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Long travel distance of landslide-induced debris flows

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Abstract

Large-scale landslides often induce debris flows and cause serious damage to humans. These events typically have water contents in the landslide mass less than 60 % and sediment concentrations more than 40 %. In spite of high sediment concentrations, landslide-induced debris flows can runout long distances. For large-scale stony debris flows, many previous studies have suggested that coarse gravels behave as a solid phase, whereas fine particles with interstitial water can behave as a fluid phase. We hypothesized this fine sediment might be one of the key processes controlling the long travel distances of landslide-induced debris flows. Here we assumed that the maximum diameter of the fine sediment behave as a fluid phase should vary depending on the friction velocity of the debris flow and the settling velocity of sediments. We conducted detailed field surveys for four landslide-induced debris flows and applied our numerical simulation model to describe the travel distance of the debris flows. Our results show that, if we set the ratio of the friction velocity of debris flow to the settling velocity of sediments around 1 to 4, the simulated travel distance agreed well with our studied four debris flows. We also confirmed that, while the total volume or mean sediment diameter of debris flows varied between study cases, the variability of ratios was small. We believe that our new method and the information it provides, may be helpful for predicting the future risk from the landslide-induced debris flows.

Keywords: debris flow, numerical simulation, travel distance; fine sediment

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1. Introduction

Debris flows induced by large-scale landslides have sometimes runout long distances (e.g., Nishiguchi et al., 2012). Nishiguchi et al. (2011) studied the relationship between the travel distance of landslide (L) and the maximum height between landslide scar and deposited area (H) of 10 Japanese debris flows caused by deep-seated rapid (catastrophic) landslides. The ratios of H to L were ranging from 0.11 to 0.35 and smaller than that for shallow landslide and small-scale debris flows. Similar processes have been studied in the last several decades in the world (e.g., Iverson et al., 2015). These long travel distanced debris-flows have serious impacts on human life and infrastructure. Therefore, in this study, we focused these large-scale debris-flow travelled relatively long distance.

It is important to identify large debris flow hazard areas. In large-scale stony debris flows, other researches considered that the gravels move like laminar flow, but the interstitial water behaves as turbulent flow（e.g., Takahashi, 2009; Hotta, 2012）. Moreover, fine particles can behave within the interstitial water as a fluid and many previous studies call this process of fine sediment as shifting from solid phase to fluid phase (e.g., Iverson, 1997; Hotta, 2012). We refer to it as “phase-shift”. Based on this phase-shift concept, Nishiguchi et al. (2014) proposed a maximum diameter of sediments that behave like a fluid as D_c and confirmed that if we use best-fit D_c, the long travel distance of several past debris flows can be described by numerical simulations. However, the problem remains of that how to determine the parameter of D_c in the simulations given D_c should be variable in time and space, yet Nishiguchi et al. (2014) assumed D_c to be constant in their simulations.

Here we developed a program in which the maximum diameter of phase-shifted sediment is varied depending on hydraulic conditions. Also, we conducted numerical simulations for landslide-induced debris flows with long runout and verified the applicability of our model.

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2. Simulation model

2.1. Phase-shift concept

Uchida et al. (2013) assumed that sediments can be classified into two groups (fine and coarse) by sediment diameter and defined the critical diameter of the sediment (D_c) as the smallest diameter that behaves as a solid in a debris flow. That is, they proposed that sediments larger than D_c move as solids, while those smaller than D_c behave as fluids in a debris flow. Here, we have adopted this concept to describe the phase shift of fine sediment. So, we defined the solid concentration of debris flow as the concentration of the sediment larger than D_c in debris flow. Also, we defined the representative grain diameter of the solid sediment as the mean diameter of the sediment larger than D_c. In addition, we calculated the interstitial fluid density (ρ) as follows.

$$\rho = \rho_s \cdot C_f/(1-C) + \rho_w\,(1 - C_f/(1-C)) \qquad (1)$$

where C is the concentration of total sediment in debris flow, C_f is the concentration of phase-shifted sediment in a debris flow, ρ_w is pure water density and ρ_s is the solid density of the sediment.

Nishiguchi et al. (2014) assumed that fine particles can be physically suspended due to riverbed shear stress in a debris flow and showed that the settling velocities of best-fit D_c were lower than the friction velocities of the debris flow from the simulation results of past debris flows. Then, we propose that D_c varies depending on the ratio of settling velocity of D_c to friction velocity of the debris flow (α) as follows.

$$u_* > \alpha w_k \qquad (2)$$

where u_* is friction velocity of the debris flow, w_k is settling velocity of diameter of d_k and α is a coefficient. α is assumed to be constant in time and space. Here we calculated u_* for each time and space using the flow depth and longitudinal gradient as follow. This means that u_* should varied in time and space, indicating that because the D_c varied with the u_*, the D_c was also varied in time and space.

We considered friction velocity and settling velocity can be calculated from riverbed shear stress and the equation of Rubey, respectively. The friction velocity (u_*) can be calculated from riverbed shear stress as

$$u_* = \sqrt{ghI}, \qquad (3)$$

where I is the slope angle and h is flow depth of a debris flow. According to Rubey (1933), settling velocity can be expressed as follows.

$$w_k = \sqrt{sgd_k} \cdot \left(\sqrt{\frac{2}{3} + \frac{36\nu^2}{sg{d_k}^3}} - \sqrt{\frac{36\nu^2}{sg{d_k}^3}}\right) \qquad (4)$$

$$s = {\rho_s}/{\rho} - 1 \,. \qquad (5)$$

where v is kinematic viscosity of the fluid (0.01 cm^2/s), s is submerged density of sediment, d_k is particle diameter, g is gravitational acceleration. Therefore, the behaviors of debris flow should be affected by friction velocity through change of fluid density and sediment diameter of solid phase due to phase-shift of fine sediment.

2.2. Simulation model

Kanako-LS, developed by Uchida et al. (2013), can describe a variety of sediment transport processes ranging from stony debris flow to bed load transport. In the model, the equations for momentum, continuity, riverbed deformation, erosion/deposition rate, and riverbed shear stress are based on previous studies by Takahashi and colleagues (e.g., Takahashi and Nakagawa, 1991; Takahashi, 2009). Kanako-LS can describe the phase-shift effect, but D_c is assumed to be constant in both space and time, regardless of solid sediment concentrations and flow condition, such as debris flow, sediment sheet flow, or ordinary turbulent water flow.

In this study, we modified the two-particle model of Kanako-LS to a multi-particle model and introduced our assumption of determining D_c, which varies depending on hydraulic condition as described in section 2.1.

3. Method

3.1. Study sites

The study sites (referred to as Sites A–D) are located in Japan. These debris flows occurred between 2003 and 2015 (Table 1). All studied debris flows were triggered by heavy rainstorms and were caused by a deep-seated rapid landslide. These depths of landslides were around 20 m, 10 m, 45 m and 15 m at Sites A–D, respectively.

We obtained the elevations of the land surface after the debris flows from prefecture LiDAR data for Sites A, C and D at a resolution of 1 m, 1 m and 2 m, respectively. For Site B, we obtained the results of field survey measurements. The landslide volumes (including the volume of the voids) determined from these topographic data ranged from 1.9×10^4 to 2.7×10^5 m^3 and the extent of travel of the debris flow ranged from 0.6–2.1 km. Maximum erosion depths at Sites A, B and C were around 5, 7 and 3 m, respectively, whereas there were no eroded areas at Site D.

We evaluated the grain size distribution of the debris flows using sieve tests, cross-sectional photographs of the deposits, and grain size distributions obtained from field measurements. Mean diameters of debris flow sediment for Sites A–D were 251, 600, 140, 735 mm, respectively.

3.2. Data preparation for numerical simulation

The longitudinal profiles of the riverbed that we used for the numerical simulations were set based on topographic data acquired before the debris flow events. The widths of the debris flows were determined as the averages of the riverbed widths before and after the debris flow. The initial depths of the movable bed layer were determined as the maximum erosion depth. Therefore, we set this variable to 5, 7, 3, and 0 m for Sites A, B, C, and D, respectively. Site B contained one grid-type sabo dam at 280 m below the landslide that was effectively blocked by the rocks and sediments of the debris flow. Therefore, we included a closed-type sabo dam in this simulation.

We assumed that the soil and weathered bedrock of the landslide material were fully saturated by water. We used water content of the landslide mass based on measured porosity data of 0.34 and 0.49 for Site A and Site C, respectively. We did not have porosity data at sites B and C; therefore, we used the data collected for Site A.

To create the input hydrographs at the lower end of landslide scar, we used the method proposed by Nishiguchi et al. (2013), who assumed that the relationship between velocity and flow depth could be described by Takahashi's theory (Takahashi, 2004) and assumed that the longitudinal length of the debris flow at the lower end of landslide scar was the same as that of the landslide scar. Peak discharges of hydrographs for Sites A–D were estimated as about 4300, 1800, 3900 and 5400 m^3/s, respectively.

We used the particle size distribution of the debris flows measured in the field. Parameters of sediment density,

Table 1. Studied debris flows

Site	Date	Total volume of landslide *	Total volume of debris flow *	Travel distance	Distance of eroded section	Maximum erosion depth	Mean diameter of debris flow sediment
A	2003/7	43,000 m^3	31,000 m^3	1.6 km	0.8 km	5 m	251 mm
B	2007/7	19,000 m^3	19,000 m^3	0.6 km	0.15 km	7 m	600 mm
C	2015/7	91,000 m^3	91,000 m^3	1.1 km	0.25 km	3 m	140 mm
D	2005/9	520,000 m^3	272,000 m^3	2.1 km	0 km	0 m	735 mm

* including volume of the voids

Table 2. Parameters for the simulations

Parameters	Value
Water density	1,000 kg/m^3
Sediment density	2,650 kg/m^3
Volumetric sediment concentration in the riverbed	0.65
Coefficient of riverbed roughness	0.06
Coefficients of erosion rates	0.0007
Coefficients of deposition rates	0.05

Table 3. Simulation cases

Case	Diameter of fine sediments of fluid phase
Case1	All sediments are regarded as solid phase.
Case2	$\alpha = 4$ in Equation (2).
Case3	$\alpha = 1$ in Equation (2).

sediment concentration of riverbed, coefficients of erosion rates and deposition rates were set to 2,650 kg/m^3 and 0.65, 0.0007 and 0.05, respectively (Table 2).

3.3. Simulation cases

To test the effect of the magnitude of phase-shift on the propagation processes of a debris flow, we assumed three different condition of phase-shift. In Case 1, we assumed that all sediments were treated as a solid phase. In Cases 2 and 3, the ratio of settling velocity of D_c to friction velocity of the debris flow (α) were 4 and 1 in the debris flow.

4. Results

In Case 1, the simulated travel distances from the lower ends of the landslide scars to the lower ends of the debris-flow deposits were less than half of the observed travel distances (Fig. 1). The lower ends of the landslide scars are zero of x-axis in Fig.1. If we consider the phase-shift of fine sediment in Cases 2 and 3, the simulated travel distances of the debris flows increased; the distances of eroded section at Sites A, B and C also increased. As the critical ratio of settling velocity of phase-shifted sediment to friction velocity of debris flow (α) decreased, simulated travel distance of the debris flows increased.

Comparing simulated results with observations, little agreement was found when all sediments are regarded as solids (Case1). The simulated travel and erosion distances matched our observations well when α was 1 (Case3) at Sites A and B, and when α was 1 or 4 at Site C (Fig.1). Although the calculated elevation riverbed change agreed well with the observed river bed change at 0–1200 m from the landslide scar in Site D, the calculated travel distance of the debris flow was shorter than observed. This might mean that α should be set as less than 1 in Site D to reproduce the observed travel distance.

Fig.2 (a) shows the relation between mean sediment diameter of debris flow sediment and α for simulations with a good match to observations for Sites A-D and Fig.2(b) shows the relation between total volume of debris flow and α. Although the mean sediment diameter and total volume of debris flow varied between study cases, α ranged from 1 to 4 and the variability of α was small. It means that phase-shifted sediment was variable in time and space and our assumption, in which D_c varies depending on the ratio of settling velocity of D_c to friction velocity of the debris flow, was effective in predicting the particle size of phase-shifted sediment.

5. Concluding remarks

We introduced the concept that the diameter of phase-shifted sediment is variable depending on friction velocity of a debris flow, which represents riverbed shear stress of a debris flow in our numerical simulations, then examined the applicability of our method to a variety of large-scale debris flows. As a result, we showed that, although their volumes and topography were diverse, the simulated results for these debris flows reproduced well the observed erosion and deposition patterns, if we set the ratio of friction velocity of debris flow to settling velocity of sediments as around 1 to 4 to account for phase-shift effects. Thus, we believe that our new method may be helpful for predicting the future risk from the long travel distance of landslide-induced debris flows.

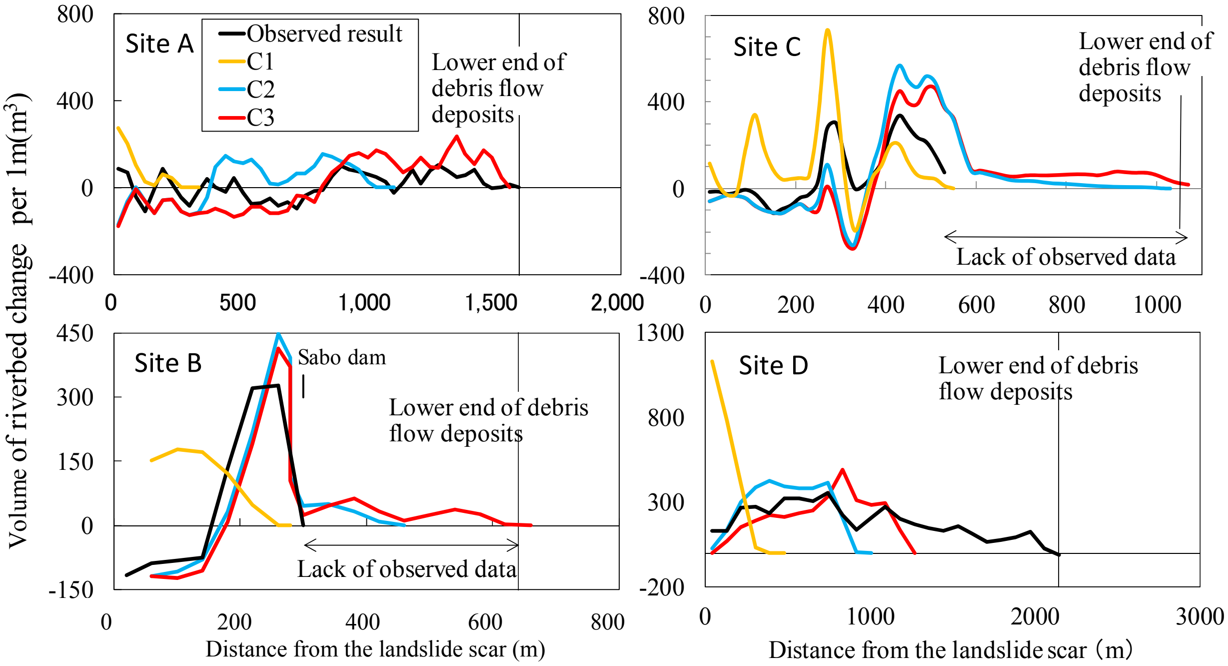

Fig. 1. Simulated Case1, Case2 and Case3 and observed riverbed change at Site A-D

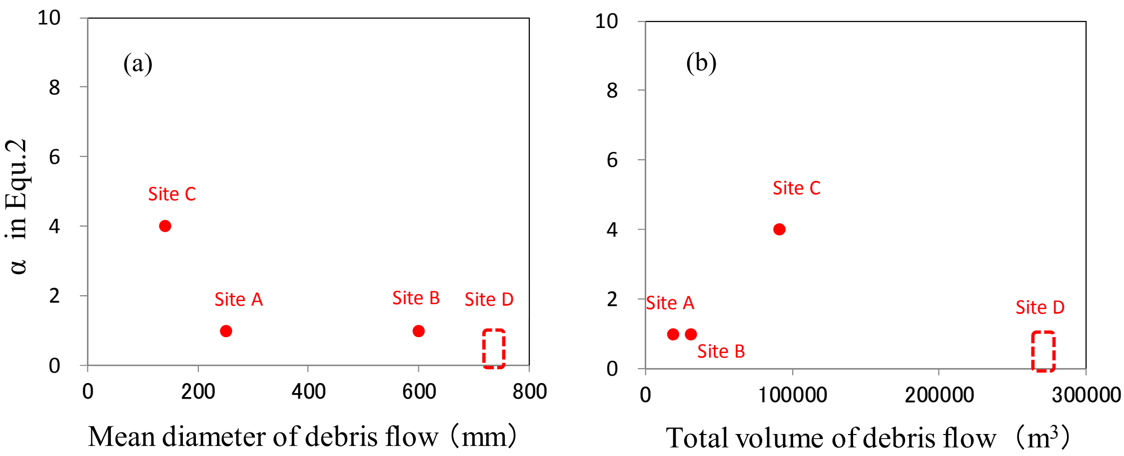

Fig. 2. (a) Relationship between mean sediment diameter of debris flows and α providing a good match to observations; (b) Relationship between total volume of debris flow and α providing a good match to observations

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