Field observations of debris-flow initiation processes on sediment deposits in a previous deep-seated landslide site

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Abstract

Although information regarding the initiation processes of debris flows is important for the development of mitigative measures, field data regarding these processes are scarce. We conducted field observations of debris-flow initiation processes in the upper Ichinosawa catchment of the Ohya landslide, central Japan. On June 19, 2012, our video-camera monitoring systems recorded the moment of debris-flow initiation on channel deposits (nine surges) and talus slopes (eight surges). The initiation mechanisms of these surges were classified into three types by analyzing the video images: erosion by the surface flow, movement of deposits as a mass, and upward development of the fluid area. The first type was associated with the progress of surface flow from the upper stream on unsaturated channel deposits. The second type was likely caused by an increase in the pore water pressure associated with the rising in the groundwater level in channel deposits; a continuous water supply from the upper stream by the surface flow might have induced this saturation. The third type was associated with changes in the downstream topography caused by erosion. The flow velocity of most surges was less than 3 m s^{-1} and they usually stopped within 100 m from the initiation point. Surges with abundant pore fluid had a higher flow velocity (about 3 - 5 m s^{-1}) and could travel for a longer duration. Our observations indicate that the surface flow plays an important role in the initiation of debris flows on channel deposits and talus slopes.

Keywords: Debris flow; Initiation zone; Field monitoring; Ohya landslide

1. Introduction

Debris flows in mountain streams and ravines can cause severe damage due to their high velocity, large volumes, and destructive power (Lin et al. 2002; Glade 2005; Cui et al. 2011). In addition, debris flow is a predominant sediment transport process in steep mountainous catchments (Imaizumi and Sidle 2007). To improve our understanding of debris flows, detailed field observations have been undertaken in many countries; e.g., Japan (Suwa et al. 2000; Okano et al. 2012), China (Zhang 1993; Zhang and Chen 2003; Hu et al. 2011), and Italy (Arattano 1999; March et al. 2002; Arattano et al. 2012). These observations have been conducted mainly in the transportation zones of the debris flows, where the entire debris flow is composed of a mixture of sediments and saturated muddy water, and runs as a fluidized mass. Very few observations have been conducted in the initiation zones of debris flows where the materials start to move, because of the extreme difficulties in monitoring within these areas (Takahashi 1991; Berti et al. 1999).

Temporal changes in channel deposits affected by the sediment supply from the hillslope play important roles in the initiation of debris flows because they comprise the flow material (Bovis and Jakob 1999, Jakob et al. 2005; Liu et al., 2011; Chen et al., 2012). Previous monitoring-based studies in the initiation zones have reported that surface flow affects the occurrence of debris flows (e.g., Suwa et al. 1989, Takahashi 1991; Berti et al. 1999). Since the hydrological characteristics in the initiation zone change associated with the sediment supply and transport processes (Bovis and Dagg 1988; Imaizumi et al. 2005), detailed monitoring in the initiation zone are needed to improve debris flow prediction.

Field observations at multiple sites along a debris flow channel reported that discharge and flow characteristics (e.g., boulder size, concentration of sediment) of debris flows vary with migration toward downstream (Arattano et al. 2012; Navratil et al. 2013). Flow characteristics in the initiation zones of debris flow are sometimes different from those in the transportation zones (Suwa et al. 1989; Imaizumi et al. 2005; Imaizumi et al. 2006). For example, debris flows in the initiation zones can migrate without abundant interstitial water affected by the steep channel gradient (Imaizumi et al. 2005; Imaizumi et al. 2006). Therefore, models based on physical flow mechanisms in transportation zones (Takahashi 1977; Iverson 1997; Egashira et al. 1997) are not applicable to such type of flow. Thus, knowledge regarding the debris-flow initiation processes needs to be improved for the prediction of their occurrence, as well as the development of countermeasures.

In the debris-flow initiation zones in the Ohya landslide, central Japan, debris flow monitoring has been conducted since 1998 (Imaizumi et al. 2005). This area is suitable for the debris-flow monitoring because of the high frequency of debris flow (about three or four events per year). Information regarding flow characteristics in the initiation zone have been obtained by the intense field monitoring (Imaizumi et al. 2005, Imaizumi and Tsuchiya 2008). On June 19, 2012, our video-camera monitoring systems successfully captured the moment of the debris flow initiation that has rarely observed in the world because of the difficulty of setting monitoring systems at exact location of debris-flow initiation point. We analyzed video images of the debris flow to clarify the debris flow initiation processes. The specific objectives of this study were: (i) to identify how debris flows occur in mountainous channel; and (ii) to discuss debris-flow initiation process based on field-monitoring data and a simple physical mechanism of the sediment movement.

2. Study area

The Ohya landslide, one of the largest deep-seated landslides in Japan (area: 2.0 km^2), is located in the Southern Japanese Alps, central Japan, and is a headwater of the Abe River (Figure 1). The Ohya landslide was initiated during an earthquake in 1707, and has an estimated total volume of 120 million m^3 (Tsuchiya and Imaizumi 2010).

Most debris flows within the Ohya landslide occur in the upper Ichinosawa catchment (about three to four events per year; Imaizumi et al., 2005); thus, this area is suitable for monitoring debris flows. The highest point of the drainage basin is the east peak (1905 m a.s.l.,), while the lowest point is a waterfall called “Ohya-Ohtaki” at 1450 m a.s.l. in the southern end of the drainage basin (Figure 1). The total length of the channel is approximately 650 m and the south-facing catchment has an area of 0.22 km^2.

The main geologic unit is Tertiary strata, which is comprised of highly fractured shale and well-jointed sandstone. Most of the catchment is characterized by rocky sequences with some high, sub-vertical walls; typical gradients of the hillslopes are 40-50˚. Typical channel gradients in the debris deposit area range from 22˚ to 37˚, and range from 36˚ to 38.5˚ for talus slopes. Channel gradients range from 22° to 28° around site P1 where initiation of debris flow was observed in this study (Figure 1).

Unstable materials have subsequently been supplied to the channel, and have affected the occurrence of debris flows since the original failure (Tsuchiya and Imaizumi 2010). The most active sediment supply process in the upper Ichinosawa catchment is freeze-thaw weathering, which promotes dry ravel in winter (Imaizumi et al. 2006). Sediment produced by freeze-thaw is rapidly transported into the channel and to the talus slopes. As a result of the active sediment supply in winter, sand to boulder-sized unconsolidated debris has accumulated on the channel bed and talus slopes (Figure 1). The thickness of debris deposits exceeds several meters in some sections. The grain size of fine channel deposits (diameter < 100 mm) sampled at three locations around P1 was analyzed in the laboratory using sieves with mesh sizes of 0.075, 0.106, 0.25, 0.425, 0.85, 2.00, 4.75, 9.50, 16.0, 19.0, 25.4, 31.7, and 63.5 mm. Since it is hard to sieve coarse channel deposits (diameter > 100 mm), we measured their grain size by the line grid method with interval of 1 m in the field. Komura and Ozawa (1970) proposed a method estimating grain size distribution in weight from the line grid method; average of the size distribution in number and the size distribution in weight, which is estimated from the grain size measured by the line grid method and the bulk density of sediment, roughly corresponds to the grain size distribution in weight analyzed by sieves. Therefore, we estimated the grain size distribution of coarse channel deposits (diameter > 100 mm) in weight by the method of Komura (1970) under assumption that the bulk density of sediment is 2650 kg m^{-3}. Grain size distribution for the entire grain size was estimated from the size distributions of fine and coarse sediment as well as volumetric fraction of fine sediment in the channel deposits investigated in site (Figure 2). Cobbles and boulders (diameter > 64 mm) occupy about 70% of the entire channel deposits in the Ohya landslide. In addition, sediment finer than silt (diameter < 8 mm) is less than 9% of the entire channel deposits. Thus, channel deposits in the Ohya landslide is characterized by its large grain size and a small fraction fine sediment. Large boulders (> 1 m) are also commonly found in the channel deposits by the field survey.

Climate at the site is characterized by a high annual precipitation (about 3,400 mm) and is influenced by orographic effects in the southern Japanese Alps. Heavy rainfall events (i.e., total rainfall > 100 mm) occur during the Baiu rainy season (from June to July) and in the autumn typhoon season (from late August to early October).

There are no anthropogenic influences on debris flow activity in this area due to the steepness of the site and harsh environmental conditions. Seventy percent of the basin slope is bare (scree and outcrop), whereas vegetation-covered areas (forest, shrubs, and tussock) occupy the remaining 30% of the basin slopes.

3. Monitoring System

The monitoring system installed in the upper Ichinosawa catchment in early spring of 1998 includes video cameras, 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 on June 19, 2012 to identify debris-flow initiation processes. Three video cameras (V1, V2, and V3) were operational in the upper Ichinosawa catchment at that time (Figures 1, 3). Locations of the video cameras were selected based on view of the channel as well as stability of the installation points. Recordings by these cameras were initiated by wire motion sensors installed at several cross sections of the channel. However, V3 did not successfully record debris flow images because of a fault in the video monitoring system. Therefore, we analyzed only video images recorded by V1 and V2. V1 was located in the debris-flow initiation zone, and recorded images of channel deposits P1 and talus cone P2 (Figure 4). V2 was located in the channel section where debris flow was initiated in the upstream pass. Bedrock was always exposed around the channel section around V3. Therefore, V3 was located in a transportation zone of debris flows.

Precipitation during the debris flow event was recorded by a tipping bucket-type rain gauge, with a 0.5 mm per tip capacity, located close to V1. A water pressure sensor, which was aimed to monitor the height of flows, was operating with interval of 10 minutes at V3 during the debris flow event on June 19, 2012.

4. Observation results

4.1 Precipitation

Total rainfall and maximum hourly rainfall observed by the rain gauge close to V1 during the June 19 event were 189 mm and 29.5 mm, respectively. The cumulative rainfall at 18:16, when the occurrence of the debris flow was first identified on the video camera image, was 82.5 mm (Figure 5). Debris flow occurred just after a small rainfall intensity peak with a maximum 10-min rainfall of 4.5 mm (27 mm h^{-1}, 18:03-18:13). Imaizumi et al. (2002) defined the critical rainfall condition for debris flow initiation in upper Ichinosawa catchment to be a maximum 10-min rainfall of 5 mm (30 mm h^{-1}) and cumulative rainfall of 30 mm. Although the cumulative rainfall before the debris flow on June 19 exceeded this critical condition, the 10-min intensity was slightly below the critical level.

4.2 Video images captured by the V1 camera

The analysis of video images revealed that deposits started to move repeatedly during the debris flow event on June 19, 2012 (Figures 6, 7). These movements of deposits differed from typical debris flow surges in two ways: pore fluid was not abundant and the grading of boulders was not clear. However, we refer to these movements as surges in this study. The initial debris-flow surges were captured by V1 at 18:16; two distinct surges occurred on channel deposit P1 and talus cone P2 at the same time (Figure 6). As with debris flows in other torrents (Liu et al. 2009; Arattano et al. 2012), the debris flow event on June 19 composed of many surges; the total numbers of surges that occurred at P1 and P2 during the June 19 event were nine and eight, respectively (Figure 6). We could not analyze debris-flow surges after18:35 because surges were not clearly seen in the video image affected by the darkness after sunset. The water pressure sensor at V3 monitored abrupt changes in the flow height until 21:30. Therefore duration of the debris flow event is estimated to be 3 h. The timing of the occurrence of debris-flow surges at P1 did not completely agree with those at P2. However, debris-flow surges occurred frequently in the period from 18:16 to 18:25 at both locations.

The occurrence of most debris-flow surges was closely related to the development of surface flow on the deposits (i.e., channel deposits and a talus cone; Figure 7, 8a). Before initiation of the debris-flow surges, no surface flow existed at both P1 and P2, because all of the surface flow had infiltrated into thick deposits (depth > 2 m) above the two locations. Such high permeability of the channel deposits is possibly affected by the large grain size of the channel material (Figure 2). As the surface flow arriving on the deposits increased, the infiltration points of the surface flow (i.e., downstream of the surface flow) migrated downward. Eventually, surface flows started to increase their discharge by the erosion of sediment, and developed into debris-flow surges. Sediment eroded by surface flow accumulated at the front of the flow.

Two other types of initiation mechanism of debris-flow surge were identified on the video images. One was the migration of a mass of sediment without the development of surface flow. This type of surge was identified around P1 at 18:26. The sediment mass appeared to be sliding at an early stage of the movement (Figure 8b). The other mechanism was an upward expansion of the fluid area from downstream part of the deposits. This type was identified at 18:27 on the talus slope P2. At the beginning of this surge, fluidization of sediment was identified in the lower part of the video image. This fluid area expanded upward as time progressed.

The mobility of most of surges observed on June 19, 2012 was low; flow velocity, estimated by the video image analysis, was low (< 3 m s^{-1}), and surges generally terminated within 100 m from their initiation point. The duration of each surge was typically from 10 s to 2 min. The mobility of a surge starting at 18:20 was relatively higher than other surges, with a flow velocity of 3-5 m s^{-1}. The ratio of pore fluid (muddy water) to the overall flow (sediment plus muddy water) of this surge was clearly higher than the other surges. In addition, the duration of this surge (4 min) was longer than other surges. Analysis of the video images revealed that surface flow from the upper stream continuously supplied a large volume of water during this surge.

Although rainfall is the trigger of debris flow in the Ohya landslide, the timing of individual debris flow surges did not clearly coincide with the temporal changes in the rainfall intensity (Figure 6). Time-lag between increases in the rainfall intensity and increases in discharge in the main channel (and increases in the water content in channel deposits), which directly cause debris flows, may affected disagreement of timings between the rainfall intensity and the occurrence of surges.

The topography of the deposits changed frequently due to the occurrence of surges during the debris flow event. The initiation point of each surge was affected by the changes in the topography, and was slightly different from the previous surge.

4.3 Video images captured by the V2 camera

In the channel section near V2, the appearance of surface flow was monitored on the video image even during the period with no debris flow. Channel deposits around V2 (< 1 m depth) were much shallower than those around V1, which possibly affected the appearance of the surface flow in this section. Two surges were captured by V2. The first surge was at 18:25, 9 min after the first surge captured by V1 (18:16). Before the arrival of this surge, only muddy water was captured by V2. Therefore, surges initiated around P1 and P2 before 18:25 were considered to have terminated in the channel section upstream of V2. Because the timing of surges captured by V2 did not coincide with those captured by V1, most of the surges during this event did not travel a long distance in one movement, but migrated downstream in stages. Changes in the debris flow discharge with migration toward downward have been monitored in transportation and deposition zones in the world (e.g., Arattano et al. 2012; Navratil et al. 2013). Our monitoring results at two sites (V1 and V2) showed that such changes in the discharge occur in the short section (< 100 m) in the initiation zone of Ohya landslide (Figure 6).

5. Discussion

As a result of field monitoring using video cameras, three debris-flow initiation mechanisms were identified in the Ohya landslide. One surge was initiated by the sliding of a mass of sediment. Increases in the pore water pressure associated with rising of the groundwater table, which is a typical initiation mechanism of a landslide (e.g., Iverson 2000; Sidle and Ochiai 2006), might have triggered this type of sediment movement. Initiation mechanism of the sliding of the mass can be expressed by comparison between the shear stress and the shear strength at a sliding surface. By assuming that the pore water pressure in channel deposits is same as the hydrostatic pressure, factor of safety for movement of the mass of cohesionless sediment on an infinite slope is given as:

$$\mathrm{FS} = \frac{(Z-h)[(1-n)\gamma_s + nS\gamma_w] + h(1-n)(\gamma_s - \gamma_w)}{(Z-h)[(1-n)\gamma_s + nS\gamma_w] + h[(1-n)\gamma_s + n\gamma_w]} \frac{\tan\phi}{\tan\alpha} \qquad (1)$$

where Z is the thickness of deposits at a right angle to the slope surface, h is the height of the water table relative to the sliding surface, n is the porosity, γ_s is the unit weight of soil particles, γ_w is the unit weight of water, S is the degree of saturation, α is the slope gradient, and ϕ is the effective internal angle of friction. Critical condition for the movement of the mass (FS=1) is expressed as:

$$\frac{\tan\alpha}{\tan\phi} = \frac{(1-\eta)[(1-n)\gamma_s + nS\gamma_w] + \eta(1-n)(\gamma_s - \gamma_w)}{(1-\eta)[(1-n)\gamma_s + nS\gamma_w] + \eta[(1-n)\gamma_s + n\gamma_w]} \qquad (2)$$

where η is the ratio of h to Z. Critical channel gradient α that gives $\eta = 1$ is 23° using the following estimated parameters: ϕ = 38.5°, n = 0.3, γ_s = 26000 kg m^{-3}, and γ_w = 9800 kg m^{-3}. If slope gradient is steeper than this critical gradient, movement of the mass of sediment occurs without full saturation of the channel deposit ($\eta < 1$). On the other hand, sliding of the channel deposits in gentler channel (channel gradient < 23°) does not occur even if the deposits are fully saturated. Erosion of sediment by the surface flow or decreasing in the factor of safety in the channel deposits by the development of the depth of surface flow is needed for the occurrence of sediment transport in such gentler channel (Takahashi 1991). Channel gradient around P1 (from 22 to 28°) ranges just around or steeper than this critical channel gradient. Therefore, sliding of the mass of sediment, which was observed once during the debris flow event on June 19, 2012, occurs around P1 when the groundwater table is just at or slightly lower than the channel bed surface. In contrast, many other surges at P1 as well as surges on the steep talus slope P2 (slope gradient of 36 to 38.5°) were associated with downward migration of the surface flow. Similar initiation mechanism of debris flow has been monitored in other debris flow torrents (e.g., Suwa et al. 1989; Okano et al. 2012). Infiltration of the surface water into channel deposits was found on the video images when surface flow migrated downward, indicating that the surface of channel deposits was in an unsaturated condition at that time. Since sediment started to move not by the sliding of a mass but by the erosion, η at the timings of initiation of these surges was lower than the critical η value given by equation (2) (critical $\eta \leq 1$ in the condition of P1 and P2).

The other debris-flow initiation mechanism was the upward expansion of the fluid area. Movement and evacuation of sediment at the lower part of deposits by surface flow destabilized the upper part of the deposits, and facilitated the upward development of the fluid area. Previous monitoring-based studies have reported that surface flow affects the occurrence of debris flows (e.g., Suwa et al. 1989; Takahashi 1991; Berti et al. 1999; Okano et al. 2012). Although roles of the surface flow on initiation of debris flow surges were different among three initiation mechanism (water supply facilitating rising in groundwater table, erosion of sediment, and destabilization of the deposits), increasing in the surface flow was the triggering factor in all three mechanisms.

Analysis of the video images also revealed that the mobility of many debris flow surges on June 19, 2012 was very low, with the velocity of most of surges being less than 3 m s^{-1}. The short travel distances of many surges (generally < 100 m) also indicate the low mobility of the debris flow. Based on observations by the ultrasonic sensors and water pressure sensors, Imaizumi et al. (2005) clarified that the amount of interstitial water in debris flows is sometimes significantly low in the Ohya landslide. There is a possibility that such small amount of the interstitial water affected low mobility of the debris flow on June 19, 2012. Channel gradient in initiation zones generally exceeds 20° (e.g., VanDine 1985; Pareschi et al. 2002), steeper than that in transportation zones (e.g., Takahashi 1991; Arattano 1999).

Such steep channel gradient enables debris flow running out without abundant interstitial water (Imaizumi et al. 2006). In debris flow torrents, deposition of sediment occurs not only in gentle deposition zones, but also in steep initiation zones associated with the low flow mobility (Guthrie et al. 2010). Termination of debris flow surges in steep initiation zone of the Ohya landslide is in accordance with such characteristic of debris flow. Based on the initiation mechanism of debris flow in the Ohya landslide, many surges were presumed to be occurred in or on the partly unsaturated channel deposits. When debris flows migrate toward downstream on unsaturated deposits, interstitial water of debris flow easily infiltrates into the deposits. Such initiation condition is also a potential factor affecting low mobility and short travel distance of debris flow surges on June 19, 2012.

The mobility of a surge starting at 18:20 was relatively higher than other surges. Surface flow from the upper stream continuously supplied a large volume of water during this surge, indicating that volume of water supply affects mobility of debris flow surges. Monitoring in the Ohya landslide since 1998 revealed that mobility of debris flow (i.e., velocity, travel distance) is also largely different among debris flow events. Although travel distance of many surges during the debris flow on June 19, 2012 was short (< 100 m), travel distance of other debris flows sometimes exceeds 1 km (Imaizumi et al., 2002). Concentration of sediment particles is an important factor controlling mobility of debris flows (Takahashi 1991; Iverson 1997). Since the sediment concentration is determined by amount of water in the flow as well as volume of eroded (and deposited) sediment, the difference in the mobility of debris flows in the Ohya landslide can be affected by both rainfall pattern and volume of channel deposits. Such influence of rainfall pattern on the mobility of debris flows has also been reported in other catchments (e.g., Okano et al. 2012).

Although channel deposits covered main channel over long distance above V2 (length of about 400 m), initiation of debris flow on the channel deposits was limited in the section around V1 and V2 during the June 19, 2012 event. Large amount of water could accumulate these sites because these sites were located around lowest part of the channel section covered by channel deposits. Therefore V1 and V2 satisfied initiation condition of debris flow preceding channel sections above V1. In addition, depth of the channel deposits around V1 and V2 (estimated 2 m) were thinner than some sections above V1 (> 5 m in some locations). Comparing with the sections with thin channel deposits, surface flow and groundwater table hardly develop at the sections with deep channel deposits. Such depth of deposits may also have affected location of debris-flow initiation points. Debris-flow initiation points are different between debris flow events in the Ohya landslide; evidence of the initiation of debris flow were frequently identified at points above V1 by field surveys. Difference in the rainfall pattern and the accumulation condition of channel deposits (e.g., spatial distribution of the depth and the slope gradient) may affect location of the debris-flow initiation points.

6. Summary and conclusions

In this study, we discussed the debris flow initiation process based on video images recorded on June 19, 2012 in the Ohya landslide, Japan. Debris-flow initiation mechanisms were classified into three types following an analysis of the video images: erosion by surface flow, sliding of deposits as a mass, and the upward development of the fluid area. The first process was associated with the progress of surface flow on unsaturated channel deposits from upstream. The second process was likely to have been caused by an increase in the pore water pressure associated with the rising in the ground water table. The continuous water supply from upstream due to the surface flow might have induced this saturation. The third process was associated with changes in the downstream topography caused by erosion. Surface flow played an important role in the initiation of all three debris-flow mechanisms. Therefore, the hydrological processes occurring in the deposits (i.e., channel deposits and the talus cone) need to be clarified to predict the occurrence of debris flow.

Analysis of the video images also revealed that the mobility of debris flows on June 19, 2012 was very low. Many debris flow surges terminated within 100 m from initiation point of the flow. These results imply that sediments in a debris-flow initiation zone sometimes migrate downstream in stages, with repeated movements and terminations as the debris flow surges occurred.

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Figure Captions

Figure 1 Location and topography of the monitoring site. (a) Location of the Ohya Landslide. (b) Location of the monitoring site in the Ohya Landslide. (c) Topographic map around the monitoring site indicating the location of monitoring instruments.

Figure 2 Grain size distribution of channel deposits.

Figure 3 View from the video camera V1 taken on August 20, 2012.

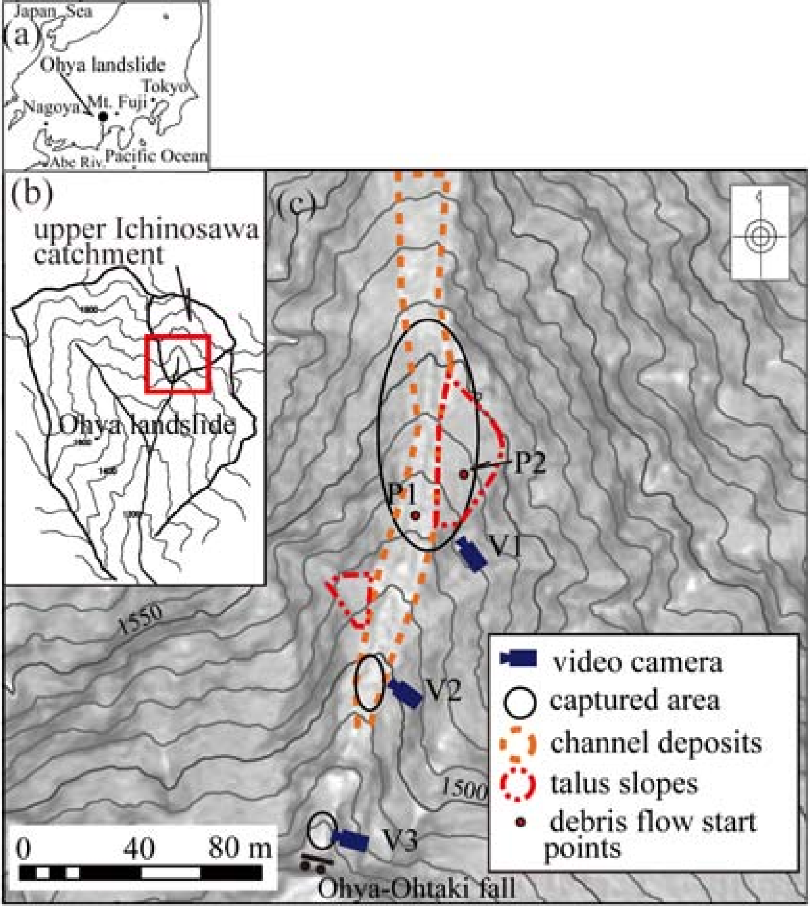
Figure 4 View of the channel deposits at P1 and the talus slope at P2 taken on May 14, 2012.

Figure 5 Precipitation during the rainfall event that triggered the debris flow on June 19, 2012.

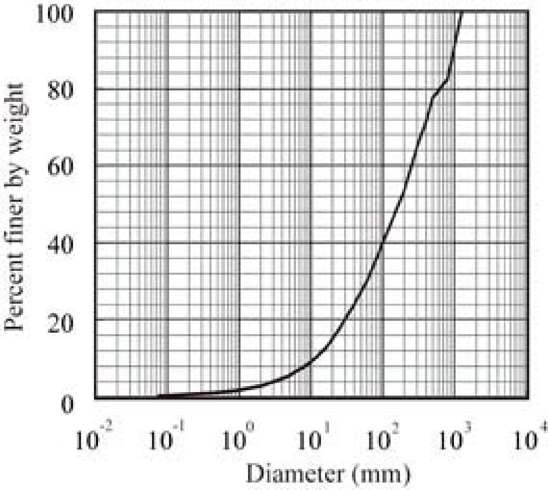
Figure 6 Timing of the debris-flow surges during the event on June 19, 2012.

Figure 7 Video image captured by the video camera V1 at 18:20 when a debris-flow surges were initiated around point P1 and P2. (a) Image at 18:20:43 just before initiation of debris-flow surges. The white painted area indicates the existence of surface flow. (b) Image at 18:20:47 just after initiation of a debris-flow surge at point P1. The area, in which the fluidization of channel deposits started, is surrounded by a dashed line. (c) Image at 18:20:51 just after initiation of a debris-flow surge at point P2. Fluidization of deposits on talus slope started around the area surrounded by a dashed line.

Figure 8 Schematic diagrams of the initiation mechanisms of debris-flow surges. (a) Erosion by surface flow. Sediment eroded by surface flow accumulated at the front of flow. (b) Sliding of a mass of sediment.

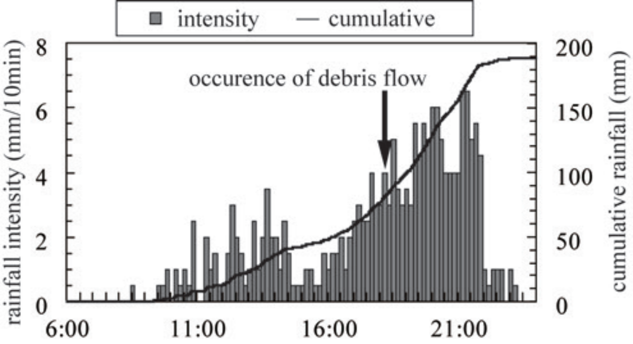


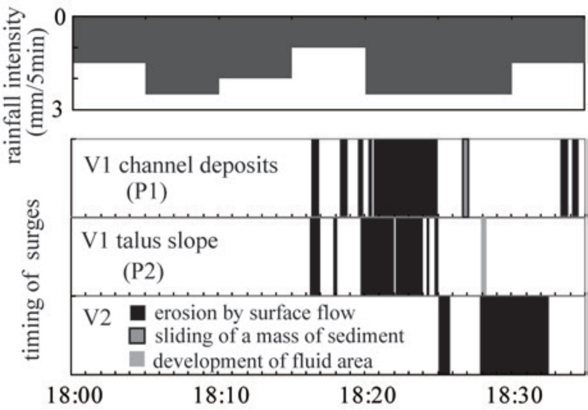
Japan Sea
(a)
Ohya landslide
Tokyo
Nagoya
Mt. Fuji
Pacific Ocean
Abe Riv.
(b)
upper Ichinosawa catchment
Ohya landslide
(c)
P2
P1
V1
1550
V2
1500
V3
Ohya-Ohtaki fall
0
40
80 m
video camera
captured area
channel deposits
talus slopes
debris flow start points



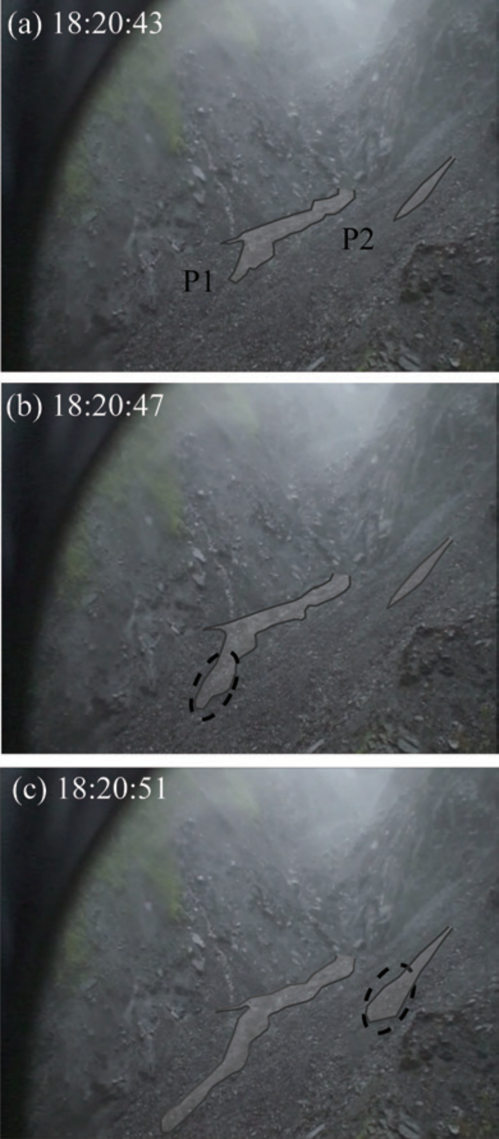
100
80
60
40
20
0
Percent finer by weight
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
Diameter (mm)

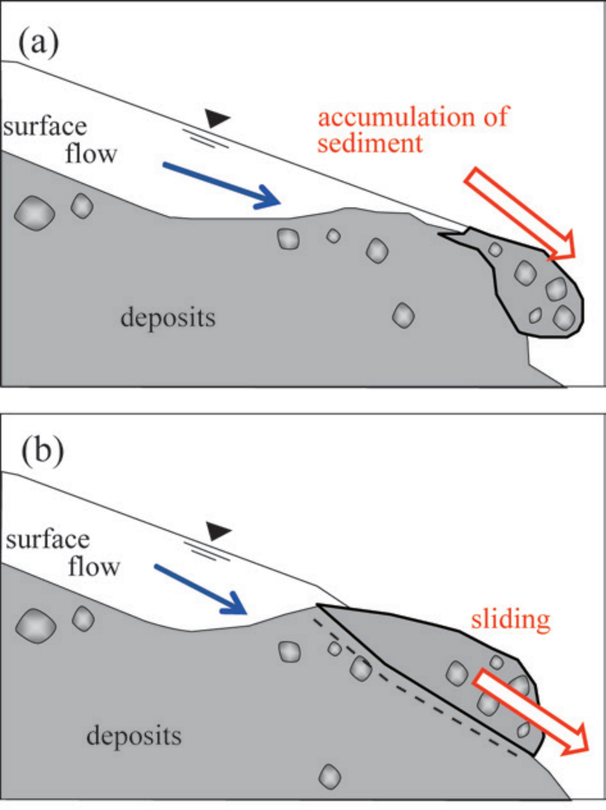

P2
P1


intensity
cumulative
occurence of debris flow
rainfall intensity (mm/10min)
cumulative rainfall (mm)
8
6
4
2
0
200
150
100
50
0
6:00
11:00
16:00
21:00



rainfall intensity (mm/5min)
0
3
timing of surges
V1 channel deposits
(P1)
V1 talus slope
(P2)
V2
erosion by surface flow
sliding of a mass of sediment
development of fluid area
18:00
18:10
18:20
18:30


(a) 18:20:43
P1
P2
(b) 18:20:47
(c) 18:20:51


(a)
surface
flow
accumulation of
sediment
deposits
(b)
surface
flow
sliding
deposits