S_{ij} S_{ij}} \ , \qquad (3)$$

where u_i : i-direction averaged velocity including gravel particle regions in a fluid calculation cell, ρ : density, P : sum of pressure and isotropic component of SGS stress, g_i : gravitational acceleration, S_{ij} : strain rate tensor, ν : kinematic viscosity, ν_t : SGS turbulent viscosity, C_S : Smagorinsky constant (0.173), Δ : calculation grid size. Physical property ϕ (density ρ , dynamic viscosity μ) and averaged velocity u_i are calculated as volume-averaged values and mass-averaged values, respectively.

Gravel particle movements are calculated by the Lagrangian method with translational and rotational equations of rigid bodies. Fluid forces acting on gravel particles are calculated by multiplying density to the second term and the third term in the right side of equation (2) and integrating them within the region of a particle. Contact forces are calculated with each small superimposed sphere consisting of a gravel particle by the Distinct Element Method and forces acting on gravel particles are calculated by the summation of the contact forces on the spheres. [1]

III NUMERICAL MOVABLE-BED CHANNEL EXPERIMENT

III – 1 Numerical experiment condition

Figure 1 shows the movable-bed numerical channel and definition of coordinate axes used for numerical analysis. The numerical channel with 15 m long, 1 m wide and 1:20 in bed gradient was designed by considering flow conditions transporting gravel particles, length of bed waves and computational load. Four different gravel particles in shape shown in Figure 2 were prepared for bed materials of movable-bed numerical channel. Five different sizes of particles (40 mm, 50 mm, 70 mm, 90 mm, 120 mm) were made by varying the size of small spheres and by superimposing them properly. The diameters of the various shape particles are given as the diameter of spherical particles with the same volume. Particles are packed ramdomly to the channel by adjusting supply rate so that the particle size distribution of the numerical bed channel agrees with the particle size distribution in Figure3. The numerical experiment was lasted for 250s. In the numerical analysis, fluid calculation Δt is set 1.0×10^{-4}s, gravel particle movement calculation Δt is set 1.0×10^{-6}s. The grid size for fluid calculation is 0.01m and other parameters are same values as the authors' paper. [1]

III – 2 The result of numerical experiments

We disscuss at first the flow condition, variation of bed level and sediment transport rate. At the time t = 250 s, average water depth is 0.23 m, average velocity is 1.92 m/s and Froude number is 1.20. The flow is a supercritical flow and the water surface varies in the same phase as the bed wave. Figure 1 shows conditions of the bed surfaces in the successive time of the numerical experiment. At t = 250 s, formations of large gravel cluster and the resulting gravel sorting at the bed are seen at sections x = 8 m and x = 10.5 m. Figure 4 shows sediment discharge rate of each particle size

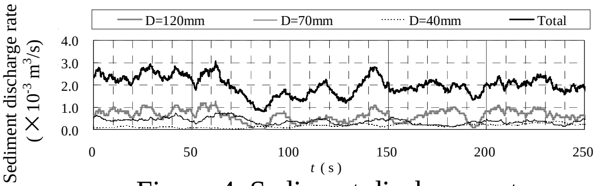


Figure 4. Sediment discharge rates.

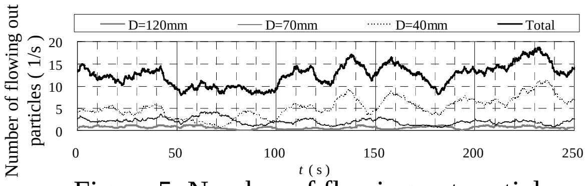
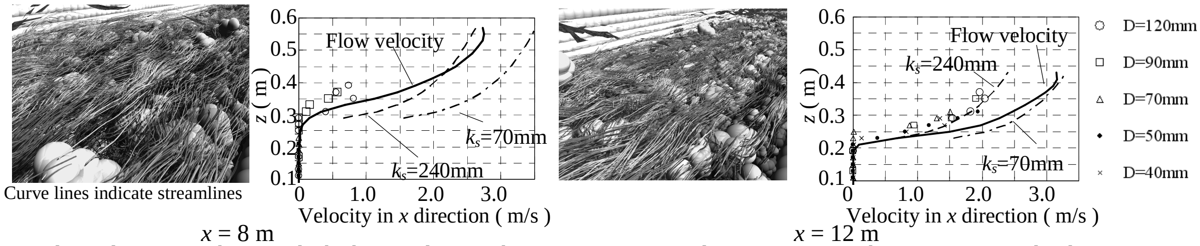


Figure 5. Number of flowing out particles.



Log law velocities are shown under both equivalent roughness 70 mm as D_{60} and 240 mm as twice the maximam particles diameter. As shear velocity, 0.29m/s averaged from x = 5 m to x = 13 m point is set.

Figure 6. Vertical velocity distributions and flow condition near the bed surfaces.

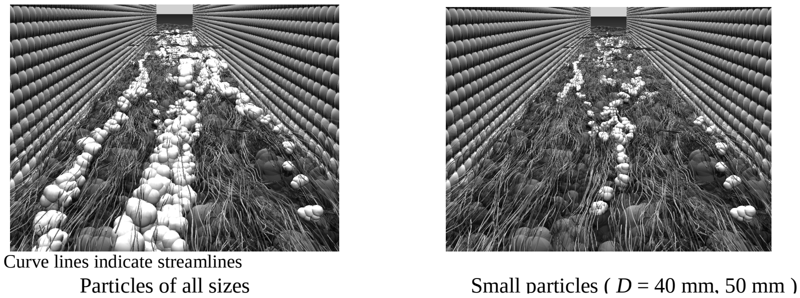


Figure 7. Trajectories of moving particles.

measured at the downstream end and Figure 5 shows number of particles discharging per unit time at the downstream end where numbers of particles smaller than 70 mm are dominated. Smaller paricles are transported actively. However, we can see that sediment discharge rate of large particles is greater than that of smaller particles.

Figure 6 shows the vertical distributions of time averaged velocities in the x-direction measured at the center of the channel at sections x = 8 m and x = 12 m. The velocities are averaged over 0.15 m lateral range from the channel centerline which is about the largest particle size. Figure 6 also shows time averaged velocities of gravel particles moving the lateral range of 0.15m and log-law velocity distribution shown by assuming k_s = 70 mm and 240 mm. The x = 8 m is the section where clusters of large particles are formed and vertical velocity distributions change gradually from bottom to upward z-direction and do not follow the log law. On the other hand, at x = 12 m point where large particles cluster is not developed, vertical gradient of velocity distribution is large and velocity is over 2 m/s at the height of 0.1m from zero velocity level. Velocity distributions of the flow are approximated to the log law velocity distiribution (k_s = 70 mm). From these investigation, we found that at the location forming large particles clusters, velocity gradually increased from bottom to vertical upward direction in the scale of large particles because there are a number of large pores in large particles clusters and large particle clusters give great resistance to flows.

Figure 7 shows trajectories of gravel particles visualized by emitting light on moving gravel particles at every 1/10s. From this figure, we can find that small particles cannot move over large projecting particles but come to take detours. Large particles are nearly in rectilinear motion over projecting particles. Therefore, large particles receive greater flow velocity and are not able to stop easily on plane bed but can stop at projecting beds as high as large particle size, which means that large particles tend to form clusters. Deep water passages are formed among large particles clusters of the bed surface and small particles come to move along meandering deeper water passages beside large particles. This results in the particle sorting of the gravel bed surface.

Next, we clarify the dynamics of particle motion by investigating how particles behave and receive forces at the time of their movement and rest. We define the long axis as the axis easiest to rotate among orthogonal principal axes and short axis as the axis hardest to rotate. Short axes difined

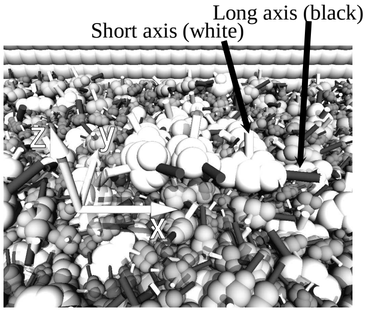


Figure 8. Conditions of long axis and short axis of particles on the bed surface.

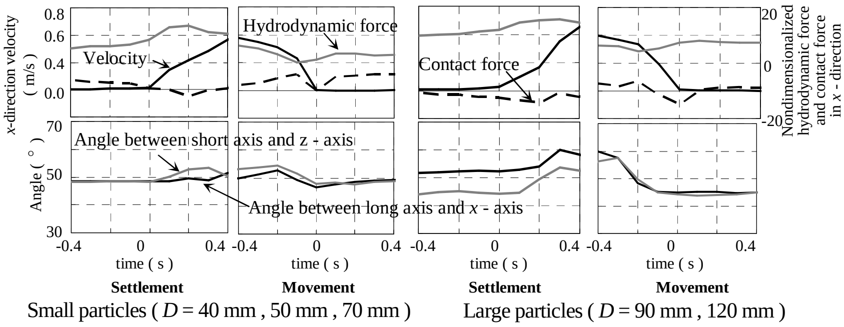


Figure 9. Time variation of the particles velocities, hydrodynamic forces, contact forces and particles direction concerning movment and settlement.

in such manner indicate almost the same direction as the normal vector to the most flat plane of particles. Long axes and short axes of the particles are shown in Figure 8. Figure 9 shows time variations of averaged gravel particles velocities in *x* – direction and contact forces and hydrodynamic forces acting among gravel particles nondimensionalized by *x* - component gravity force and angles between a long axis and *x* - axis and angles between short axis and *z* – axis. The time zero in Figure 9 is selected at the time when a particle bigins to move and comes to a stop. These values are evaluated by averaging individual particles motion. When large particles stop, the angle between long axis and *x* - axis becomes smaller. Apparently, large particles incline long axes toward lateral direction easy to roll downstream in their moving stage, and in their stopping stage, they incline the long axes to the downstream direction. Moreover, large particles tend to direct a flat plane upward at the instant of the stopping in order to decrease the angle between short axes and *z* - axis. These dynamic features are also seen in small particle motion, but not so clear compared to large particles. This is because that smaller particles at the time of movement and rest are affected by the irregular shape of gaps and water passages formed by surrounding larger particles at the bed surface. Time variations of long axes and short axes at the movement stage of larger particles tend to be opposite to that at the time of the stopping stage. Hydrodynamic forces acting on larger particles increase a little after the stopping in the process of the particle stop, on the other hand, hydrodynamic forces acting on smaller particles decrease after stopping. The reason of the differences is considered that small particles can stop at small velocity regions behind stationary large particles, while large particles stand high positions and recieve large hydrodynamic forces and therefore cannot stop easily but do by the collision and support of surrounding large particles.

IV CONCLUSIONS

We developed the movable-bed numerical channel with various shape particles. The numerical channel was used to investigate the movement of streams and gravel particles near the bed surface. Following main conclusions were obtaind:

1. The movable-bed numerical channel experiment drew a new methodology to understand three dimensional motions of particles, vertical velocity distribution near the bed surface, effects of shape and size of particles on the movement and the rest of gravel particles, the sorting mechanism of the bed surface and sediment transport rate.
2. Large particles move high position in rolling and saltating manner along the bed surface and receive large flow velocity, therefore cannot stop easily. Large particles stop by the collision force with surrounding large particles and tend to form large particle clusters. Small particles move deeper water passages beside large particle clusters. This mechanism is important for particle sorting on the bed surface.
3. Vertical velocity distributions at the location forming large particles clusters has a convex form upward in a larger particle diameter range near the surface and on bed surface where large particle clusters are not formed, velocity distribution follows approximately the log law velocity distribution.

Ⅳ REFERENCES

[1] Fukuda, T., Fukuoka, S. and Uchida, T.; (2012). – *Three-dimensional numerical modeling for the motion of stones with different sizes and shapes in streams.* Proceedings of tenth international conference on hydroscience and engineering.