Behavior of Boulders within a Debris Flow Initiation Zone

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Although it is important to understand the behavior of debris flows in the initiation zone for the development of mitigative measures, data are scarce due to difficulties in field monitoring. To clarify debris flow behavior within the initiation zone, we established a monitoring system in the upper Ichinosawa catchment within the Ohya landslide, central Japan. In the Ohya landslide, loose sediments, previously deposited on steep channel bed, is the main source of debris flow material. Video image analysis of six debris flows revealed that the largest boulders in the debris flows were usually smaller than those in the channel deposits. Thus, debris flows appear to facilitate the selective transport of channel deposits in the upper Ichinosawa catchment. Flows that occur during debris flow surges can be classified as either i) flows comprising mainly cobbles and boulders, or ii) flows comprising mainly muddy water. The duration of each flow type is different amongst debris flow events. Flows mainly composed of cobbles and boulders accounted for most of the surges when channel deposits, which were the main source of debris flow material, were abundant. In contrast, flows were mainly composed of muddy water in surges when channel deposits were scarce. The particle size of the boulders had no clear relationship with flow height, with the size of the largest boulders generally ranging from 15 to 40 cm regardless of flow heights (ranging 0-5 m). The particle size of the material entrained by the debris flow differed among debris flow events. Coarse particles were frequently found on the flow surface when the particle size of the channel deposits was larger. Therefore, the characteristics of boulders in debris flows within the debris-flow initiation zone were affected by the volume and the size of sediment at the source of the debris flow material.

Key words: debris flow, field monitoring, initiation zone, Ohya landslide

1. INTRODUCTION

Debris flows in mountain areas can be extremely hazardous due to their high velocity, large volumes, and destructive power [Lin et al., 2002; Glade, 2005; Cui et al., 2011]. To improve debris flow hazard mitigation, detailed field observations have been undertaken in many countries; e.g., Switzerland [Hürlimann et al., 2003; Berger et al., 2011], China [Zhang, 1993; Zhang and Chen, 2003; Hu et al., 2011], and Italy [Arattano, 1999; March et al., 2002; Arattano et al., 2012]. Many of these observations have been conducted in the transportation zones of the debris flows, where the entire flows are composed of mixtures of sediment and saturated muddy water. Only a few observations have been conducted in the initiation zones of debris flows, where the materials start to move [Takahashi, 1991; Berti et al., 1999].

Debris flows can be classified into various types by flow dynamics, solid fractions, and material types [Takahashi, 1991; Coussot and Meunier, 1996; Hunger, 2005]. Various types of flows appear even in the same torrent [Imaizumi et al., 2005; Okano et al., 2012]. However, classification of the debris flow type is mainly based on monitoring results obtained in the transportation zone. Field observations at multiple sites along a debris flow channel have revealed that discharge and flow characteristics (e.g., boulder size, solid fraction) change as the flow migrates downstream [Arattano et al., 2012; Navratil et al., 2013]. In addition, the characteristics of the debris flow in transportation zones are affected by erosion and deposition during downstream migration [Takahashi, 1991, Berger et al., 2011]. Thus, flow characteristics in the transportation zone possibly differ from those in the initiation zone. In the initiation zone, flow containing an unsaturated layer has also been observed by field monitoring [Imaizumi et al., 2005]. Information on the characteristics of debris flow in the initiation zone is needed to explain the sequence of debris flow processes from initiation in the headwaters to the termination at the debris flow
One of the best-known characteristics of a debris flow is size segregation of particles, with the particle size at the front of surge being generally greater than at the tail of the surge [Takahashi, 1991; Hürlimann et al., 2003]. However, the behavior of particles in the initiation zone is not well understood because of a lack of field data.

In terms of debris flows caused by transportation of loose sediment on the bottom of valley, both the volume and grain size of debris flow material (e.g., channel deposits, talus slope) change over time and are associated with sediment supply from hillslopes as well as evacuation of the sediment by debris flows and fluvial processes [Bovis and Jakob, 1999; Imaizumi et al., 2006; Berger et al., 2011]. These temporal changes in the debris flow material play important roles in the initiation of the next debris flow [Bovis and Jakob, 1999; Jakob et al., 2005; Chen et al., 2012]. Although some previous studies have focused on conditions at initiation of the debris flow in the context of the characteristics of the debris flow material [Bovis and Jakob, 1999; Jakob et al., 2005], only a few studies have considered the relationship between debris flow material and flow characteristics (e.g., size and number of boulders in the flow).

In the debris-flow initiation zone within the Ohya landslide, central Japan, debris flow monitoring has been conducted since 1998 [Imaizumi et al., 2005; Imaizumi et al., 2006]. This area is suitable for debris-flow monitoring because of the high frequency of debris flows (about three or four events per year). In this study, we analyzed video images of the debris flow to clarify the behavior of boulders in debris flow surges in an initiation zone. The specific objectives of this study were: (i) to clarify temporal changes in the flow type during debris flow events and the size of boulders in debris flows; and (ii) to investigate the relationship between storage of boulders and their behavior in debris flows based on field-monitoring data.

2. STUDY AREA

The Ohya landslide, in the Southern Japanese Alps (Fig. 1), was initiated during an earthquake in 1707, and has an estimated total volume of 120 million m$^3$ [Tsuchiya and Imaizumi, 2010]. Unstable materials have subsequently been supplied to the old landslide scar and have affected the occurrence of debris flows since the original failure. The climate at the site is characterized by a high annual precipitation (about 3,400 mm) [Imaizumi et al., 2005]. Heavy rainfall events (i.e., total rainfall > 100 mm) occur during the Baiu rainy season (from June to July) and the autumn typhoon season (from August to October). The main geological unit is Tertiary strata, comprised of highly fractured shale and well-jointed sandstone.

Fig. 1 Map of the Ohya landslide and upper Ichinosawa catchment.

The highest point of the drainage basin is the east
peak (1,905 m a.s.l.), while the lowest point is the waterfall called “Ohya-Ohtaki”, located at 1,450 m a.s.l at the south end of the drainage basin (Fig. 1). The total length of the channel is approximately 650 m and the south-facing catchment has an area of 0.22 km². There are no anthropogenic influences on debris flow activity in this area due to the steepness of the site and the harsh environmental conditions. Seventy percent of the basin slope is bare (scree and outcrop), whereas the remaining 30% is vegetation-covered (forest, shrubs, and tussocks). Most of the catchment is characterized by rocky sequences with some high sub-vertical walls. The typical gradient of the hillslopes is 40°-50°.

Unconsolidated debris, ranging from sand to boulders, previously deposited on the steep channel bed, is the main source of debris flow material in the upper Ichinosawa catchment (Fig. 2) [Imaizumi et al., 2006]. Sediment infilling of the channels is dominated by a freeze-thaw process that promotes dry ravel and rockfall because of the steep hillslopes [Imaizumi et al., 2006]. Large boulders (> 1 m, mainly sandstone) are common in the channel deposits. The thickness of debris deposits attains several meters in some sections. Typical channel gradients in the area of the debris deposits, measured by a laser range finder, range from 28° to 37°, with a range from 36° to 39° for talus slopes. Channel gradients range from 16° to 28° between sites P3 to P1 (Fig. 1), where the channel bed is alternatively composed of deposited sediments and bedrock. Sediment infilling of the channels is dominated by a freeze-thaw process that promotes dry ravel and rockfall because of the steep hillslopes [Imaizumi et al., 2006].

Table 1 Limit of the particle size that can be clearly identified on the video image.

| Date            | Particle size (m) |
|-----------------|-------------------|
| July 12, 2003   | 0.15              |
| August 30, 2004 | 0.30              |
| July 19, 2006   | 0.05              |
| August 25, 2006 | 0.20              |
| September 6, 2007 | 0.10          |
| August 5, 2008  | 0.10              |

3. METHODOLOGY

The monitoring system was installed in the upper Ichinosawa catchment in early spring of 1998 includes video cameras, pore-water pressure sensors, and a rain gauge [Imaizumi et al., 2005]. In this study, we used motion images of debris flows captured by video cameras installed at sites P1, P2, and P3. The video camera was initially installed at site P1 in 2003. Then the camera was moved to sites P2 and P4 in 2004 and 2005, respectively. The camera images were initiated by wire motion sensors installed at several cross sections of the channel. Flow depth and surface velocity of debris flows at 1 second intervals were obtained from video image analysis. The video image analysis provides surface velocity measurements; however, surface velocity does not represent the mean velocity of all layers of the flow. Mean velocity of all layers of the flow was estimated by multiplying surface velocity by 0.6, based on the velocity profile throughout the flows on movable beds obtained from a physically based model by Takahashi [1977]. Changes in cross-sectional area of debris flow were calculated from changes in flow depth and cross-section measurement of the channel topography. Discharge of debris flows were estimated from the cross-section area multiplied by mean velocity of all layers.

The size of the largest boulders on the flow surface within the analyses section in the image (about 2 m length along flow direction) was investigated with 1 second interval of the video. Images of the channel view with scales (measurement poles) shot on the days without debris flows were used as a ruler when we measure size of boulders in the debris-flow images. The size of boulders was measured along flow direction, which is same direction as measurement poles in the referential images. This might be a source of potential analysis error, because shape of boulders were not spherical and size along flow direction is not always representative size of boulders.
Table 2 Fundamental information on rainfall and discharge during analyzed debris flow events.

| Date          | Total rainfall (mm) | Maximum 10-min. rainfall intensity (mm/10min.) | Rainfall duration | Total discharge (m³) | Peak discharge (m³/s) | Location of video camera |
|---------------|---------------------|-----------------------------------------------|-------------------|----------------------|-----------------------|--------------------------|
| July 12, 2003 | 38.0                | 9.0                                           | 3 h 50 min.       | (174)²               | (3.6)²                | P1                       |
| August 30, 2004 | 276.5              | 7.5                                           | 31 h 50 min.      | (4024)³              | (75.7)³               | P3                       |
| July 19, 2006  | 178.0               | 5.5                                           | 37 h 10 min.      | 2312                 | 33.8                  | P2                       |
| August 25, 2006 | 61.5               | 21.5                                          | 1 h 10 min.       | (609)⁴              | (29.5)⁴               | P2                       |
| September 6, 2007 | 501.5          | 9.5                                           | 37 h 30 min.      | (6767)⁵              | (65.4)⁵               | P2                       |
| August 5, 2008 | 39.5                | 13.5                                          | 1 h 30 min.       | 3049                 | 29.7                  | P2                       |

*¹ First half of the debris flow event was not analyzed because of the darkness before the sunrise. Therefore, first half of the event is not included in this data.
*² Latter half of the debris flow event was not analyzed because of the darkness affected by the sunset. Therefore, latter half of the event is not included in this data.
*³ Latter half of the debris flow event was not monitored by the video-camera system because of the destruction of the system by the debris flow. Therefore, latter half of the event is not included in this data.

The quality of the motion image were different affected by resolution of images (ranging from 0.02 to 0.10 m), distance between cameras and the channel, and weather conditions (e.g., fog, darkness of sky). Thus, accuracies of flow height and velocity were different among debris flow events. Since other factors, such as roughness of flow surface and temporal changes in the cross-sectional topography of the channel, potential errors in the flow height and flow velocity are larger than the video image resolution (assumed errors ranging 0.50 to 0.2 m and 0.1 to 0.4 m/s for flow height and velocity, respectively). Particle size that could be clearly found on these images were also different among debris flow events affected by the difference in the resolution of the video images (Table 1).

Amount of the channel deposits was monitored by the periodical photography from 550 m downstream of the Ohya Ohtaki (site P4 in Fig. 1) as well as by field surveys. In the rainfall seasons (from June to October), the volume of channel deposits changes only during debris flow events in the upper Ichinosawa catchment, and no clear changes have been found during rainfall events without debris flows. Therefore, photographs taken after the previous debris flow event were used to know accumulation conditions of the channel deposits when the next debris flow occurs.

4. RESULTS

4.1 General characteristics of debris flows

During the period 1998 to 2012, 48 debris flows occurred in the upper Ichinosawa catchment. We analyzed video images of six debris flows that were captured clearly by video cameras (Table 2). We failed to obtain clear video images of other debris flows because of mechanical troubles of monitoring system, darkness at nights, and fog.

A debris flow on July 12, 2003 was triggered by a high-intensity rainfall event (maximum 10-min rainfall of 9.0 mm) of short duration (3 h 50 min., Table 2). The video image was initiated by the wire sensor at 4:21 on July 12, 2003. However, we could not analyze the image from 4:21 to 4:33 because of dark conditions before sunrise. Imaizumi et al. [2006] classified the flow phase during debris flow events into two primary types: flows that consist mainly of muddy water (type 1) and flows comprising mainly cobbles and boulders (type 2). Type 1 flows are turbulent and are characterized by black surfaces due to high concentrations of silty sediment sourced from shale. Cobbles and boulders occasionally appear on the surface of a type 1 flow. In contrast, muddy water is almost always absent in the matrix of the surface of a type 2 flow. A type 1 phase was a predominant feature of the surge on the video image from July 12, 2003 (Fig. 3a). The second and third surges had short-term type 2 phases at their fronts.

A debris flow on August 30, 2004 was triggered by Typhoon Chaba. The peak discharge of this event was the highest of the six debris flow events analyzed in this study (Table 2). This debris flow was composed of four series of debris flow surges. Two series of surges that started at 16:09 and 16:28 were clearly captured by the video camera at site P3 (Fig. 3b). However, the other two series of surges that started at 21:02 and 22:16, detected by water pressure sensors, could not be captured by the camera because of dark conditions at night. A type 1 phase was a predominant feature of this debris flow (Fig. 3b). A type 2 phase appeared only at the front of each surge.
A debris flow on July 19, 2006 was caused by a low-intensity rainfall event, of long duration, associated with the Baiu rain front. The entire debris flow was recorded by the video camera. Most surges were classified as type 2 (Fig. 3c). Only low-discharge flows between surges were classified as type 1.

The rainfall that triggered a debris flow on August 25, 2006 was characterized as a short but high-intensity event. The duration of the rainfall was the shortest of all the events studied, but the maximum 10-min intensity was the highest of all six.
analyzed events (Table 2). Video camera monitoring was stopped at 14:17, 35 s after the arrival of a debris flow surge, because of destruction of the monitoring system by the flow. Therefore, we could not analyze the latter half of the debris flow. All flow in the video image was classified as type 2 (Fig. 3d).

A debris flow on September 6, 2007 was triggered by Typhoon Fitow. The duration and total rainfall of this rainfall event was the largest of the six events (Table 2). The latter half of this debris flow (after 17:58) was not analyzed because the image was affected by dark conditions after sunset. The total discharge in the analysis period (before 17:58) was the highest of the six analyzed events. During this debris flow event, the first halves of all larger surges (i.e., discharge > 10 m$^3$/s) were of type 2, and the latter halves of type 1 (Fig. 3e).

The last debris flow, which occurred on August 5, 2008, was triggered by a short but high-intensity rainfall event, and was similar to those of July 12, 2003 and August 25, 2006. As with the debris flow on July 19, 2006, type 2 flow was the predominant phase in all surges (Fig. 3f). Type 1 flow was observed during the low-discharge period between surges.

4.2 Behavior of boulders

The numbers of cobbles and boulders found in the video image during type 1 flow were usually less than 10 per second. In contrast, almost all of the flow surface of type 2 flow was comprised of cobbles and boulders. The monitoring system did not provide information on the concentration of solids within the flows, however, there is a strong possibility that cobbles and boulders were transported in the under layer of the type 1 flows.

Concentrations of larger particles at the fronts of the surges, which is a common characteristic of debris flows in other torrents [Takahashi, 1991; Hürlimann et al., 2003], was not observed in the upper Ichinosawa catchment (Fig. 3). During the passage of a type 2 flow, the particle size changed frequently, but no difference in particle size between material at the front and the end of the surge was evident. Travel distances from initiation points to monitoring points (< 500 m) may be too short for occurrence of the size segregation.

The diameter of boulders on the debris flow...
4.3 Debris flow material

The volumes of channel deposits before the debris flow events clearly differed between the six debris flow events studied here (Fig. 4). A large part of the channel was covered by deposits before the debris flow events of June 21, 2003, July 8, 2006, and August 12, 2006. The volume of the deposits on June 21, 2003 was estimated to be more than 12,000 m$^3$ [Imaizumi et al., 2006]. The volume of the deposits before the July 17, 2008 event was slightly less than before the events on June 21, 2003, July 8, 2006, and August 12, 2006. The volume of the deposits on the September 4, 2007 event was the second-lowest of the six events analyzed. Channel deposits were almost absent at the lower reaches of the upper Ichinosawa catchment. Almost no channel deposits were present before the event on August 28, 2004, with the total volume of deposits estimated from photographs and field surveys being < 2000 m$^3$.

5. DISCUSSION

5.1 Initiation of debris flow

In the upper Ichinosawa catchment, large volume of unconsolidated sediments always covers channel [Imaizumi et al., 2005; Imaizumi et al., 2016a]. Critical rainfall condition of debris-flow initiation is given by 10-min rainfall of 5 mm and total rainfall of 30 mm [Imaizumi et al., 2005], which is also applicable to six debris flow events analyzed in this study (Table 2). Since sediment supply from hillslope is not a factor limiting initiation of debris flow, upper Ichinosawa catchment can be classified as transport limited basin [Bovis and Jakob, 1999]. Three initiation mechanisms of debris flow have been monitored in the upper Ichinosawa catchment; sliding of channel deposits, erosion of channel deposits by overland flow, and destabilization of talus slopes [Imaizumi et al., 2016b]. Water supply from intense rainfall facilitates development of overland flow and/or rising in ground water level, triggering all three mechanisms.

5.2 Particle size

Although boulders larger than 1 m in diameter were commonly found in the channel deposit area (Fig. 2) [Imaizumi et al., 2016b], transportation of such large boulders was rarely recorded by the video cameras. Our measurement of the particle size in the video images has some errors due to resolution of
the video images and direction of the measurement of the particles, however, it is clear that maximum particle size in the debris flow is usually smaller than that in the channel deposits. Therefore, selective transport of channel deposits occurred during debris flow events in the upper Ichinosawa catchment. The maximum particle diameter generally ranged from 15 to 40 cm regardless of flow height or flow type (Fig. 5). The particle size during the August 28, 2004 event was larger than during the other events (Figs. 3, 5). A difference in particle size among debris flow events was also observed in other debris flow torrents [Ikeda and Hara, 2002]. The particles of the channel deposits before the August 28, 2004 event were coarser than before the other events because of selective transport by an antecedent debris flow earlier in the year (Fig. 6). The larger particle size of stored material before the August 28, 2004 event may have resulted in frequent detection of larger boulders (> 0.4 m) in the video image.

The particle size of some boulders exceeded the flow height (Fig. 5). These large boulders rotated as they migrated downstream, while most of the other smaller boulders, typically during type 2 flow, migrated without rotation. Most boulders in the debris flow were smaller than twice the flow height (Fig. 5). Therefore, the upper limit of the particle size that can be transported by debris flows is about twice that of the flow depth in the upper Ichinosawa catchment.

The concentration of larger particles at the front of debris flow surges has been monitored in many debris flow torrents worldwide [Takahashi, 1991; Hürlimann et al., 2003]. Such morphology is caused by differences in the solid-fluid stresses among particles of different size [Iverson, 2005]. In the upper Ichinosawa catchment, no size segregation of particles was evident (Fig. 3). The short distance between the initiation and monitoring points (generally < 300 m) may have been insufficient for size segregation to occur.

5.3 Flow type

The durations of flow types in each surge differed among debris flow events. The surges during July 19, 2006, and August 5, 2008 were mostly composed of type 2 flow. Most of the valley bottom in the upper catchment was filled by channel deposits before these events (Fig. 4). Therefore, type 2 flow was predominant in debris flows with abundant channel deposits. Although monitoring of large surges was not possible during the July 12, 2003 and August 25, 2006 events, it is possible that type 2 flow was also predominant in these surges because large volumes of channel deposits were present before the events.

The surges during the September 6 event were composed of both type 1 and type 2 flows. The first halves of the surges were type 2 flow and the latter halves type 1 flow (Fig. 3e). The volume of channel deposits before this event was the second lowest of the six events analyzed here. The small volume of channel deposits probably affected the appearance of the type 1 flow, which rarely included boulders.

Surges during the August 30, 2004 event were also composed of both type 1 and type 2 flow. Type 1 flow was the predominant phase during the surges, whereas the duration of type 2 flow in each surge was short (< 4 s). Before this debris flow event, the volume of channel deposits was the smallest of the six events (Fig. 4). The lack of debris flow material was probably the reason for the short duration of the type 2 flow. As previously described, the upper Ichinosawa catchment is considered as transport limited basin in terms of occurrence of debris flow. In contrast, our monitoring results on the flow type imply that the volume of storage affects the characteristics of the flow.

As to the amount of debris flow material, the rainfall pattern is also an important factor determining the characteristics of debris flow [Okano et al., 2012]. Rainfall events that trigger debris flows in the upper Ichinosawa catchment can be classified into two groups: (1) long-lasting rainfall events with high total rainfalls caused by typhoon and stationary front (e.g., August 30, 2004, July 19, 2006, and September 6, 2007), and (2) short-duration convective rainfall events of high intensity (e.g., July 12, 2003, August 25, 2006, and August 5, 2008; Table 2). During short-duration rainfall events, type 2 flow dominated during both of debris flow events in which main part of the debris flow were successfully observed by video cameras (August 25, 2006, and August 5, 2008). However, events dominated by type 1 flow (e.g., August 30, 2004) and type 2 flow (e.g., July 19, 2006) were monitored during long-lasting rainfall events. Consequently, the flow type does not simply correspond to the rainfall pattern.

6. SUMMARY AND CONCLUSION

To determine the behavior of boulders in debris flows developing within the initiation zone, we analyzed video images of six debris flows in the upper Ichinosawa catchment within the Ohya landslide, central Japan. Our analysis revealed that the sizes of the largest boulders in the debris flows were generally smaller than the sizes of the channel
deposits. Thus, debris flows appear to facilitate the selective transport of channel deposits. Debris flows in the upper Ichinosawa catchment can be classified into two primary types; (1) flows comprising mainly cobbles and boulders, and (2) flows comprising mainly muddy water. The duration of each flow type differed between debris flow events. Flow composed of mainly cobbles and boulders was predominant when channel deposits, which are the main source of debris flow material, were abundant. In contrast, flow composed mainly of muddy water was predominant when channel deposits were scarce. Consequently, the flow type in the upper Ichinosawa catchment was affected by the volume of debris flow material. The particle size of boulders in debris flows was not related to the flow height, with the maximum boulder size generally ranging from 15 to 40 cm regardless of flow height. The particle size of boulders in debris flow differed between debris flow events, and was possibly affected by differences in the particle sizes of channel deposits. Size segregation of particles, which has been monitored in the transportation and deposition zones in other torrents, was not clearly evident in the Ichinosawa catchment. Thus, debris flow in the debris flow initiation zone is considered to be an early stage in the size segregation process.

Our video image analysis qualitatively clarified boulder behavior in the debris flow. The characteristics of boulders in debris flows within the initiation zone are affected by the volume and size of sediment at the source of debris flow material. Therefore, we need to consider sediment storage in the initiation zone, to improve the prediction of debris flow characteristics.

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