Experimental study on the effects of local sediment accumulation on a debris flow surge in a steep channel

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Abstract. Debris flow surges can terminate in a steep channel of > 15°. However, the termination process and mechanisms remain unknown. This study conducted small-scale flume experiments to investigate the effects of local sediment accumulation on debris-flow surges in a steep channel. The experiments demonstrated that local accumulation of bed sediment terminates a debris flow surge owing to abrupt changes in bed gradients and infiltration of debris flow interstitial water. Subsequently, the mass of the terminated debris-flow surge and bed sediment began to move, triggering a larger debris-flow surge. This result suggests that predicting the scale of a debris flow arriving downstream requires measuring the distribution of bed sediment in the debris flow initiation zone.

1 Introduction

Debris flow can reach a gradual channel of approximately 2–3° [1] owing to the maintenance of excess pore-water pressure inside a debris flow [2] and the dominance of particle collisional stress among the internal stresses of a debris flow [3]. However, debris flow surges do not always flow down to gentle channel sections but terminate in steep channel sections of > 15° [4]. The termination processes and mechanisms in steep channel sections remain unknown.

Bed sediment in a steep channel is often in unsaturated states before and during the descent of a debris flow [5]. A debris flow surge over unsaturated bed sediment slows down owing to the rapid dissipation of excess pore pressure through the bed sediment pore air [6]. If the bed sediment and debris flow rarely contain mud-sized grains, unsaturated bed sediment decreases the velocity of the debris flow surge because of the infiltration of debris flow interstitial water [7]. Presence of unsaturated bed sediment is one of the causes of debris-flow surge termination in steep channels.

Single rainfall events can generate multiple debris-flow surges [4]. Field observations in the Ichinosawa catchment within the Ohya landslide, Japan, showed that a debris flow surge entrained local bed sediment accumulated by preceding surges in a steep channel, resulting in an increased scale [8]. Field observations in the Chalk cliffs, United States, showed that the termination of a debris flow surge formed a permeable dam (~1 m high and ~3m wide) in a steep channel of approximately 14°, and its failure triggered a debris flow surge [9]. Such local accumulation of bed sediment in a steep channel may affect the descend of a debris flow surge; however, the effects are still unclear.

Multiple rainfall events, which have large time intervals (days, months, years), also form local accumulations of bed sediment in a steep stream. Local accumulations of bed sediment in a steep stream also change over longer time scales affected by termination of multiple debris flows and sediment supply from adjacent slopes.

This study conducted small-scale flume experiments to investigate the effects of local sediment accumulation on the descend of debris flow surges in steep channels.

2 Method

This study used a straight rectangular flume (3.6 m long, 0.10 m wide, and 0.20 m deep; Fig. 1). The flume gradient was set at 25°, assuming a steep initiation zone in the Ichinosawa catchment [4]. The flume walls were made of transparent acrylic panels, which allowed us to observe the side views of the descending processes of a debris flow surge. The flume walls were much smoother than those of the flume bed covered with uniform sand of 1 mm diameter. The dried bed sediment of the triangular longitudinal profile was placed 1.2 m upstream from the downstream end of the flume. The gate was installed 0.30 m downstream from the upstream end of the flume. Debris flow material (2.0 kg) was placed upstream of the gate. To begin the experiments, we opened the gate to trigger a debris flow surge and simultaneously supplied a subsequent water flow of 70 cm^3 s^{-1} from the upstream end of the flume. Although the sediment and water in the gate were not mixed, the channel gradient was steep enough for these to flow down immediately after the gate release.

Ultrasonic sensors were installed immediately upstream and downstream of the bed sediment. These

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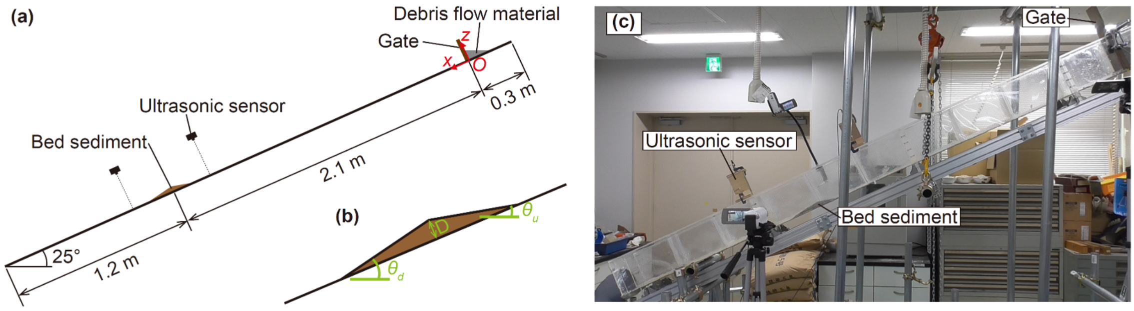

Fig. 1. Experimental set-up. (a) Schematic diagram. (b) Bed sediment geometry. (c) Image of the experimental setup.

Table 1. Experimental cases.

Test case	w_d (-)	D (cm)	θ_d (°)	θ_u (°)	d_m (mm)	h_u/D (-)
T1	0.500					0.3-0.8
T2	0.625	3				0.7-0.8
T3	0.750		35			0.4-0.7
T4		1		10		2.0-3.0
T5		2			1.75	0.7-1.6
T6			29			0.5-1.0
T7			32			0.6-1.0
T8	0.500			15		0.5-0.7
T9		3		20		0.4-1.0
T10			35	10	0.50	0.5-0.8
T11					0.33	0.4-1.0

w_d is the water content of the debris flow material, D is the bed sediment height, θ_u and θ_d are the upstream and downstream bed sediment slope, d_m is the mean particle diameter of the bed sediment, and h_u is the peak flow depth immediately upstream of the bed sediment.

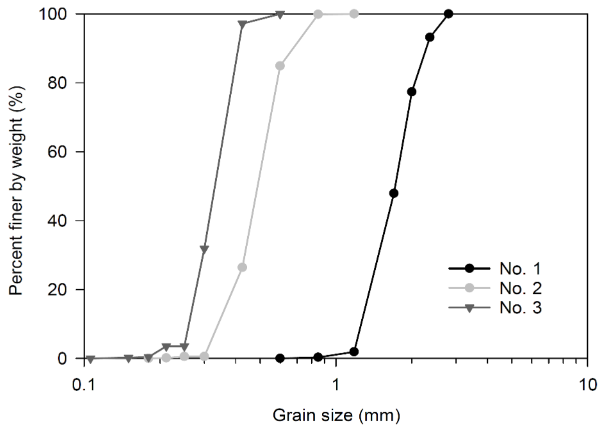

Fig. 2. Particle size distribution of the experimental materials. The debris flow material was No.1. The bed sediment material in T1–T9, T10, and T11 were No. 1, No. 2, and No. 3, respectively.

sensors precisely identified the time at which a debris flow surge passes through the installation points. These measurements were used to calculate the average front velocities of a debris flow passing between the two ultrasonic sensors (i.e., the average front velocity of a debris flow through the bed sediment). In addition, the front velocities of the debris flow along the flume were measured using video cameras recording the side of the flume.

In the present experiments 11 test cases were considered as T1–T11 (Table 1). Each case was tested at least thrice. The first, second, and third tests of T1 were referred to as T1-1, T1-2, and T1-3. The same applied to the other test cases. T1 was used as a standard test case. The other test cases had different parameter values from the standard case for the water content of the debris flow material ($w_d = m_w/m_s$, where m_w is the mass of water and m_s is the mass of solids), bed sediment height (D), upstream bed sediment slope (θ_u) (Fig. 1b), downstream bed sediment slope (θ_d), and mean particle diameter of the bed sediment (d_m).This study used silica sands of No. 1, No.2, and No.3, which have the mean particle diameter of 1.75, 0.50, and 0.33 mm, respectively (Fig. 2). Silica sand No. 1 was used as debris flow material. Silica sand samples No. 1, No. 2, and No. 3 were used as bed sediment materials T1−T9, T10, and T11, respectively.

When D was 3 cm, debris flow depths upstream of the bed sediment were smaller than D (Table 1). When D was 1 cm, the debris flow depths were larger than D.

3 Results

In T1, T2, and T6−T11, a debris flow surge terminated over the bed sediment (3.0 s in Fig. 3). The phreatic surface in the bed sediment progresses in the downstream direction because the interstitial water of a debris flow infiltrates the bed sediment. A subsequent flow accumulated just upstream of the bed sediment (3.5 s in Fig. 3). The mass of the terminated debris flow surge and the bed sediment began to move, triggering a larger debris flow surge (4.0−6.0 s).

In T3 and T4, a debris-flow surge passed through the bed sediment without stopping. In T5, two of the four experiments flowed down with stopping and two flowed down without stopping.

In the test cases with temporary stopping of a debris flow surge, the front velocity of the debris flow rapidly increased just downstream of the gate and gradually decreased between the gate and bed sediment (Figs. 4a, 4b, and 4f−4k). Subsequently, the front velocity decreased rapidly in the bed sediment. The front velocity increased downstream of the bed sediment, although it did not reach the velocity immediately downstream of the gate. Even in the test cases without temporary stopping of a debris flow surge, the bed sediment played a role in reducing the front velocity of the debris flow (Figs. 4c, 4d, and 4e).

Debris flow surges flowed down without stopping when the water content of the debris flow material (w_d) was large and the bed sediment height (D) was low (Figs. 5a and 5c).

The average front velocity of a debris flow through the bed sediment (u) was higher for a larger water content of the debris flow material (w_d) (Fig. 5a). u decreased as the mean particle diameter of the bed sediment (d_m) increased (Fig. 5b) and the bed sediment height (D) increased (Fig. 5c). u was smaller for a larger upstream bed sediment slope (θ_u) (Fig. 5d). u increased with the downstream bed sediment slope (θ_d) (Fig. 5e).

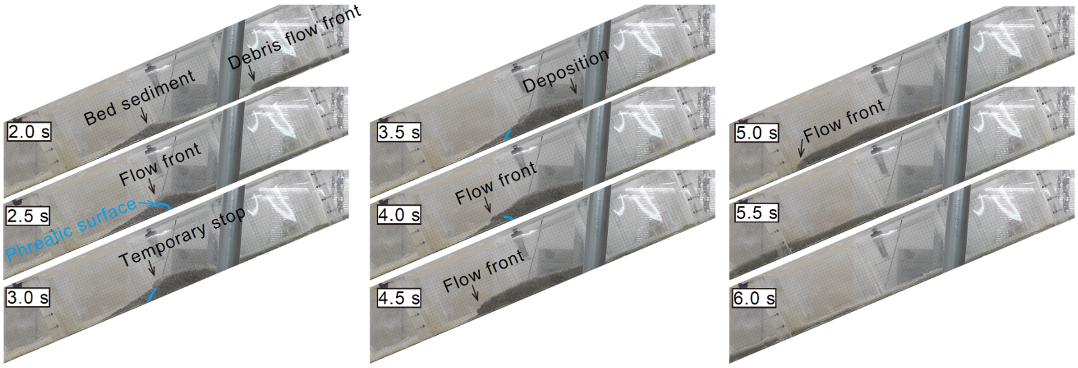

Fig. 3. Experimental debris flow through the bed sediment in T1. Phreatic surfaces in the bed sediment were visible because the bed sediment was dry initially.

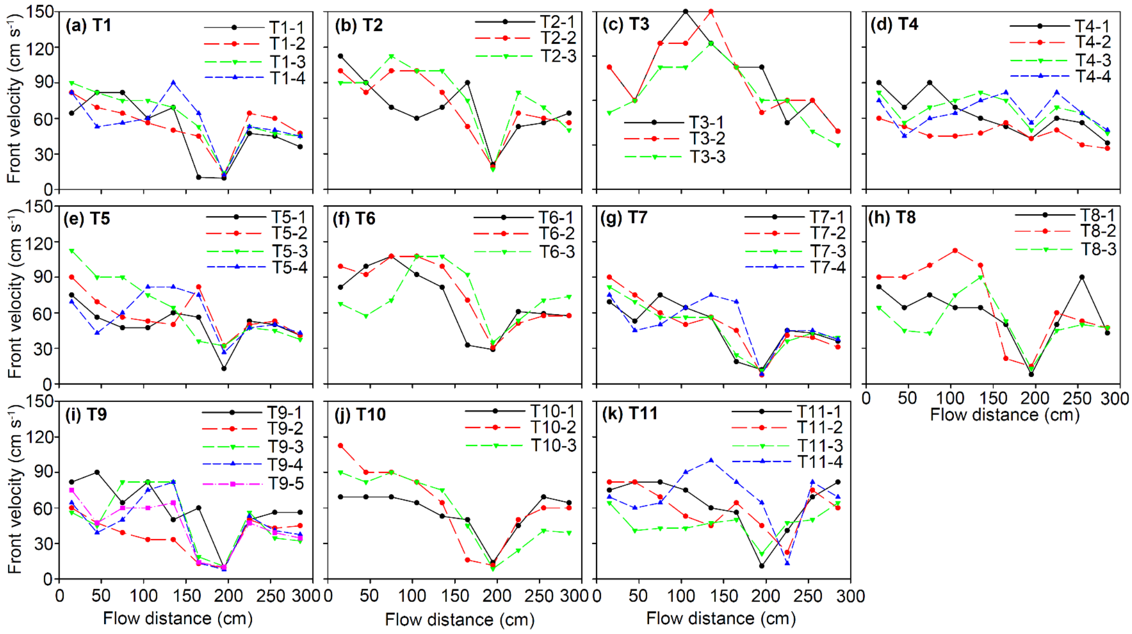

Fig. 4. Experimental results on debris flow front velocity along the flume.

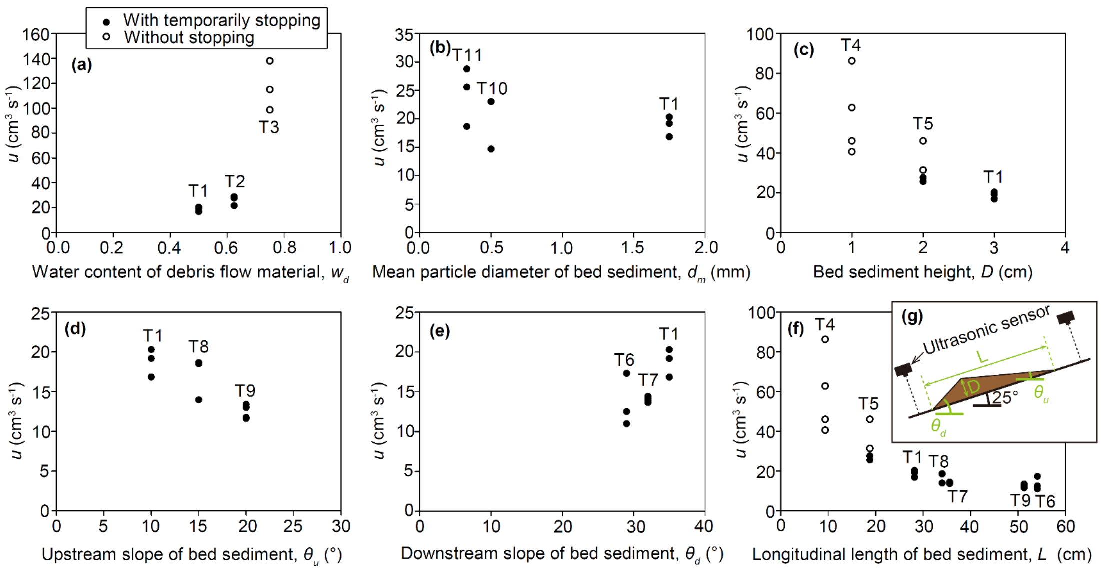

Fig. 5. Relationship between the front velocity through the bed sediment (u) and the experimental conditions (for all test including replicates).

Comparing the test cases in which only bed sediment geometries differed, u decreased as the longitudinal length of the bed sediment (L) increased.

4 Discussion

The debris flows generated in the experiments were in the range of $0.3 < h_u/D < 3.0$. Our experiments thus simulated both highly uneven riverbed and a dam like topography observed at Chalk Cliff [9].

Local accumulation of bed sediment reduced the front velocity of the debris flow (Fig. 4). In many test cases, the debris flow surge terminated over the bed sediment (Fig. 5). Subsequently, the mass of the terminated debris-flow surge and bed sediment began to move, triggering a larger debris-flow surge. The results demonstrated that local accumulation of bed sediment can increase the scale of a debris flow surge, which is consistent with the results of field observations in the Ichinosawa catchment [8].

The debris flow surge was terminated owing to the bed gradient change and dry bed sediment. Infiltration of debris flow interstitial water in bed sediment can contribute to the termination of a debris flow because the material of a debris flow and bed sediment has high permeability owing to the lack of mud-sized grains (Fig. 2) [7].

The debris flow surge passed through the bed sediment without stopping when the water content of the debris flow material (w_d) was large (Fig. 5a), which is consistent with field observations in the Ichinosawa catchment [4]. In this catchment, partly saturated flows had a shorter flow distance than fully saturated flows. This could be because collisional stress dominates over frictional stress when a debris flow has rich interstitial water [10], decreasing the effects of bed gradient changes on flow resistance.

A debris flow surge that terminated over the bed sediment began to move after the subsequent flow was deposited upstream of the bed sediment (Fig. 3). This process is similar to that observed at Chalk Cliff [9]. In Chalk Cliff, the dam was formed by the termination of a debris flow surge. The dam began to move after its scale increased, owing to the deposition of a subsequent flow. The scale of a dam can continue to increase until the frictional force within the dam can no longer resist gravity and pressure in the downstream direction.

The average front velocity of a debris flow through bed sediment (u) decreased as the longitudinal length of bed sediment (L) increased because a debris flow surge that terminated over bed sediment required more time to move again (Fig. 5f). Bed sediment with a larger L is more stable to resist movement, and it can store more water and sediment, delaying the time for a debris flow surge to move again. In addition, the phreatic surface in bed sediment with a larger L required more time to reach the toe of the bed sediment, resulting in a delay in time for a debris flow surge to move again.

Although experimental bed sediment was dried initially, natural bed sediment is wetted by water flows. Unstable bed sediment, which has a large downstream slope, small grain size, and low permeability, thus can be washed out before arrival of a debris flow surge .

5 Conclusion

This study conducted small-scale experiments to investigate the effects of local accumulation of bed sediment on debris flow surges in steep channels. The experiments demonstrated that local accumulation of bed sediment terminated a debris flow surge and triggered a larger debris flow surge later. In these experiments, the local accumulation of bed sediment decelerated or terminated a debris flow surge owing to abrupt changes in bed gradients and infiltration of debris flow interstitial water. Subsequently, the mass of the terminated debris-flow surge and bed sediment began to move, triggering a larger debris-flow surge. These results imply that predicting the scale of a debris flow surge arriving downstream requires measuring local accumulations of bed sediment in the debris flow initiation zone.

The present experiments were small-scale experiments using uniform grains for the material of a debris flow and bed sediment. There can be discrepancies between the experimental findings and the actual phenomena. Therefore, an increase in the experimental scale and the use of non-uniform materials are needed to better understand the effects of local sediment accumulation on debris flow surges in a steep channel.

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