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FORTY YEARS OF DEBRIS-FLOW MONITORING AT KAMIKAMIHORIZAWA CREEK, MOUNT YAKEDAKE, JAPAN

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ABSTRACT

Kamikamihorizawa Creek on the slopes of Mount Yakedake, Nagano Prefecture, was selected as a monitoring site for debris flows considering a high frequency of debris flow and instrumented with monitoring equipments in 1970: eight years after the last phreatic explosion of this volcano. The monitoring system was improved by adding speedometers, stage meters, seismometers and so on, in addition to the off-line monitoring surveys on the interaction between debris flows, hillslope hydrology and slope morphology. During the last 40 years, data were obtained from 91 debris-flow events that contained more than 200 episodes of debris-flow surges. Studies from the data supplied a general concept of the debris-flows and their geomorphic effects at volcanic slopes as follows. Debris flows are triggered by a large intensity of rainfall in a short duration as much as 10 minute. Threshold of rainfall intensity for debris flows increases with time after the end of volcanic eruption, while it drastically decreases with the eruption. Three types of debris flows were found: Large flows with boulder dam without openwork structure (Type I), small flows with boulder dam with openwork structure (Type II), and small flows with boulder dam without openwork structure (Type III). Rainfall conditions were found to have controlled the difference between these types through water availability to debris flows at the source and growth reaches of debris flows. Mass and boulder focusing to the flow front are marked, and due to this focusing the flow radiates elastic waves whose energy is from the potential energy of the flow. The energy conversion efficiency from the potential energy to elastic-wave energy is a magnitude of 10-3 much smaller than the efficiency for earthquake at 10-1 from the strain energy to the elastic-wave energy. Debris flows terminate in the fan leaving two types of debris-flow lobes: swollen lobes and flat lobes. Main source of the flat lobes is attributed to the Types I and III, while the swollen lobe to the Type II. It would be important to understand this concept for volcanic debris flows from its initiation to termination for the mitigation of debris-flow hazards.

Key words: *debris flow, Mount Yakedake, volcanic eruption, boulder dam, rainstorm control*

INTRODUCTION

In the late 1960s, several severe disasters were caused by debris flows in Japan (e.g., Iwasaki, 1968; Saito, 1973). The disasters were resulted from an irrelevant preparedness and inadequate countermeasures against the hazards due to a lack of debris-flow data which were not available at that time. Field surveys had been executed every time after each disaster. However the surveys had supplied no actual data of debris-flow motion but only the data of the results of erosion, deposition and damages brought about by debris flows. Therefore monitoring of actual debris flows was required to obtain data for designing

Fig. 1 - Debris-flow monitoring sites at Mount Yakedake

new effective countermeasures and preparedness against debris flows. Considering this situation, a study group of debris flows in Disaster Prevention Research Institute, Kyoto University and Matsumoto Sabo Construction Office of Ministry of Construction started a debris-flow monitoring at Kamikamihorizawa Creek on the eastern slope of Mount Yakedake in 1970 (Suwa *et alii*, 1973).

The authors were acquainted afterwards with the fact that monitoring of debris flows had been conducted and successful earlier in the Guxiang-gou Gully in Tibet during 1964-1965 (Ma, 1994) and in the Jiangjia-gou Gully, Yunnnang, China since 1973 (e.g., Li *et alii*, 1983; Davies *et alii*, 1991), followed by the monitoring of debris flows at Mt Thomas, New Zealand (Pierson, 1980), Muddy River of Mount St. Helens (Pierson, 1986), again at the Guxiang-gou (Suwa *et alii*, 1994), Bebeng River of Mount Merapi (e.g., Suwa & Sumaryono, 1996; Lavigne *et alii*, 2000), Curah Lengkong River of Mount Semeru (e.g., Lavigne & Suwa, 2004; Thouret *et alii*, 2007), the slopes of Mount Pinatubo (e.g., Marcial *et alii,* 1996), Moscardo Torrent (e.g., Arattano *et alii*, 1997; Marchi *et alii*, 2002) , Acquabona Creek (Genevois *et alii*, 2000) and so on. Majority of these studies have put their large efforts on understanding the general characters of debris-flow travel processes. On the other hand, a synthetic and systematic monitoring of debris-flow initiation, travel motion, inundation and deposition in the fan, and the interaction between debris flows and topographic changes of the basin have been intended in the observations at Kamikamihorizawa Creek. It would be worthwhile to synthetically summarize the characteristics of debris flows obtained from the monitoring at this creek in the followings.

Fig. 2 - View of monitoring slopes. (A) Eastern slope of Mount Yakedake. (B) Headwaters of Kamikamihorizawa Creek. (C) View upwards at the middle reach observation site. (D) Monitoring view field of a video camera at the fan

STUDY SLOPES AND METHODS

Monitoring slopes are shown in Figures 1 and 2. Debris flows initiate in the gully bottom near the point indicated by the arrow "Confluence" (Figure 1) with an intense storm runoff. Weather observation equipments including rain gauges were installed on the slope near the source of debris flows as shown in Figure 2B. Debris flows travel down the gully running through the middle reach observation site as shown in Figure 2C, where visual data of motion, surface velocity, flow depth etc were monitored with 6 video cameras, an electromagnetic Doppler speedometer and an ultrasonic distance meter respectively. An online system controlled with multiple wire sensors synchronized the operation of monitoring equipments with a travel of debris flow (Okuda *et alii*, 1980a).

This creek was selected because of the high frequency of debris flows it experiences, more than ten per year in the 1960s. The high frequency was due to the activation in gully erosion after the last phreatic eruption of Mount Yakedake in 1962, in which the explosion was from new fissures that opened at the headwaters of this creek. The volcano consists of lava domes of andesite surrounded by numerous sets of pyroclastic-flow deposits and debris-flow deposits.

The region has a temperate humid climate with annual precipitation of about 2500 mm; nearly two-thirds falls as rain while the rest occurs as snow. The watersheds and the fans are moderately vegetated except the slopes of gully walls where soil removal continues.

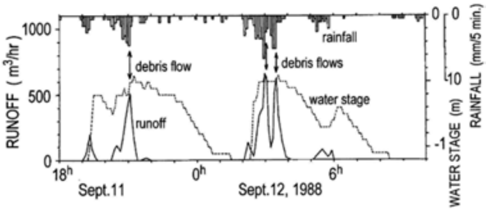

Fig. 3 - Debris-flow initiation, 5-min rainfall, surface runoff, and subsurface perched-water stage. Modified after Suwa (1989)

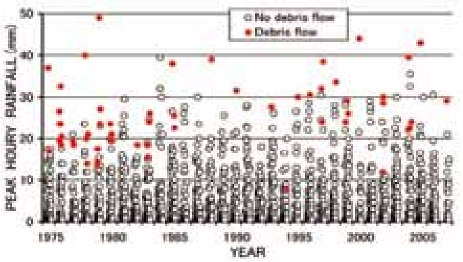

Fig. 4 - Relationship between debris-flow occurrence and the peak of hourly rainfall

The slopes are neither farmed nor inhabited because the area belongs to the Central Japan Alps National Park and the Kamikochi National Forest.

RAINFALL CONDITION FOR DEBRIS FLOW

Even if the duration of rainfall is short, high rainstorm intensities can trigger debris flows in volcanic torrents. Figure 3 shows an example of the hydrologic response at the headwaters of Kamikamihorizawa Creek that led to debris flows (Suwa, 1989). The diagram shows that the high rainstorm intensity raises the subsurface perched-water stage in the deposits. The peaks in the perched-water stage coincide with the increases in surface runoff that trigger debris flows. This temporal coincidence of debris flow and surface-runoff peak indicates that debris flows are not initiated by landslides, but by a drastic incorporation of gully bottom deposits due to appearance of a rapid storm runoff.

Threshold of rainfall intensity for debris flows increase with time after the end of volcanic eruption, while it drastically decreases with volcanic eruption (Suwa & Yamakoshi, 1997). Temporal changes are found in the rainfall intensity for debris flows over years. Figure 4 uses solid circles to show the peak intensities of hourly rainfall that triggered debris flows, and open circles for those that triggered no debris flow for all rainfall events since 1975. The diagram indicates that the lower limit intensities for debris flows after 1985 are somewhat higher than those before 1985. This means debris flows are not as likely to occur as they were in the past.

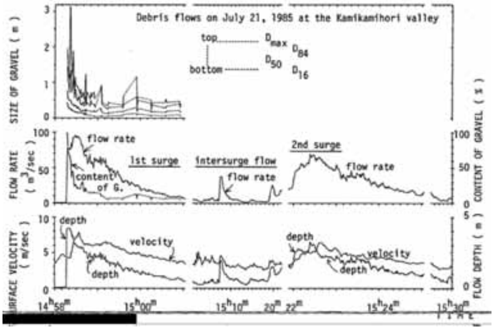

Fig. 5 - Hydrograph of the July 21, 1985 debris flow showing the gravel content and size parameters. Modified after Suwa (1988)

A similar trend might exist in the longer temporal trend in the hydrologic response of hillslopes to rainstorms after a volcanic eruption. Yamakoshi *et alii* (2001) described the changes in hillslope hydrology caused by vegetation recovery. The changes occur largely in the first few years after volcanic eruptions as well as more gradually over a period of several decades (Yamakoshi & Suwa, 2000). These temporal changes decrease the storm-runoff ratio of hillslopes resulting from a combined effect of the increase in infiltration coefficient and roughness parameter, and the decrease in contributing area for runoff generation.

MOTION OF DEBRIS FLOW

Over the last 40 years, data were obtained from 91 debris-flow events that contained more than 200 episodes of debris-flow surges, which mean that major portion of debris-flow events contain multiple surges (e.g., Suwa & Okuda, 1988; Suwa *et alii*, 1993)

HYDROGRAPH

Observations have revealed that debris flows are hydraulically unsteady and non-uniform. Figure 5 shows an example of the hydrographs of the 21 July 1985 debris flow, where the flow consists of an abrupt rise of flow depth at the front and a recession limb behind. However, the surface velocity at the front was markedly smaller than the velocities in the middle and at the back. This low velocity is ascribed to large internal friction caused by the higher frequency of mutual collision and interlocking of boulders at the frontal part

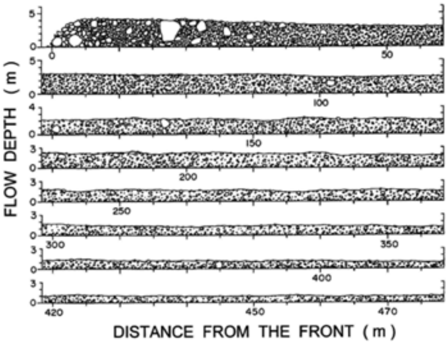

Fig. 6 - Shape and structure of the July 21, 1985 debris flow illustrated after the data shown in Fig. 5. Modified after Suwa *(1989)*

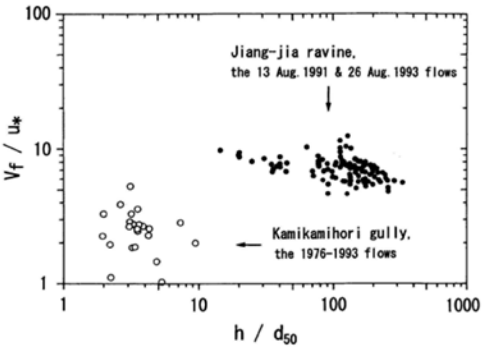

Fig. 7 - Velocity coefficient Vf/u versus relative depth h/d50. Modified after* Suwa *et alii (1997)*

that causes a marked difference in the vertical velocity gradients at the front and rear. Overall, the data indicate a common feature where peaks in hydraulic parameters appear in order of flow depth, discharge, and then surface velocity (Suwa, 1988).

The temporal change in discharge shows a significant focusing of mass on the surge front. This is clear in Figure 6, which shows the longitudinal cross-section of the first surge of the 21 July 1985 debris flow based on the same data as in Figure 5. The horizontal axis, the distance from the surge front, corresponds to the time integral of surface velocity.

BOULDER DAM

The focusing of large boulders towards the surge front is a common feature in boulder-rich debris flows, and is the result of a combination of a few factors. Takahashi (1980) attributed the faster transportation of larger boulders towards the front to the combination of two processes in the flow: an inverse grading process resulting from the upward migration of larger boulders due to a dispersive pressure, and the upward increase in the flow velocity that is common in open-channel flows. Namely, larger boulders tend to migrate upwards to be exposed to higher velocities, and are transported more quickly to the front. Suwa (1988) added another remarkable factor for this boulder focusing as follows. The terminal velocity of boulders on steep slopes is larger than the mean velocity of the surrounding slurry, and the larger boulders attain higher terminal velocities to arrive earlier at the front. In addition, larger boulders are assumed to be transported faster even if the inverse grading effect does not work, because the larger boulders are exposed to higher velocities if the transportation mode is near to bed load, i.e., if the flow mode is hyper-concentrated stream flows. Under these conditions, taller or larger boulders are exposed to higher velocities, depending on the height above the bottom. The actual focusing of large boulders may be caused by a combination of these major factors, and results in the formation of boulder-rich frontal part which is often called as boulder dam.

MOBILITY

Multiple wire-sensors were installed at 30 locations from the source reaches at 1950 m a.s.l. through to the distal fan at 1500 m a.s.l. They recorded data related to the spatial change in frontal velocities of debris flows. Integration of these data indicated that frontal velocities as large as 6–16 m/s appeared at the upper reaches with slope angles of 14–26°. However, they decreased to less than 4.5 m/s at the middle reach observation site with the angle of 7°, and decelerated to less than 1 m/s in the terminal reaches with the angle of 2-6° (Okuda *et alii*, 1980).

The data have indicated that large-scale debris flows with high mobility tend to have higher frontal velocities. The mobility of debris flows may be evaluated by the velocity coefficient, defined as the ratio of the frontal velocity V_f to shear velocity $u*$ which is approximately equal to

$$\sqrt{gh\sin\theta} \tag{1}$$

in which $\boldsymbol{\theta}$ is the channel floor slope angle, h is the flow depth, and g is gravity acceleration. This coefficient is proportional to $f^{-1/2}$ where f is drag coefficient. Figure 7 shows the relationship between velocity coefficient and relative depth of debris flows, where relative depth is defined as the ratio of flow depth to the median di-

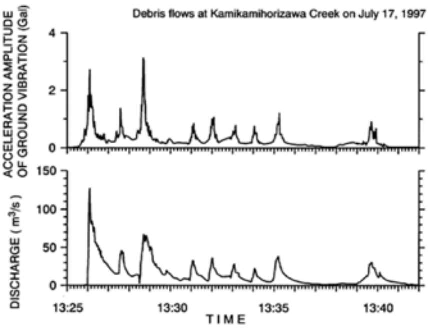

Fig. 8 - Temporal changes in the acceleration amplitude of ground tremor and the discharge of the July 17, 1997 debris flow. Modified after Suwa et al. (2003)

ameter of the solid particles in the flow. The figure shows that the mobility of the Kamikamihorizawa debris flows is much smaller than that of the Jiangjia debris flows in China (Suwa *et alii*, 1997).

GROUND TREMOR

Travel of boulder-rich debris flow is accompanied by ground tremors and sounds like long-lasting thunder, the intensity of which increases as the debris-flow surges approach the monitoring sites. Figure 8 shows the temporal change in the acceleration amplitude of ground tremors along with a hydrograph of a debris flow. The time series data clearly show the approach and passage of the surges. The seismic signal can be monitored before the arrival of the surge at the monitoring site, showing that debris-flow warning using seismometers would be effective for the mitigation of hazards. Attempts have been made to develop an intelligent system to warn about debris flows for evacuation using seismic signal detection (e.g., Kurihara *et alii*, 2007). On the other hand, seismic signal detection has been applied to trigger video camera operation at many monitoring sites of debris flows (e.g., Suwa & Sumaryono, 1996), while it should be stated that the intensity of the ground tremor was too small to trigger the same sets of video cameras at Jiangjia creek where debris flows do not radiate very strong elastic wave due to complete absence of boulder dams.

Studies of the debris-flow seismicity resulted in several new insights. The intensity of the ground tremor increases as the boulder dam approaches the monitoring site and decreases as they passes, as shown in Figure 8. The dominant frequency, i.e., the peak spectrum of the ground tremor, is in the 20-30-Hz range during the approaches and in the 40-60-Hz range as the flows pass by (Suwa & Okuda, 1985). This may due to collision of the larger boulders in the boulder dam that contributes strong wave radiation with longer periodicity, while collision of smaller gravels contributes weaker wave radiation with shorter periodicity.

A clear positive correlation with correlation coefficient of 0.89 was found between the peak of the flow discharge and the peak of the tremor acceleration amplitude. This strong correlation suggests that estimation of the peak discharge is possible by monitoring the acceleration amplitude. There is also a positive correlation with coefficient of 0.98 between the total volume of the surges and the time integral of the acceleration amplitude of the tremors. This strong correlation suggests that estimation of debris-flow volume is possible using the time integral of the acceleration amplitude (Suwa *et alii*, 2000). A small fraction on the order of 10^{-3} of the total kinetic energy consumed as internal and boundary friction is radiated as elastic-wave energy by the passage of debris-flow surges. The conversion efficiency in debris flows from the loss of kinetic energy to elastic-wave energy through friction is estimated at about 10^{-3}, which is much smaller than efficiencies on the order of 10^{-1} found in the case of earthquakes (Suwa *et alii*, 2003).

RAINSTORM CONTROL

Boulder dams have a number of different features. In some cases, all the interstices between the boulders are filled with slurry matrix, while in the others, the interstices remain completely empty. Namely the dam consists of an openwork structure. Okano *et alii* (2009) analyzed the rainstorm control on such different features to find that the large and longer-duration rainfalls, for instance, in the previous 24 hr increase the water content in the source deposits, causing debris flows with large boulder dams in which the inter-boulder spaces are filled with slurry. However, the combination of small rainfalls in the previous 24 hr and large rainfall intensities with durations as short as 10 min cause low water content in the source deposits, resulting in debris flows with small boulder dams in which the inter-boulder spaces are completely empty as arranged in Figure 9. Namely they characterized three types of debris flows: Large flows havng boulder dam without openwork structure (Type I), small flows having boulder dam with openwork structure (Type II), and small

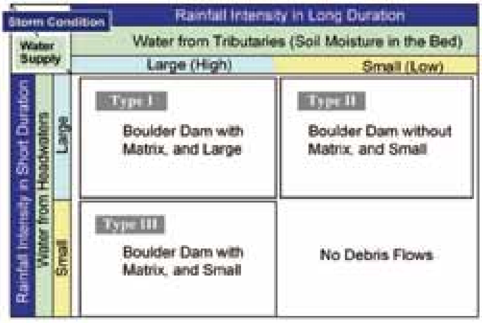

Fig. 9 - Rainstorm control of debris flows at Kamikamihorizawa Creek, Mount Yakedake

flows having boulder dam without openwork structure (Type III). Rainfall conditions were found to have controlled the difference of these types through water availability to debris flows at the source and growth reaches of debris flows.

DEPOSITION

Debris flows decelerate with a decrease in the slope of downstream reaches or of the fan, and halt there to deposit coarse clastic materials. Figure 10 shows the debris flows in motion (A), deposits artificially trapped by a ring-net debris-flow breaker (B) near the middle reach observation site, and a debris-flow lobe in the fan (C). The pictures show that the main part of boulder dams consists of openwork structure. It should be marked that the Type II out of the three types of debris flows leaves this openwork structure in its deposits. The result may be caused also by escape of slurry matrix at the moment of debris-flow termination. Hooke (1967) found the openwork structures consisting of boulders on the alluvial fans in an arid region of California and named them sieve deposits differentiating it from debris flow deposits. However the sieve deposits may be equivalent to the boulder-dam deposits with openwork structure, because Suwa & Okuda (1983) reported very similar openwork structures of fresh debris-flow deposits and named them as swollen lobe of debris-flow deposits. The swollen lobes have steep fronts, referred to snouts (Johnson, 1970).

Afterwards Suwa & Yamakoshi (1999) reported the regulated distribution of debris-flow lobes in the fan where swollen lobes locate in the upper parts in the fan and the flat ones locate in the lower parts. The distribution now indicates that the debris-flows types I and II as indicated in Figure 9 can travel longer distances in the fan and leave flat lobes without openwork structure, on the other hand the flows type II would travel shorter distances and leave the swollen lobes with openwork structure as found in Figure 11.

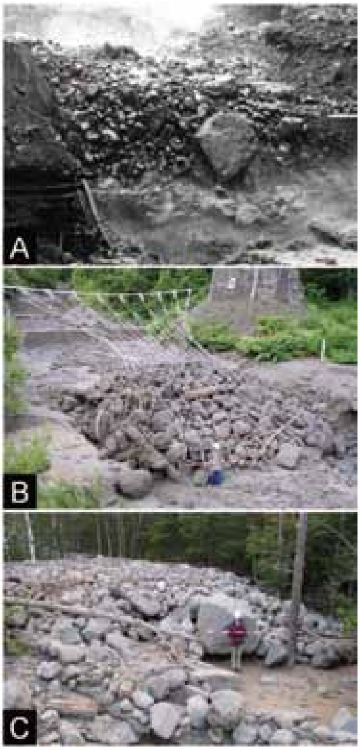

Fig. 10 - The 6 August 1976 debris flow in motion (A), the 18 July 2004 debris flow trapped by the ring-net breaker (B) both at the middle reach observation site, and the terminal part of the 18 July 2004 debris flow on the fan (C)

Debris flow discharge at each event does not cover whole surface of the fan, but cover only a narrow belt in a radial direction of the fan. Debris flows keep their travel courses in this narrow belt during a period of several years or more as shown in Figure 11. Termination point would migrate upwards in the belt. The orientation of the travel course would abruptly migrate when the termination point reaches at the fan head (Suwa & Yamakoshi, 1999).

CONCLUDING REMARKS

Studies from the data from the 40 years of debris-flow monitoring at Kamikamihorizawa supplied a general concept of the debris-flows and their geomorphic effects at volcanic slopes as follows. Debris flows would occur with heavy rainfall. Threshold of rainfall intensity for debris flows increase with time after the end of volcanic eruption, while it drastically

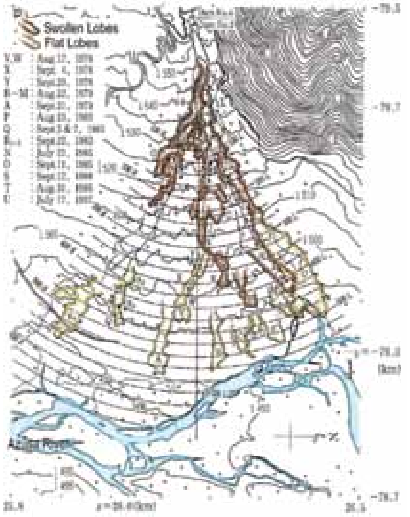

Fig. 11 - Superposition of debris-flow lobes on the Kamimaihorizawa fan during 1978–1997, modified after SUWA *&* YAMAKOSHI*, 1999. Routes (a), (b), and (c) denote the three main orientations in which the previous debris flows were conveyed*

decreases with volcanic eruption. Three types of debris flows were found: Large flows with boulder dam without openwork structure (Type I), small flows with boulder dam with openwork structure (Type II), and small flows with boulder dam without openwork structure (Type III). Rainfall conditions were found to have controlled the difference in these types through water availability for debris flows at the source and growth reaches of debris flows. Mass and boulder focusing to the frontal part of the flow is marked, and due to this focusing the flow radiates elastic wave whose energy is from the potential energy of the flow, and the energy conversion efficiency is calculated as a magnitude of 10^{-3} much smaller than the efficiency of earthquake at the magnitude of 10^{-1} from strain energy to elastic-wave energy. Debris flows terminate in the fan leaving two types of debris-flow lobes: swollen lobe and flat lobe. Main source of the flat lobe is attributed to the Types I and III, while the swollen lobe to the Type II. It would be important to understand this concept of volcanic debris flows from its initiation to termination for mitigation of debris-flow hazards.

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