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Flume experiments and numerical simulation focused on fine sediments in stony debris flow

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Abstract

In stony debris flow, it has been considered that the gravels move like laminar flow, but the interstitial water behave as turbulent flow. Moreover, fine particles can behave with the interstitial water as fluid and many previous studies call this process of fine sediment as shifting solid phase to fluid phase, “phase-shift”. Phase-shifted sediment affect the fluidity of debris flow. Therefore, it is necessary to consider fine sediments behavior to describe run-out processes of debris flow. However, the hydraulic conditions that fine sediment can behave as a fluid are not well understood. Here, we analyzed this hydraulic condition through flume experiments and numerical simulations. We examined effects of grain size distribution on the equilibrium sediment concentration, which has been defined as the sediment concentration that in which there is neither erosion nor deposition on the experimental flume bed. We found that for the same hydraulic conditions the equilibrium sediment concentration differed due to variations in the grain size distribution. Based on these experimental results, we tested the following three models for describing the conditions that fine sediment can behave as a fluid. First, we fixed fine sediment concentration in interstitial fluid (Model 1), then, we fixed the maximum diameter of phase-shifted sediment (Dc) (Model 2). In Model 3, Dc is assumed to be variable according to the ratio of the friction velocity to the settling velocity of Dc. As the result, the experimental relationship between grain size distribution and longitudinal gradient of deposited sediment surface under steady-state condition can be described by using the Models 2 and 3, but Model 1 could not describe.

Keywords: debris flow, simulation model, fine sediments

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1. Introduction

Debris flow is a mixture of water and high concentrations of sediment. It can cause serious damage to downstream houses and human lives. It is important to predict the area of inundation and depth of sedimentation for mitigating debris-flow disasters. Numerical models tested with flume experiments can be used to help make these predictions. In stony debris flow, it has been considered that the gravels move like laminar flow, but the interstitial water behave as turbulent flow (Takahashi, 2004). Moreover, fine particles mixed with the interstitial water can behave as a fluid (Takahashi, 1977). We call the process of fine sediment shifting from a solid phase to a fluid phase, “phase-shift”. Phase-shifted sediment affects the fluidity of debris flow. Therefore, it is necessary to consider the effects of fine sediments on the run-out processes of debris flow.

In the previous numerical analyses considering phase-shift sediment, a method of setting the interstitial fluid density to a certain fixed value larger than the pure water and a method of setting the maximum diameter of phase-shifted sediment (Dc) (Nishiguchi, 2014) has been used. It is necessary to set the interstitial fluid density and the particle diameter of Dc at which phase-shift occurs so that the calculation result fits the actual result. On the other hand, studies using flume experiments have shown that the grain size distribution affects the equilibrium concentration of debris flow (Hasegawa et al., 2013) and Dc is larger as the ratio of friction velocity of debris flow to

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settling velocity of Dc (Nakatani et al., 2018). However, the hydraulic conditions that fine sediment can behave as fluid are not well understood. Here, we analyzed this hydraulic condition through flume experiments and numerical simulations.

2. Hypotheses

2.1. Hypotheses about phase-shift

It is assumed that the phase-shift of the fine sediments occurs because some of the sediment in the debris flow is incorporated into the interstitial fluid by the turbulent stress of the interstitial fluid. In this study, we defined that phase-shifted sediment is "fine sediment". The maximum diameter of the fine sediment is "Dc", and we assume that all sediment smaller than Dc flows as part of the interstitial fluid. Then, the interstitial fluid density of the debris flow is expressed by the equation (1).

$$\rho_m = \sigma \frac{C_f}{1-C_c} + \rho_w \left(1 - \frac{C_f}{1-C_c}\right) \tag{1}$$

$$C = C_f + C_c \tag{2}$$

where ρ_m is interstitial fluid density of the debris flow, σ is mass of sediment, C_f is fine sediment concertation, C_c is coarse sediment concertation, ρ_w is water density, C is total sediment concertation.

We use three models to describe sediment phase shift. In Model 1, the interstitial fluid density, i.e., the fine sediment concentration in interstitial fluid, assumed to be constant, regardless of grain size distribution of the debris flow. In Model 2, the maximum diameter of phase-shifted sediment (Dc) remained constant in time and space. This assumption is based on the concept proposed by Nishiguchi (2014). Thus, the interstitial fluid density varied with grain size distribution and total sediment (coarse and fine sediment) concentration. In Model 3, we assumed that Dc varies with the ratio of the friction velocity of the debris flow to the settling velocity of Dc. Dc increases as the ratio of the friction velocity of the debris flow to the settling velocity of Dc increases (Nakatani et al., 2018). Thus, in Model 3, the interstitial fluid density varied with not only grain size distribution and total sediment concentration, but also hydraulic condition. This relationship is described by the following three equations:

$$u_* = a\, w_s \tag{3}$$

$$u_* = \sqrt{g\ h\ tan\theta_w} \tag{4}$$

$$w_s = \left(\sqrt{\frac{2}{3} + \frac{36\nu^2\rho}{sgD_c^3(\sigma-\rho)}} - \sqrt{\frac{36\nu^2\rho}{sgD_c^3(\sigma-\rho)}}\right)\sqrt{\left(\frac{\sigma}{\rho} - 1\right) gD_c} \tag{5}$$

where u_* is friction velocity, α is coefficient, w_s is settling velocity, g is gravitational acceleration, h is flow depth, $tan\theta_w$ is water surface gradient, ν is kinematic viscosity coefficient, σ is mass density of sediment.

2.2. Numerical simulation model

We used the debris-flow simulator, Kanako LS (Uchida et al., 2013) to describe the relationship between grain size distribution and longitudinal gradient of deposited sediment surface of flume experiments under steady-state condition (see section 3.1). We used the three different models to set the interstitial fluid density in Kanako-LS. In this numerical simulation model, the equilibrium concentrations of the debris flow and immature debris flow are calculated by the equations (6) and (7).

$$C_\infty = \frac{\rho_m tan\theta_w}{(\sigma-\rho_m)(tan\emptyset - tan\theta_w)} \tag{6}$$

$$C_\infty = 6.7\left\{\frac{\rho_m tan\theta_w}{(\sigma-\rho_m)(tan\emptyset - tan\theta_w)}\right\}^2 \tag{7}$$

where C_∞ is equilibrium concentration, $\emptyset$ is friction angle.

3. Methods

3.1. Experiment and analysis methods

We analyzed the results of previous debris-flow flume experiments (Shima et al., 2014). The experimental flume is a straight rectangular channel with a width of 10 cm and a length of 7 m. The gradient of the flume can be adjusted from 5 degrees to 15 degrees. Coarse sediments are supplied from the upstream end of the flume by a hopper and water and fine sediments are circulated by a pump for circulation to constantly supply water and sediments (Fig. 1a). A plate with a height of 20 cm is installed at the downstream end of the flume. Moreover, the supplied sediment was deposited upstream from the plate, and we measured water surface gradient to clarify the longitudinal gradient of the deposited sediment surface was measured by the ultrasonic sensor. Using 4 types of mixed particle size materials (fig. 1b), 56 cases with different flume gradient (5-15 degrees), flow rate (0.75-2.5 ℓ /sec) and sediment concentration (6.2-29.8 %) were conducted.

In this study, we assumed that once the deposited sediment surface became steady-state condition, the sediment concentration in debris flow became the equilibrium concentration that in which there is neither erosion nor deposition on the experimental flume bed. So, we hypothesized the sediment concentration of debris flow can be calculated using the equilibrium concentration theories of (1), (2), (6) and (7). We set C_f to describe relationship between total sediment concentration and water surface gradient using equations (6) and (7).

3.2. Calculation conditions

Calculation conditions, such as supply flow rate, grain size distribution of materials, supply sediment concentration, flume gradient, width and length, were set to the same values as the experimental conditions. The simulation was run until the plate installed at the downstream end of the flume filled up and the flow upstream stabilized. Furthermore, reproducibility was evaluated for each model by comparing the observed and calculated longitudinal gradient of the deposited sediment surface under steady-state condition.

We set fluid density, Dc-diameter, and α in equation 3 set for Models 1, 2 and 3, respectively. We used several values for each parameter (Table 1).

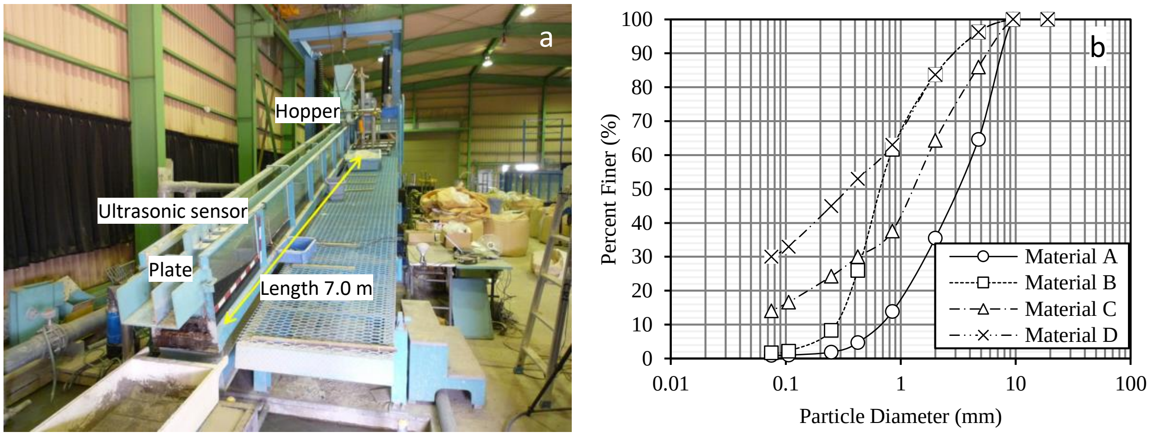

Fig. 1. (a) Grain size distribution and (b) flume of the experiments of Shima et al. (2014)

Table 1. Calculation conditions

Model	Method	Setting value
1	fixing interstitial fluid density (ρ_m)	ρ_m =1.05, 1.10, 1.15 g/cm^3
2	fixing the maximum diameter of phase-shifted sediment (Dc)	Dc= 0.2, 0.425, 0.9 mm
3	Varying Dc according to the ratio of friction velocity of flow to settling velocity of Dc (α)	α =3

4. Results

4.1. Analysis results of experiments

The interstitial fluid density estimated by equations (6) and (7) increased from Material A to Material D (Fig. 2). Dc estimated by grain size distribution of the materials, equations (1) and (2) roughly decreased from Material A to Material D (Fig. 2). However, the estimated values of the interstitial fluid density and Dc fluctuated even same material. This result shows that the condition of the phase-shift does not depend only on the grain size distribution of the debris flows.

Next, the relationship between Dc and the ratio of friction velocity during experiment to settling velocity of Dc is shown in Fig. 3. Dc tends to decrease as the ratio of the friction velocity to settling velocity of Dc is larger, and the friction velocity and settling velocity of Dc are distributed in the range of approximately 2 to 13. Furthermore, in the range where Dc is larger than 0.3 mm, the ratio of the friction velocity to settling velocity of Dc is 2 to 4 regardless of grain size distribution of materials.

4.2. Calculation results

As a result of calculation in Model 1, the gradient of deposited sediment surface in the equilibrium state is roughly 0.8 to 1.6 times (correlation coefficient 0.29) with respect to the experiment result in the case of ρ_m=1.05 g/cm^3, 0.7 to 1.5 times (correlation coefficient 0.61) in the case of ρ_m=1.10 g/cm^3, 0.6 to 1.3 times (correlation coefficient 0.54) in the case of ρ_m=1.15 g/cm^3 (Fig.4). When the density was set to ρ_m=1.10 g/cm^3, the experiment result could be relatively well reproduced by calculation, however it is not possible to express the difference in the grain size distribution of debris flows, so the concentration of fine sediments can not be calculated appropriately.

Second, as a result of calculation in Model 2, the sediment gradient in the equilibrium state is roughly 1.0 to 1.3 times (correlation coefficient 0.63) with respect to the experiment result in the case of Dc=0.2 mm, 0.9 to 1.2 times (correlation coefficient 0.91) in the case of Dc=0.425 mm, 0.7 to 1.1 times (correlation coefficient 0.78) in the case

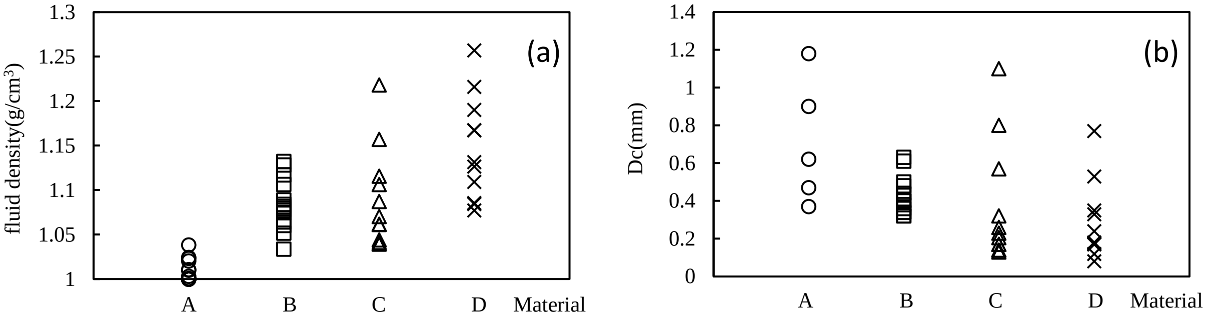

Fig. 2. (a) Estimated result of interstitial fluid density; (b) estimated result of Dc based on analysis results of experiments

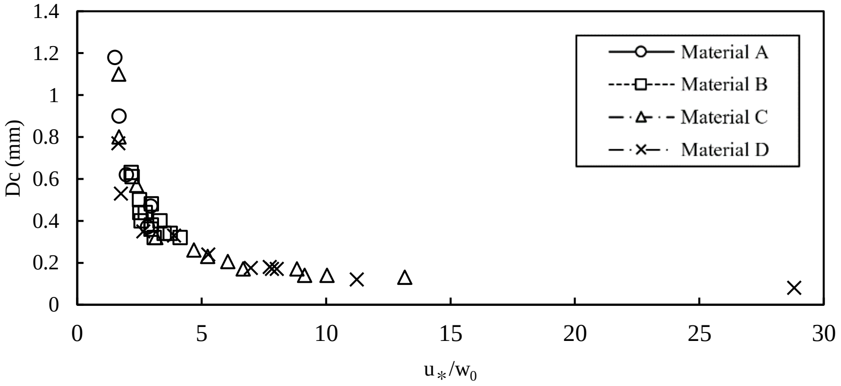

Fig. 3. The relationship Dc and the ratio of friction velocity to settling velocity of Dc

of Dc=0.95 mm (Fig.5). When the density was set to Dc=0.425 mm, the experiment result could be well reproduced by calculation.

Third, in Model 3, the gradient of deposited sediment surface in the equilibrium state is roughly 0.9 to 1.2 times (correlation coefficient 0.91) with respect to the experiment result (Fig. 6). Model 3 was able to reproduce the experiment result better by calculation.

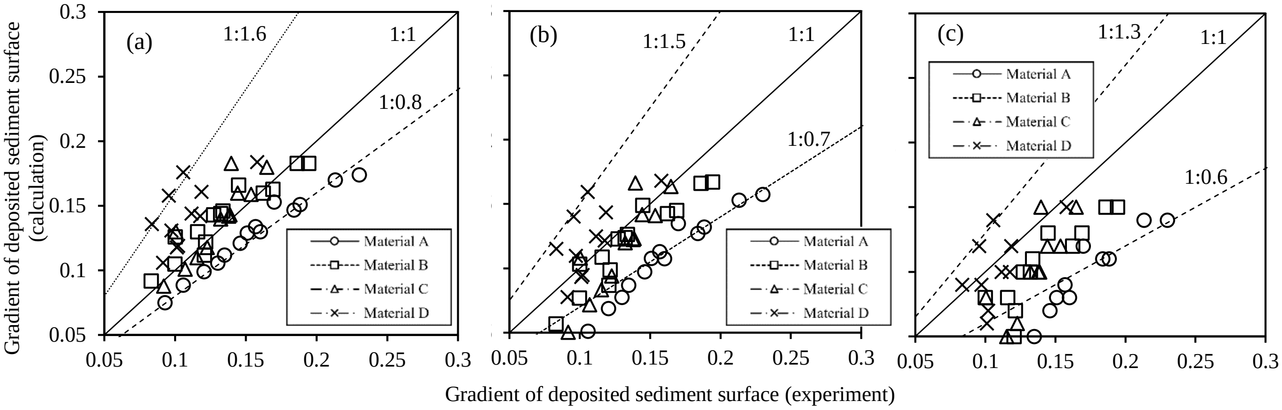

Fig. 4. Relationship between observed and calculated longitudinal gradient of deposited sand surface using Model 1: (a) ρ_m=1.05 g/cm^3; (b) ρ_m =1.10 g/cm^3; (c) ρ_m =1.15 g/cm^3

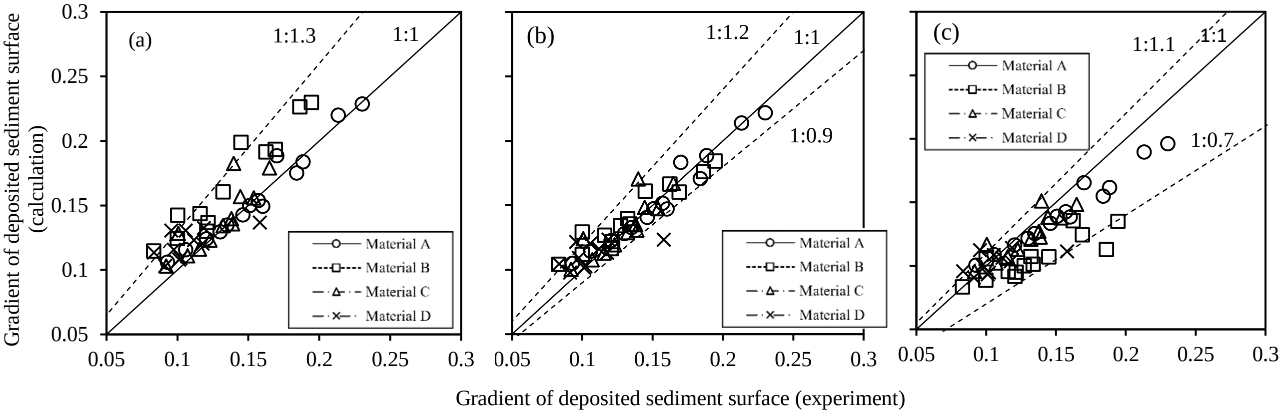

Fig. 5. Relationship between observed and calculated longitudinal gradient of deposited sand surface using Model 2: (a) Dc=0.2 mm; (b) Dc=0.425 mm; (c) Dc=0.95 mm

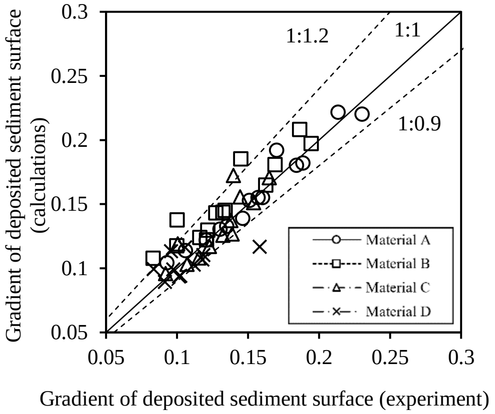

Fig. 6. Relationship between observed and calculated longitudinal gradient of deposited sand surface using Model 3

5. Conclusion

We tested following three models for describing condition that fine sediment can behave as fluid through the comparison between results of flume experiment and numerical simulation. First, we assumed constant fine sediment concentration in interstitial fluid (Model 1). Then, we fixed the maximum diameter of phase-shifted sediment (Dc) (Model 2). In Model 3, Dc is assumed to be variable according to the ratio of the friction velocity to the settling velocity of Dc. As the result, the experimental relationship between grain size distribution and longitudinal gradient of deposited sediment surface under steady-state condition can be described by using the Models 2 and 3, but Model 1 could not describe. In particular, Model 3 is expected to be versatile simulation model because it does not depend on the change in Dc due to the scale and the particle size of debris flow.

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