# Effects of particle shapes and sizes on fundamental movement processes of particles and sediment transport rates in gravel streams

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*Gravel-bed rivers are composed of particles with a large variety of sizes and shapes. Large particles would resist against flood flows, but are picked up and move intermittently. We estimate fundamental movement processes of particles with different sizes and shapes and the sediment transport rate based on fundamental movement processes by numerical movable-bed simulations. The effect of particle shapes on movement processes of large particles is greater than that of small particles. Therefore, the effect of different particle shapes on sediment transport rate appears conspicuously in large particles.*

**Key Words:** *gravel bed river, particle shape, particle size, fundamental movement process, sediment transport rate, numerical movable-bed channel.*

## 1. Introduction

Gravel-bed rivers consist of a large variety of particle sizes and shapes. Large particles at the bed resist against flood flows, but are picked up and move intermittently. These particle motions are different from those in sandy rivers where most of particles tend to move continuously. The sediment transport rate of mixed particles is given by Eq.(1) based on fundamental processes such as pick-up rate and step length of particle with diameter $d_{ij}$.

$$q_{Bij} = f(d_{ij}) \frac{A_3 d_{ij}{}^3}{A_2 d_{ij}{}^2} \cdot \Lambda_{ij} \cdot p_{s_{ij}} \tag{1}$$

Where $i$: particle size , $j$ particle shape, $p_s$ : pick-up rate, $\Lambda$ : step length, $A_3 d^3$ : particle volume, $A_2 d^2$ : particle area projected from above, $f(d_{ij})$: area ratio of $d_{ij}$.

To estimate sediment transport rates in gravel-bed rivers, fundamental movement processes of particles with different sizes and shapes have to be investigated. Fukuoka et al. (2014) developed a numerical movable-bed channel which could simulate three-dimensional motions of flows and gravel

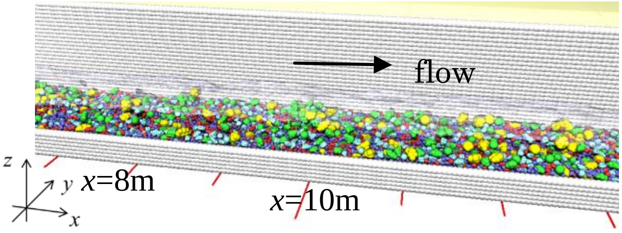


Fig.1 Numerical movable-bed channel.

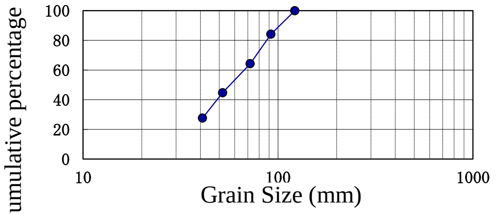


Fig.2 Particle size distribution.

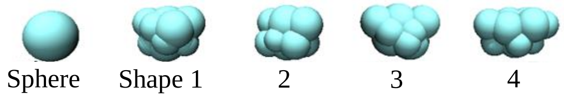


Fig.3 Shape of gravels particles.

Table 1. Shape factor and length of gravel particles.

| Shape No. | Sphere | Shape 1 | Shape 2 | Shape 3 | Shape 4 |
|---|---|---|---|---|---|
| a: Longest | 1 | 1.26 | 1.29 | 1.36 | 1.49 |
| b: Intermediate | 1 | 0.98 | 1.06 | 0.99 | 0.89 |
| c: Shortest | 1 | 0.88 | 0.81 | 0.78 | 0.76 |
| Shape Factor | 1 | 0.79 | 0.69 | 0.67 | 0.66 |

particles with different shapes and sizes (see Fig.1). In this paper, numerical movable-bed simulations were conducted under three conditions of spheres, gravel particles and mixed particles, and sediment transport rates and fundamental processes were measured to estimate respective effects of the own particle shape and surrounding particles on sediment transport.

## 2. Numerical computation method

Particle motions were simulated in the Lagrangian method as the rigid-body and fluid motions were in the Eulerian method. To take into account the effect of the solid phase on the liquid phase, fluid motions were simulated by the governing equations of one-fluid model for solid-liquid flows. Particle contacts were computed by distinct element method (DEM). Fluid dynamic forces on particles were computed directly by integrating the forces on a particle. Gravel particles with different shapes and sizes were made by the superposition of small spheres. The validation of the numerical computation method was checked by distributions of velocities and concentrations of real gravel particles measured in a large open channel flow(Fukuoka et al., 2014).

## 3. Simulation conditions

In the numerical simulations, we used five particle sizes(40, 50, 70, 90, 120 mm) (see Fig.2), and four gravel particle shapes (see Fig.3). Particles of 40, 50 and 70 mm were categorized as small particles, 90 and 120 mm as large particles. The diameter of gravels was defined by a diameter of spheres having the same volume. This means that $A_3 d^3$ of Eq (1) is the same value for every particle sizes in this stady. It is common to use the shape factor (Eq.(2)) which consists of long, middle and short axes of particles.

$$S.F. = \frac{c}{\sqrt{ab}} \tag{2}$$

Where a: long axis, b: middle axis, c: short axis. The shape factors are close to 1 as particle shapes are alike to the sphere shape. Shape No.1 is the closest to the sphere, and other gravel shape factors are almost similar values (see Table1). Particles were packed in numerical movable-bed simulation channels (length is 15 m, width 1 m, depth 1 m and bed slope 1/20). A water discharge of 0.5 $m^3/s$ was supplied at the upstream end of the channel, and the zero pressure condition was set at the downstream end. The equal amount of water and particle volumes discharging out from the channel were supplied at the upstream end of the channel. Sediment transport rate and movement processes of particles were measured in sections from $x$=2 m to $x$=12 m.

## 4. Transport rates of particles with different shapes and sizes

Figure 4 and 5 show average sediment transport rates measured in 2m and 60 seconds intervals with respect to space and time. To compare sediment transport rates of every particle with that mixed particles, transport rates of spherical particles and gravel particles were multiplied by 1/5, and by 4/5 respectively. Transport rates of large particles become greater than that of small particles. Moreover, sediment transport rate became large as particle shapes were close to the sphere. Sphere transport rates in mixed particles were smaller than that of sphere particles only due to the increase in engagement effects of surrounding particles. In other words, the particle movement was affected by not only own particle shape, but also surrounding particle shapes.

## 5. Fundamental movement processes of particles

Fundamental movement processes (pick-up rate, step length and particle projected area) of sediments with different sizes and shapes are estimated from results of the numerical movable-bed simulation. Effects of particle sizes and shapes on fundamental movement processes and sediment transport rates were discussed below.

The $A_2d^2$ is defined as a projected area measured from above at the time just before particles are picked up. Figure 6 shows dimensionless average areas of particle from above just before picking up a particle. They were nondimensionalized by the projected area of the equivalent size sphere ($\pi d^2/4$). We assume that particles are picked up when the velocity of particles exceeds 0.05m/s. Figure 7 shows the pick-up process of particles. The $A_2d^2$ becomes large as the particle shape deviates from a sphere shape, because particles tend to rest stably by directing flat plane toward the top and lowering a center of gravity (see Fig.7(a)). The dimentionless $A_2d^2$ of large particles is larger than that of small particles. It is reason why large particles were not affected much by surrounding particles compared with small particles.

Pick-up rates of particles in every shapes and sizes were evaluated by the ratio of area which some particles picked up in a unit time had occupied on the bed surface to the area which the same particles occupied on the bed surface. Figure 8 shows averaged pick-up rate of particles in every sizes and shapes. Pick-up rates of small particles became smaller as particle shapes deviate from a sphere, but those of large particles took almost constant values. Pick-up rates did not greatly vary in comparison with $A_2d^2$. In short, pick-up rates were mainly affected by the placement of the surrounding particles. Therefore, it is hard to recognize conspicuously the effect of particle shape on pick-up rate.

The step length was defined as the distance that particles move from pick-up to deposition. Step lengths of large particles were unable to be measured within length of the numerical channel. Figure 9 shows step lengths of small particles nondimensionalized by particle diameters. The step length became larger as particle shapes differed much from a sphere shape. Rolling particles had large projected area to the flow and hard to stop as particle shapes deviated from a sphere. However, No.3 and 4 particles do not show such a characteristic. Therefore, it is difficult to evaluate effects of particle shapes on step lengths by only using the conventional shape factor (Eq.(2)). Figure 10 shows the relationship between the step length and the smallest projected area of particles during moving periods. Dimensionless step lengths are small except spheres as particles are small and have smallest projection areas. Then, rolling particles are easy to stop, because projected areas in the streamwise direction

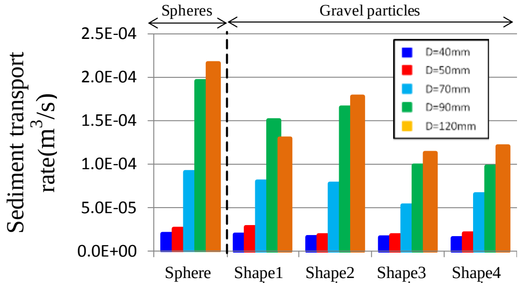


Fig.4 Sediment transport rate in sphere and gravel.

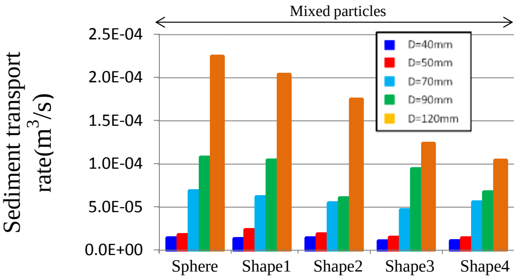


Fig.5 Sediment transport rate in mixed conditions.

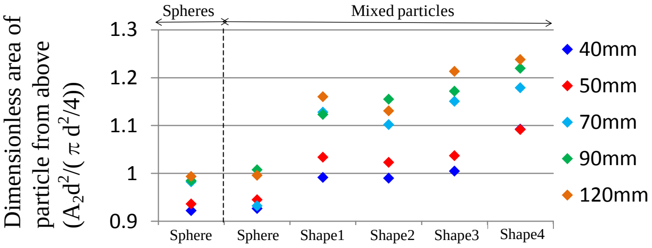
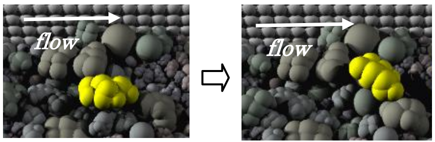


Fig.6 Average area of particle measured from above, just before picking up particles.



(a) Stop (b) Pick-up

Fig.7 An example of picked up particle.

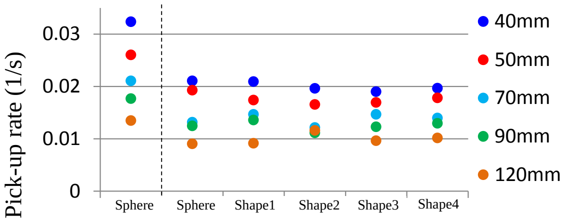


Fig.8 Pick-up rate with respect to particle shapes and sizes.

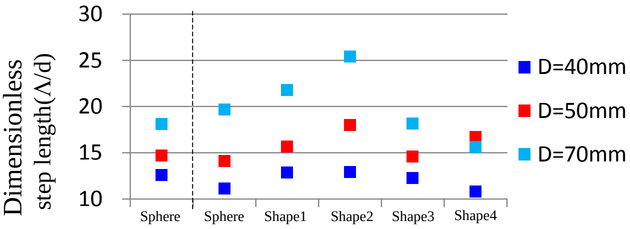


Fig.9 Step length with respect to particle shapes and sizes.

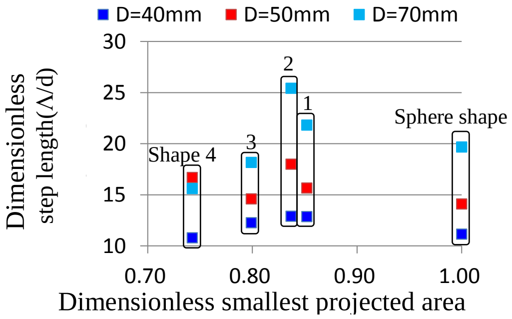


Fig.10 Comparison between step length and smallest projected area.

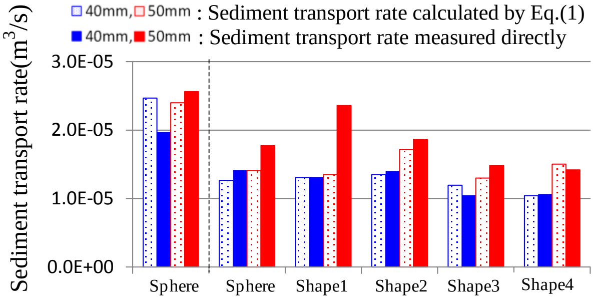


Fig.11 Comparison between Eq.(1) and sediment transport rate.

become small.

Sediment transport rates of Eq.(1) calculated using results of fundamental movement processes were compared with those of numerical movable-bed simulations(see Fig.11). It was confirmed that Eq.(1) reproduced well sediment transport rates of each particle sizes and shapes measured directly in the numerical channel.

Finally, we investigated further the relationship between sediment transport rate and fundamental movement processes (step length, pick-up rate and $A_2d^2$). In both small and large particles, $A_2d^2$ become large as particle shapes varied from the sphere, but the pick-up rate did not greatly change in comparison with $A_2d^2$. In short, the number of picked up particles per unit time ($p_s/ A_2d^2$) become small as particle shapes differ from the sphere. The step length becomes large as particle shapes are different from the sphere. The product ($(P_s /A_2d^2)\times\Lambda$) of the number of picked up particles and step length is affected by the number of picked up particles ($p_s/ A_2d^2$) than step length ($\Lambda$) , because of the effect of particle shapes. Therefore, sediment transport rates are small as particle shapes vary from the sphere. In regard to large particles, effects of the bottom roughness on particle motions were relatively small compared to own particle shapes. Therefore, the difference in particle shapes on sediment transport rates appears markedly on large particles. Sediment transport rates of small spheres and large spheres were maximum 1.3 times larger and 2 times larger than those of gravel particles, respectively (see Fig.5). Fundamental movement processes are different in every sizes and shapes. Therefore, to assess direct effects of particle shapes and sizes on fundamental movement processes are important for estimations of transport rates of mixed sediments.

## 6. Conclusions

The applicability of sediment transport equation(1) was checked with the fundamental movement processes measured in the numerical channel. Eq.(1) reproduced well sediment transport rates of each particle sizes and shapes measured directly in the numerical channel. However, they are different in every sizes and shapes. From the present investigations, it was found that the assessments of direct effects of particle shapes and sizes on fundamental movement processes are important for more accurate estimations of mixed sediments transport rates.

## References

[1] Fukuoka, S., Fukuda, T. and Uchida, T. (2014). Effects of sizes and shapes of gravel particles on sediment transports and bed variations in a numerical movable-bed channel., Advances in Water Resources, Volume 72, p. 84-96.