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Observations on the development and decay processes of debris-flows

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Abstract

It is important to understand the development and decay processes of debris-flows in order to plan effective debris-flow countermeasures. However, few studies have successfully observed the development and decay processes of debris-flows. This study aimed to reveal changes in characteristics of debris-flow surges as they flow down, based on observation using time lapse cameras installed at multiple sites along a debris-flow torrent in the upper Ichinosawa catchment within the Ohya landslide, central Japan. Observation results showed that debris-flow surge volume and flow velocity tended to increase in the section just below their initiation point. In the subsequent section, debris-flow surges tended to maintain their volume and flow velocity while descending. Increases in flow velocity were observed in sections with a fixed bed, the channel bed consists of exposed bedrock with no sediment cover. Debris-flow surge volume and velocity tended to decrease in these sections, in which channel gradient decreases abruptly. These observation results can be explained by the theory of equilibrium concentration, which states that sediment concentration in the flow approaches the equilibrium concentration given from the channel gradient by the erosion and deposition of sediment. At the same time, small debris-flow surges tended to terminate with a short travel distance, which cannot be explained fully by the theory of equilibrium concentration.

Keyword: Ohya lindslide; observation; development and decay; the equilibrium concentration; fixed bed

1. Introduction

Debris-flows cause severe natural disasters due to their high velocity, and destructive power. It is important to understand the development and decay processes of debris-flows in order to plan effective debris-flow countermeasures. To clarify these processes, laboratory experiments have been conducted and developed the models based on physical flow mechanisms (Egashira et al., 1986; Iverson, 1997; Suzuki et al., 2009). One of representative models is the theory of equilibrium concentration, which states that sediment concentration in the flow approaches the equilibrium concentration given from the channel gradient by the erosion and deposition of sediment (Takahashi, 1977; Imaizumi et al., 2017; Lazoni et al., 2017).

Field observations are another approach to understand the behaviors of debris-flows, and have been conducted in many countries including China (Chu et al., 2011), Italy (Arattano et al., 2012), Japan (Okano et al., 2009; Suzuki and Suzuki., 2009), Switzerland (Berger et al., 2010). These studies have confirmed that debris-flows consist of multiple surges (Abanćo et al., 2014; Imaizumi et al., 2016), and a surge frequency near the initiation zones of debris-flows is usually higher than that observed downstream (Kean et al., 2013). However, most of these observations have been conducted in the transportation and deposition zones, while observations on the changes of characteristics of debris-flows at multiple sites in the initiation zones are scarce (Arattano et al., 2012; McCoy et al., 2012). These observations are needed in order to reveal the development processes of debris-flows and verify the correspondence with the theories.

In this study, field observations of debris-flows were made using time-laps cameras at multiple sites along a debris

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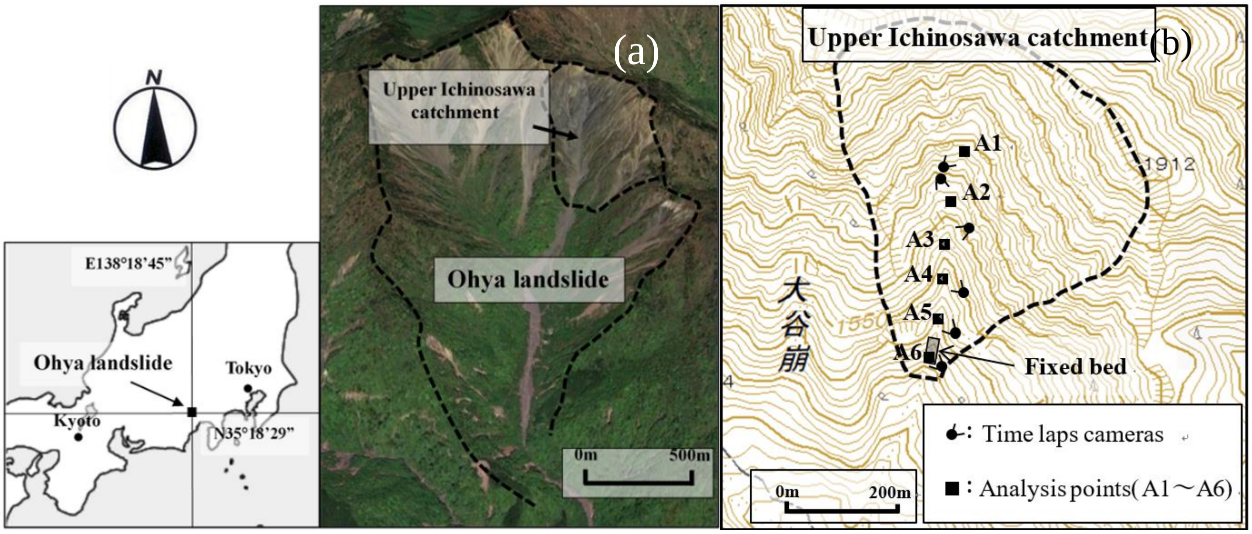

Fig. 1. Map of the Ohya landslide and the upper Ichinosawa catchment. (a) Satellite image of the Ohya landslide (Google Earth). (b) Topographic map of the upper Ichinosawa catchment showing locations of the time laps cameras and analysis ponts

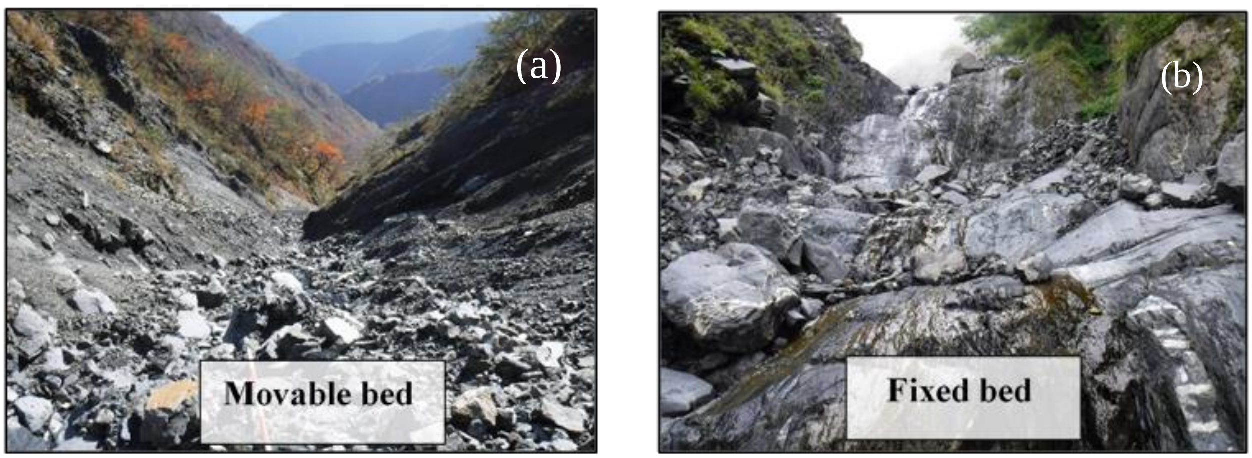

Fig. 2. Photograph of the channel bed in the upper Ichinosawa catchment. (a) The movable bed in the section between A3 and A4. (b) The fixed bed in the section between A5 and A6.

flow torrent in the upper Ichinosawa catchment within the Ohya landslide, which is the one of the most active debris-flow initiation zones in Japan. The aim of this study is to observe the changes of characteristics of debris-flow surges, as they flow downstream after their initiations. We also compare the observation results with the theory of debris-flow mechanics.

2. Study area

The Ohya landslide is located in the Southern Alps, central Japan (Fig. 1a). The Ohya landslide, which is in the headwaters of the Abe river flowing in Shizuoka prefecture, was formed by an earthquake in 1707 (Tuschia and Imaizumi, 2010). The horizontal area is about 1.8 km^2 and the height difference is about 800 m. The geological unit belongs to Tertiary strata which consists of sandstone, shale and their alternation. It is fractured by two faults existing on both sides of the Ohya landslide.

The upper Ichinosawa catchment is located in the northern part of the Ohya landslide (Fig. 1). This area is an initiation zone of debris-flows, where three or four debris-flows occur every year triggered by heavy rainfall during rainy season (June to July) and autumn typhoon season (late August to early October). The horizontal area is approximately 0.20 km^2, the total length of the channel is approximately 500 m, and the average gradient of the channel is 30 °. There is a little vegetation due to the harsh environmental conditions, and most of the slope is scree

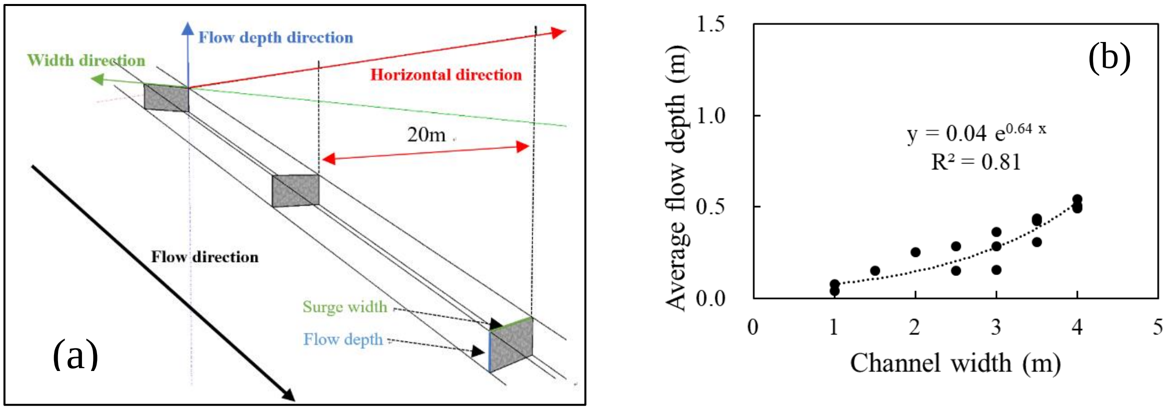

Fig. 3. Calculation method of volume of debris-flow surges. (a) Schematic diagram of debris-flow surge approximated to multiple truncated square pyramids. (b) Relationship between the channel depth and average flow depth in the section between A1 and A2.

Fig. 4. Image of the channel in the section between A4 and A5 before and during debris-flow event. Red rectangles in the image show the location where the surge width was measured. (a) The channel before debris-flow event. A pole at the center of image indicates 3 m. (b) The channel during debris-flow event captured by a time-laps camera.

and rock outcrop. Sediment on the channel bed, which was supplied from the outcrops by freeze-thaw weathering in winter, is several metres thick in some sections (Imaizumi et al., 2006, 2017). Most of the channel bed in the upper Ichinosawa is the movable bed, which is covered by erodible sediment (Fig. 2a). However, in the section between A5 and A6, the channel bed is a fixed bed, where the bedrock is exposed without sediment cover (Fig. 1b and 2b).

3. Methodology

3.1 Instrumentation

Six time-lapse cameras (TLC200pro, Brinno, Taipei City, Taiwan) with a frame rate of 15 s were installed in this study to interpret volume and runoff timing of debris-flow surges (Fig. 1b). The analysis points A1~A6 were set in the imaging range of cameras. The volume and flow velocity of the front of each surge were analyzed at each analysis point. In this study, the movements of sediment, which did not pass through two or more analysis points, were excluded from the analysis, because the changes in their flow characteristics cannot be interpreted.

Semiconductor-type water pressure sensor (S&DLmini, OYO, Tokyo, Japan) was installed at A6 analysis point to record hydrostatic pressures with a logging interval of 1 min, with an accuracy of ±3%. A tipping bucket rain gauge (LR5061, HIOKI, Ueda City, Japam) was also installed at A4 analysis point to record rainfall with a logging interval of 1 min.

3.2. Calculation method of volume of debris-flow surges

The volume of the debris-flow surge was estimated by approximating the shape of the surge as a series of truncated square pyramids. To obtain the volume of each truncated square pyramid, we set rectangles, of which width and height are the surge width and average flow depth, respectively, with intervals of 20 m (horizontal distance) from the front to the tail of the surge (Fig. 3a). The surge width was measured by comparing the length of 3 m pole in the image, which was taken on a day without debris-flow, with the width of debris-flow in images taken by the time-lapse cameras during debris-flow event (Fig. 4). The average flow depth was calculated by applying the surge width to the equations which represent the relationship between the channel width and the average flow depth obtained by measurement of cross-sectional topography at several points within each channel section before the debris-flow event (On September 5, 2016; Fig. 3b). The volume of each debris-flow surge, which was obtained by adding the volume of all truncated square pyramids, was calculated when head of the surge passed each analysis point. The volumes at the A6 analysis point could not be calculated, because of the long section outside the imaging range of the time-lapse camera.

3.3. Calculation method of flow velocity of debris-flow surges

The mean velocity of the debris-flow surge front between adjacent analysis points was obtained by their distance divided by the time lag of the passages of the surge front between the two analysis points. This mean velocity was taken as the flow velocity of the surge front at the down-site analysis point. The velocity was calculated when surges passed each analysis point.

4. Results

4.1 Debris-flow surges observed on 8 September 2016

A debris-flow was observed in the upper Ichinosawa catchment on 8 September 2016 (Fig. 5). The debris-flow surges occurred intensively in the three periods (8:30 ~ 9:00, 10:30 ~ 11:30, 15:30 ~16:00). Total of 21 surges passed through two or more analysis points (Fig. 6). Surges initiated mainly in the section upstream from the A1 analysis point (9 surges) and in the section between A2 and A3 (7 surges). According to this result, the following analyses of the changes in volume and flow velocity were conducted by classifying surges into two groups depending on their initiation positions

4.2. Changes in volume of debris-flows surges with distance downstream

The surges initiated in the section upstream from A1 tended to increase their volumes in the section between A1 and A3, which is just below their initiation points. Development of the surge volume stopped below the A3 analysis point (Fig. 7a and 7b). In the section between A4 and A5, where the channel gradient decreases rapidly from approximately 30 ° to 25 ° (Fig. 7c), they tended to decrease their volume. The small surges stopped in this section

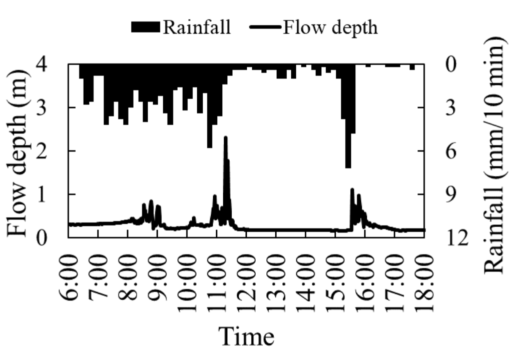

Fig. 5. Hyetohydrograph on 8 September 2016.

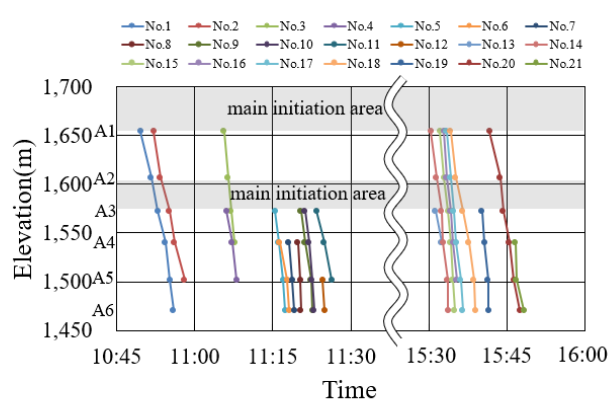

Fig. 6. Arrival time of surges at each analysis point.

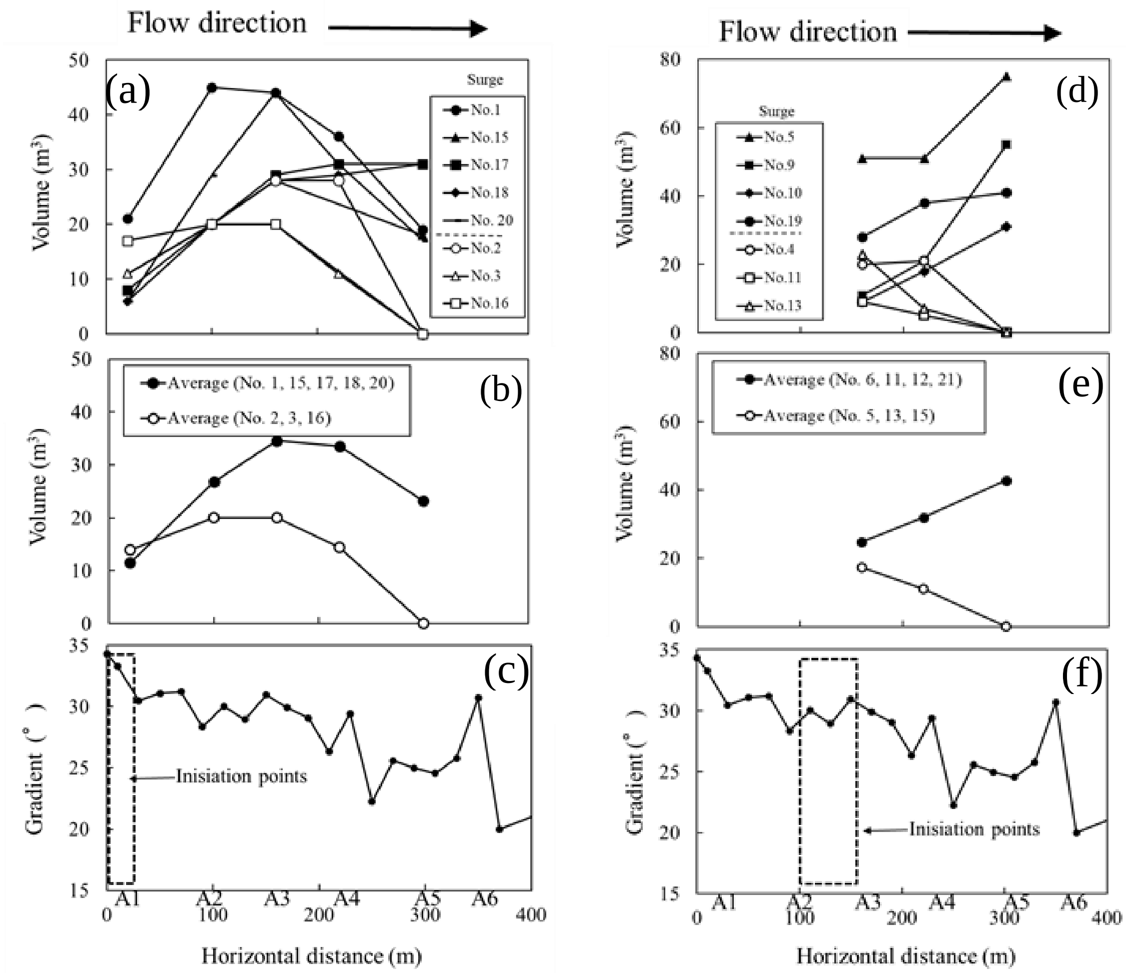

Fig. 7. Changes in volume of debris-flow surges as they flowed downstream. (a) Surges that initiated in the section upstream from A1. The black symbols are the volume of the surges which did not stop in the section between A4 and A5, the white symbols are that of the surges which stopped in this section. (b) Average volume of the surges that initiated in the section upstream from A1. (c) The channel gradient in the study area. The black rectangle indicates the initiation points of the surges that initiated in the section upstream from A1. (d) Surges that initiated in the section between A2 and A3. (e) Average volume of the surges that initiated in the section between A2 and A3. (f) The channel gradient in the study area. The black rectangle indicates the initiation points of the surges that initiated in the section between A2 and A3.

(white symbols in Fig. 7a and 7b). Half of the surges, which initiated in the section between A2 and A3, increased their volumes in the section between A3 and A5, which is also just below their initiation point (black symbols in Fig. 7d and 7e). The other surges continued to decrease their volume throughout their traveling, and stopped in the section between A4 and A5 (white symbols in Fig. 7b and 7e).

4.3. Changes in flow velocities of debris-flow surge fronts with distance downstream

The surges that initiated in the section upstream from A1 tended to increase their velocity in the section between A1 and A3, which is just below their initiation points (Fig. 8a and 8b). Most of these surges stopped accelerating in the subsequent sections. The surges that did not stop in the section between A4 and A5 tended to increase their velocity rapidly in the section between A5 and A6, in which the channel bed is fix bed (black symbols in Fig. 8a and 8b). Half of the surges that initiated in the section between A2 and A3 also increased their velocity in the section just below their initiation points and the section between A5 and A6 (black symbols in Fig. 8d and 8e). The other surges continued to decrease their velocity throughout their traveling, and stopped in the section between A4 and A5 (white symbols in Fig. 8d and 8e).

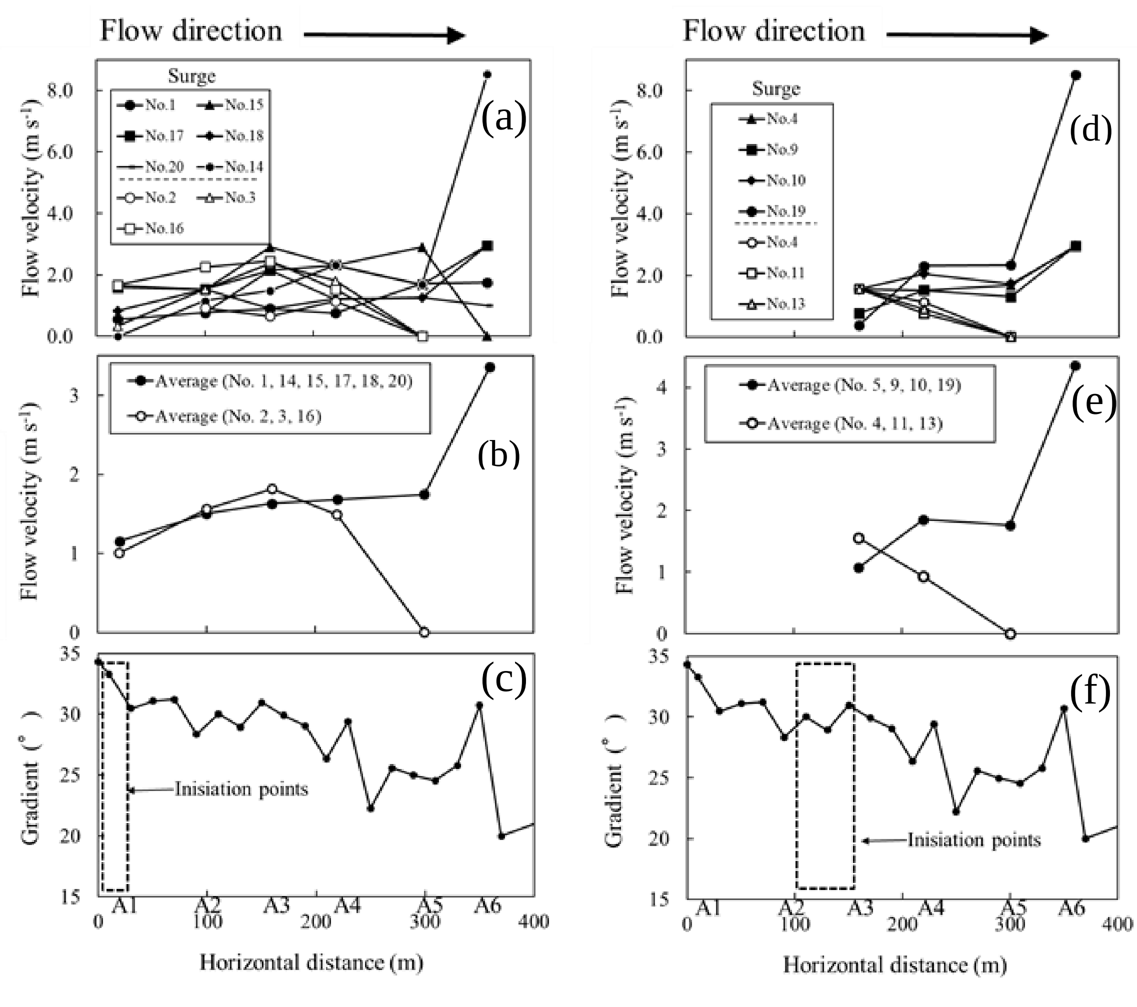

Fig. 8. Changes in flow velocity of debris-flow surges as they flowed downstream. (a) Surges that initiated in the section upstream from A1. The black symbols are the flow velocity of the surges which did not stop in the section between A4 and A5, the white symbols are that of the surges which stopped in this section. (b) Average velocity of the surges that initiated in the section upstream from A1. (c) The channel gradient in the study area. The black rectangle indicates the initiation points of the surges that initiated in the section upstream from A1. (d) Surges that initiated in the section between A2 and A3. (e) Average velocity of the surges that initiated in the section between A2 and A3. (f) The channel gradient in the study area. The black rectangle indicates the initiation points of the surges that initiated in the section between A2 and A3

5. Discussion

5. 1. Changes in volumes of debris-flow surges with distance downstream

The volume of surges changes by erosion and deposition of sediment (Takahashi, 1977; Hungr et al., 2005). The processes of erosion and deposition by debris-flows can be explained by the equilibrium concentration, which is the sediment concentration of debris-flows when they are in steady state under the given channel gradient. The equilibrium concentration is given by the balance between the shear stress coming from slope direction component of gravity force and the shear resistance, which are both static forces. The equilibrium concentration is expressed as a function of the channel gradient as follows.

$$G = \{c(\sigma - \rho) + \rho\}gh \sin\theta \qquad (1)$$

$$\tau = c(\sigma - \rho)gh \cos\theta \tan\emptyset \qquad (2)$$

$$G = \tau \quad \therefore \quad c_e = \frac{\rho \tan\theta}{(\sigma - \rho)(\tan\emptyset - \tan\theta)} \tag{3}$$

where G is the shear stress at the bottom of the debris-flow surge, τ is the shear resistance, g is the gravity acceleration, h is the flow depth, e is the sediment concentration, c_e is the equilibrium concentration, ρ is density of water, σ is the density of sediment particles, θ is the channel gradient, $\emptyset$ is the internal friction angle. Takahashi (1977) explained that the sediment concentration in the flow approaches the equilibrium concentration by erosion and deposition of sediment. That is, when the sediment concentration in the flow is lower than the equilibrium concentration, the surge erodes sediment on the channel bed until their sediment concentration reach the equilibrium concentration. After the sediment concentration in the flow become equivalent to the equilibrium concentration, the surge is in steady state and stops eroding sediment. On the contrary, when the sediment concentration in the flow is higher than the equilibrium concentration, the surge deposits sediment.

In the section just below their initiation points, the debris-flow surges, which are considered to be in the early stage of development with low sediment concentration (Takahashi, 1977), actively eroded sediment and increased their volume (Fig. 7a, b, d, and e). As a result, surges are considered to have approached the equilibrium concentration. Surges stopped eroding and maintain their volumes in the subsequent section, because the sediment concentration in the surges likely reached the equilibrium concentration (Fig. 7a and b). Then, surges deposited the sediment and decreased their volume in the section between A4 and A5 where the channel gradient decreases rapidly (Fig. 7a, b, and c). In this section, the sediment concentration in the flow likely exceeded the equilibrium concentration, because the equilibrium concentration became lower due to decreases in the channel gradient. In contrast, surges with comparatively small volume stopped in the section between A4 and A5 without the control of sediment concentration by deposition of sediment (white symbols in Fig. 7a, b, d, and e). In addition, some surge started to deposit their sediment just after their initiation, (white symbols in Fig. 7d and e). These surges are assumed to have high sediment concentrations from their initial stage.

5. 2. Changes in flow velocity of debris-flow surges with distance downstream

In the sections where the debris-flow surges are accelerating, the shear stress at the bottom of the surge exceeds the shear resistance. On the contrary, in the section where the surges are decelerating, the shear resistance is higher than the shear stress. Equations (1) and (2) indicate that the shear resistance increases as the sediment concentration in the surge increases and its increase rate exceeds that of the shear stress. Equation (3) indicates that the shear resistance balances with the shear stress at bottom of the mass when the sediments concentration reaches the equilibrium concentration (Takahashi, 1977).

Therefore, in the section just below their initiation points, surges, which eroded sediment actively because of the lower sediment concentrations than the equilibrium concentration, accelerated as they flowed down (Fig. 8a, b, d, and e). Such surges stopped acceleration in the subsequent sections because the sediment concentration likely reached the equilibrium concentration (Fig. 8a and 8b). Then, surges tended to rapidly increase their flow velocity in the section between A5 and A6, where the channel bed is fixed bed (Black symbols in Fig. 8a, b, d, and e). In this section, the sediment concentration in the flow likely became lower than the equilibrium concentration, because there is no erodible sediment although the equilibrium concentration became higher due to the increase in the channel gradient (Fig. 8c and 8f). As another factor for the rapid increase in the flow velocity in this section, it is thought that shear resistance at the bottom of the flow decreased because of the smoother surface of the fixed bed compared with that of the movable bed (Fig. 2) (Suzuki et al., 2003). In contrast, surges with comparatively small volume continued deceleration and stopped with a short travel distance without deposition of sediment, which decreases sediment concentration (white symbols in Fig. 8a, b, d, and e). Such behaviors of small surges in their terminal stage cannot be explained by the relationship between the shear stress and the shear resistance at the bottom of the flow.

6. Conclusion

To clarify the changes in the characteristics of debris-flow surges as they flow down, field observations using time laps-cameras was conducted at multiple sites along the debris-flow torrent in the upper Ichinosawa catchment. The results of our observations are summarized below.

- Debris-flow surges increased their volume and velocity in the section just below their initiation points, and maintained them in the subsequent section.
- Debris-flow surges decreased their volume in the section where the channel gradient decreases rapidly, and surges with a comparatively small volume stopped there.
- Debris-flow surges increased their velocity rapidly in the fixed bed.

These results of our observations are consistent with the theory of the equilibrium concentration. In contrast, the theory of the equilibrium concentration cannot fully explain the observation that surges with a small volume stopped and deposited all sediment with a short travel distance. In addition, some surges lost volume and velocity in their initial stage.

References

Arattano, M., Marchi, L., and Cavalli, M., 2012, Analysis of debris flow recordings in an instrumented basin: confirmations and new findings: Natural Hazards and Earth System Science, 12, p. 679–686, https://doi.org/10.5194/nhess-12-679-2012.

Abancó, C., Hürlimann, M., and Moya, J., 2014, Analysis of the ground vibration generated by debris-flow and other torrential processes at the Rebaixader monitoring site (Central Pyrenees Spain): Natural Hazards and Earth System Sciences, 14, p. 929–943. https://doi.org/10.5194/nhess-14-929-2014.

Berger, C., McArdell, B. W., Fritschi, B., and Schlunegger, F., 2010, A novel method for measuring the timing of bed erosion during debris flows and floods: Water Resources Research, 46, W02502, doi:10.1029/2009WR007993.

Cui, P., Hu, K., Zhuang, J., Yang, Y., and Zhang, J., 2011, Prediction of debris-flow danger area by combining hydrological and inundation simulation methods: Journal Mountain Sciences, 8, p. 1–9, https://doi.org/10.1007/s11629-011-2040-8.

Egashira, S., Ashida, K., and Sasaki, H., 1988, Mechanics of debris-flow in open channel: Proceedings of the Japanese Conference on Hydraulics, 33, p. 485–490. [In Japanese with English abstract.]

Hungr, O., S. McDougall, and M. Bovis, 2005, Entrainment of material by debris-flows: in Debris-flow Hazards and Related Phenomena, edited by M. Jakob and O. Hungr, pp. 135–158, Springer, Berlin.

McCoy, S. W., Kean, J. W., Coe, J. A., Tucker, G. E., Staley, D. M., and Wasklewicz, T. A., 2012, Sediment entrainment by debris-flows: In situ measurements from the headwaters of a steep catchment, Journal of Geophysical Research, 117, F03016, doi:10.1029/2011JF002278

Imaizumi, F., Sidle, R. C., Tsuchiya, S., and Ohsaka, O., 2006, Hydrogeomorphic processes in a steep debris flow initiation zone: Geophysical Research Letters, 33, L10404, https://doi.org/10.1029/2006GL026250.

Imaizumi, F., Tsuchiya, S., and Ohsaka, O., 2016, Behavior of boulders within a debris flow initiation zone: International Journal of Erosion Control Engeneering, 9, p. 91–100, https://doi.org/10.13101/ijece.9.91.

Imaizumi, F., Hayakawa, Y. S., Hotta, N., Tsunetaka, H., Ohsaka, O., Tsuchiya, S., 2017, Relationship between the accumulation of sediment storage and debris-flow characteristics in a debris-flow initiation zone, Ohya landslide body, Japan: Natural Hazards and Earth Science Systems, 17, p. 1923-1938.

Iverson, R.M., 1997, The physics of debris-flows: Reviews of Geophysics, 35, p. 245–296.

Kean, J. W., McCoy, S. W., Tucker, G. E., Staley, D. M., and Coe, J.A., 2013, Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency: Journal of Geophysical Research, 18, 2190–2207, https://doi.org/10.1002/jgrf.20148.

Lanzoni, S. Gregoretti, C., and Stancanelli, L. M., 2017, Coarse-grained debris-flow dynamics on erodible beds. Journal of Geophysical Research: Earth Surface, 122, p. 592–614. https://doi.org/10.1002/2016JF004046.

Okano, K., Suwa, H., and Kanno, T., 2009, Rainstorm control of scale and type of debris-flows at Kamikamihorizawa Creek of Mount Yakedake, Japan: Journal of the Japan Society of Erosion Control Engineering, v. 62, no. 4, p. 3–10. [In Japanese with English abstract].

Suzuki, Y., and Suzuki, T., 2009, Observation system of debris-flow on Kitamata valley of the Name river, Journal of the Japan Society of Erosion Control Engineering, v. 61, no. 6, p. 43–46. [In Japanese with English abstract.]

Suzuki. T., Hotta. N., and Miyamoto, k., 2003, Influence of riverbed roughness on debris-flows: Journal of the Japan Society of Erosion Control Engineering, v. 56, no. 2, p. 5-13. [In Japanese with English abstract.]

Suzuki. T., Hotta. N., and Miyamoto, k., 2009, Numerical simulation method of debris-flow introducing the non-entrainment erosion rate equation, at the transition point of the riverbed gradient or the channel width and in the area of sabo dam: Journal of the Japan Society of Erosion Control Engineering, v. 63, no. 3, p. 14–22. [In Japanese with English abstract.]

Takahashi, T., 1977, A mechanism of occurrence of mud-debris-flows and their characteristics in motion: Annals of the Disaster Prevention Research Institute, Kyoto University, 20(B-2), p. 405– 435. [In Japanese with English abstract.]

Tsuchiya, S., and Imaizumi, F., 2010, Large sediment movement caused by the catastrophic Ohya-kuzure landslide: Journal of Disaster Science, No. 5, Vol. 3, p. 257-263.