A study on vertical sorting mechanism in gravel bed rivers with graded sediment using the APM method

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1. Introduction

Studies on armoring of grain size materials in gravel bed rivers have been investigated actively. Many models have been attempted to evaluate sorting mechanism of bed materials on grain size profiles and shielding effects. There are still issues to be addressed in the modeling of bed variation analysis method with assumptions for simplifications (e.g., neglecting interactions between moving particles and assuming no movement of large particles in the riverbed). In bed variation analysis models, the bed load is often evaluated based on the processes of entrainment, transport, and deposition. In particular, it is important to properly evaluate the entrainment and deposition rate, which are directly related to changes in the riverbed structure.

Physical Experimental observations have limitations in obtaining detailed mechanism of each particle motion in graded sediment. On the other hand, numerical approaches have advantages for analyzing space and time variation motions on each particle motion. Fukuoka et al.[1)] developed APM method (a type of resolved-CFD-DEM model) that can directly analyze solid-liquid phase interactions, and obtain trajectories, velocities, and distributions of gravel particles flowing on a fixed bed. They compared the computational result with experimental results and showed the validation of their APM model.

In this study, APM method applied for gravel bed with a wide distribution of grain-size of one order of magnitude in order for better understanding the mechanism of the bed load. And the vertical sorting mechanism of the bed structure was analyzed and discussed on the basis of the data of particles movement for each grain size obtained by this numerical computation.

2. Numerical methods

The numerical simulation model of Fukuoka et al. [1)] is used for this investigation. Fluid motions were simulated using the governing equations of a single-fluid model for the solid-liquid multiphase flows in the Eulerian approach. Particle motions were computed by the Lagrangian approach using DEM method. The free-surface variation was simulated using the continuity equation of the fluid volume fraction based on the volume-of-fluid (VOF) method. The particle motion was simulated using the momentum and angular momentum equations as a rigid body. The parameters used in the simulation re shown in Table 1.

Table. 1 Simulation parameters.

cell size	0.00375	m
Time step for the fluid simulation	5×10^{-5}	s
Time step for the particle simulation	2.0×10^{-6}	s
Density of water	1,000	kg/m^3
Density of particles	2,650	kg/m^3
Fluid viscosity	8.9×10^{-4}	Pa・s
Smagorinsky constant	0.173	-
Elastic modulus	5×10^{10}	Pa
Poisson's ratio	0.33	-
restitution coefficient	0.7	-
Friction Coefficients	0.5	-

Table. 2 Experimental conditions.

Water discharge Q	3.99	m^3/s
Water depth	0.93	m
Froude number	1.39	-
mean bed elevation	0.26	m
Packing depth	0.31	m
bed slope	1/30	-

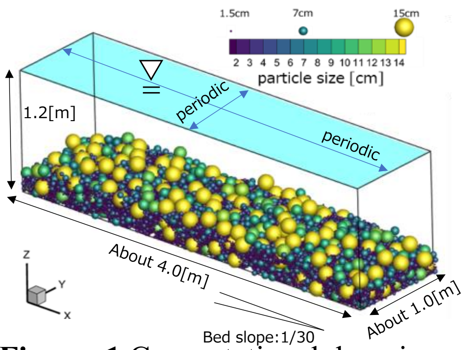


Figure. 1 Computational domain and boundary conditions.

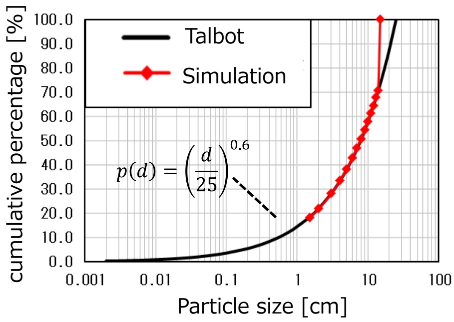


Figure. 2 Particle size distribution.

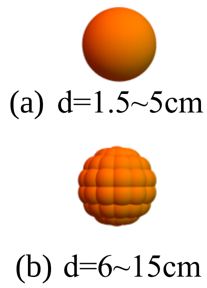


Figure. 3 Particle shape.

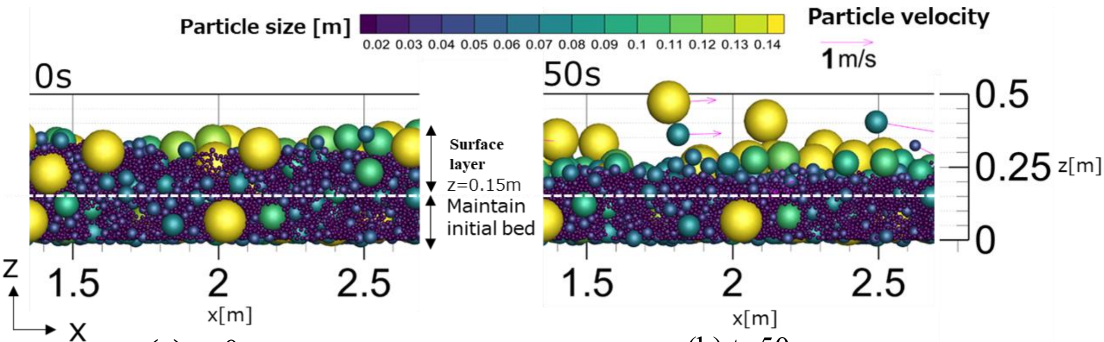
3. Experimental conditions

Figure 1 shows the Computational domain, coordinate axes and boundary conditions. The numerical channel is 4.01 m long, 1.01 m wide with a bed slope of 1:30. The periodic boundary condition was applied to the longitudinal and transverse boundaries. Figure 2 shows the particle size distribution used in the numerical experiment. The particle size distribution is set based on the Talbot type and has a spread of one order, d=1.5~15 cm. Figure 3 shows the particle shapes used in the numerical analysis. In order to speed up the calculation, a single sphere shape was used for particle sizes d=1.5~5 cm, as shown in Figure-3(a), and for particle sizes d=6~15 cm, several small spheres without gap were connected to form a spherical shape, as shown in Figure-3(b).

The particles were packed randomly to make a riverbed. The Initial water level was set to 1.2m. Table 2 shows the experimental conditions. The mean bed elevation was calculated by the bed particles with velocity less than 0.05 m/s. The water depth and the Froude number were calculated by spatially averaged over the entire simulation area.

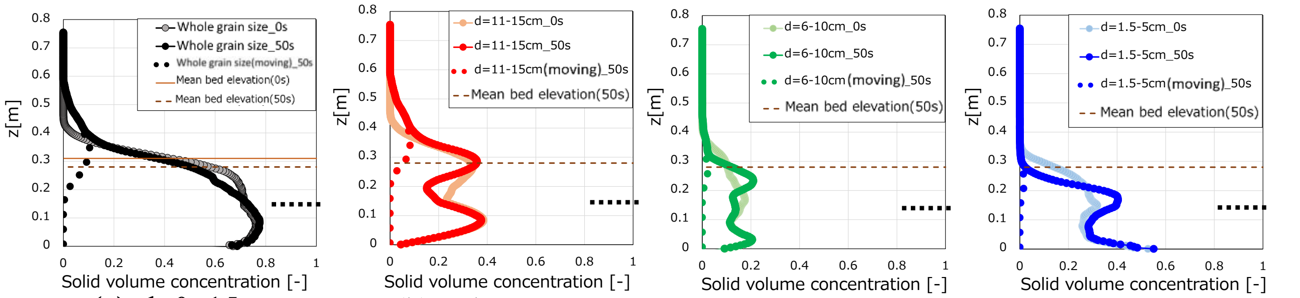
4. Simulation Results

Figure 4 shows gravel bed structures on the vertical plane at t=0 and 50s. From the comparison of Figures. 4 (a) and 4 (b), it can be seen that vertical sorting of particles occurs in the surface layer of the riverbed and the particles below z=0.15 m does not shift at all. Figure-5 shows the temporal variation of the vertical distribution of the solid volume concentration, spatially averaged over the entire analysis area in the x-y plane. Figures 5 (b), (c) and (d) show the solid volume fractions of large, medium and small particles, respectively. In Figure 5(b), the volume fraction around z = 0.20 m is particularly reduced. This is due to the vertical upward displacement of large particles, which were initially buried in the surface layer. On the other hand, the small particles shown in Figure 5(d) drop into the pore spaces between the large and medium particles and are displaced vertically downward. As a result, the volume fraction of the layer above z=0.20m decreases, and the volume fraction below



(a) t=0 s (b) t=50 s

Figure. 4 Time change of riverbed structure.



(a) d=0~15cm (b) d=11~15cm (c) d=6~10cm (d) d=1.5~5cm

Figure. 5 Vertical distribution of solid volume concentration.

z=0.20m increases. In Figure 5(c), the volume fraction of medium particles at z = 0.10~0.20m and above z = 0.30m decreased due to both the rise of buried particles and the drop of exposed particles.

Next, the entrainment and deposition rate, which are related to the armoring of the mixed particles are calculated. Now consider an arbitrary control volume (C.V.), and the continuity equation for the solid phase is ,

$$\frac{\partial V_s^k(x,y,z,t)}{\partial t} = Q_{in}^k(x,y,z,t) - Q_{out}^k(x,y,z,t) \tag{1}$$

where V_s:volume of solid phase [m^3],Q_{in}: volume of solid phase flowing into C.V. per unit time [m^3/s] and Q_{out}: volume of solid phase flowing out of C.V. per unit time [m^3/s]. k indicates particle numbers.

If we divide the volume of the solid phase V_s into the volume of moving particles V_{sm} and the volume of bed (stationary) particles V_{sb}, and consider the continuity equation, we can write the following for V_{sm} and V_{sb} respectively.

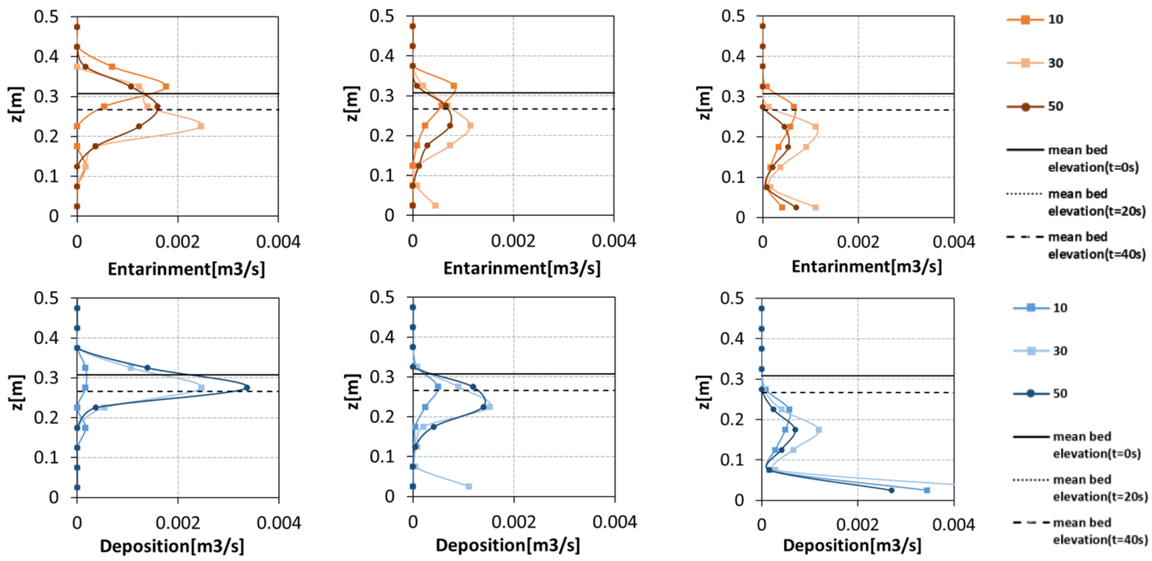
$$\frac{\partial V_{sm}^k(x,y,z,t)}{\partial t} = E^k(x,y,z,t) - D^k(x,y,z,t) + Q_{in}^k(x,y,z,t) - Q_{out}^k(x,y,z,t) \tag{2}$$

$$\frac{\partial V_{sb}^k(x,y,z,t)}{\partial t} = D^k(x,y,z,t) - E^k(x,y,z,t) \tag{3}$$

$$V_s^k(x,y,z,t) = V_{sm}^k(x,y,z,t) + V_{sb}^k(x,y,z,t) \tag{4}$$

where D: deposition rate [m3/s], E: entrainment rate [m3/s]. D and E are the volume of particles deposited from moving particle to bed particle and the volume of particle detached from bed particle to moving particle within the C.V. per unit time, respectively.

Figure.6(a)~(c) shows the vertical distributions of the entrainment and deposition rates for respective particle sizes (d=1.5,6-9,15 cm). The C.V. was set as follows: channel width (4.02 m) in the longitudinal direction, channel length (1.02 m) in the transverse direction, and 5 cm each in the vertical direction. And the C.V. to which each particle belongs is determined from the position of the particle center of gravity. The entrainment and deposition judgement are made for each particle every 10 s.



(a)d=15cm (b)d=6-9cm (c)d=1.5cm

Figure. 6 Vertical distributions of Entrainment and Deposition rate

Entrainment was evaluated when the particle velocity was greater than 5 cm or when the C.V. belonging to the particle at the time of judgement was different from the C.V. before 10 s. Deposition was evaluated when the particle velocity was less than 5 cm or when the C.V. belonging to the particle at the time of judgement was different from the C.V. before 10 s. The amount of entrainment (or deposition) is given by each particle volume for the C.V. to which it belonged before 10s.The volume of entrainment and deposition in each C.V. was divided by the observation time of 10 s to obtain E and D as values per unit time.

In terms of the vertical distribution of D, the larger the grain size is, the higher the vertical position of deposition occurs, and the temporal change in vertical distribution is relatively small for each particle size. In the vertical distribution of E, as in the vertical distribution of D, the larger the particle size is, the higher the particle detachment occurs. In particular, for all grain sizes, the Entrainment occurs at higher vertical positions at t=0-10s. Thus, for each particle size, as the water flow began, the surface particles were detached, and when moving particles were deposited, the large particle size group stayed at a higher position on the surface, and the small particle size group was deposited at a lower position, resulting in formation of vertical sorting.

In particular, at t=40-50s, the vertical distributions of E and D tend to be similar for each grain size. Therefore, from equation (3), the time variation of the vertical distribution of the volume of bed particles for each grain size becomes small, and the bed structure reaches an equilibrium state.

5. Conclusion

A numerical movable-bed experiment of the mixed particle size was conducted to investigate the vertical distribution of the entrainment and deposition rate, and to better understand the formation mechanism of vertical sorting.

6. Acknowledgment

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References

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