**Original Article**

**Direct Debris Flow Measurements using DFLP system at Kamikamihorizawa Creek**

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Monitoring tools for direct debris flow measurements using sensors such as load cells were first installed in Japan in the Arimura River on Sakurajima Island, Kagoshima Prefecture, where volcanic activity is severe, and numerous debris flows have occurred due to falling ash after eruptions. This system, which is collectively referred to as a DFLP system and is equipped with load cells and pressure sensors, collects information on debris flow characteristics such as specific weight and volumetric sediment concentration. Another DFLP system was installed at Kamikamihorizawa Creek, on the eastern side of Mt. Yakedake, Nagano Prefecture, in November 2014, where significant sediment deposition and large numbers of debris flows have been observed. The present study reports on debris flow surges monitored by this system on August 29, 2019. More than five surges were monitored using the DFLP during 20-minute period, and the rainfall intensity for a 10-minute period just before those events was 12mm, resulting in an accumulated depth of 56mm. During the debris flow surges, both stable and continuous sediment concentration measurements were performed. Using the flow discharge calculated from closed-circuit television video images, the time-averaged sediment concentration and relative mass density were calculated as 0.470 and 1.73, respectively. The equilibrium sediment concentration of coarse sediment particles for the slope bed was estimated at 0.160 by the previous knowledge and 0.201 by the DFLP, with the higher DFLP value attributed to the presence of fine sediment particles in the mud phase.

**Key words**: DFLP system, Debris flow, Sediment concentration

1. INTRODUCTION

Observations of debris flows have been reported in numerous studies over many previous decades [e.g., Arattano, 1999; Rickenmann, 1999; Suwa et al., 2019], and systematic research into the mechanics of these flows, including detailed investigations in flume tests, has been carried out for approximately 60 years [e.g., Daido, 1971; Rickenmann, 1999].

Previous studies of debris flow mechanisms have examined non-uniform-sized debris in mountain torrents via flume tests and field observations as part of efforts to clarify those mechanisms. However, it is still difficult to grasp the vertical and longitudinal component segregation of sediment particles and the vertical profiles of velocity and volumetric concentration that are related to pressure and stress.

In Japan, the Disaster Prevention Research Institute of Kyoto University (DPRI) and the Matsumoto Sabo Office of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) began debris flow monitoring and observations at Kamikamihorizawa Creek on the eastern slope of Mt. Yakedake in 1970 [e.g., Suwa et al., 1973; Okuda et al., 1980]. Heavy rainfalls have caused numerous debris flow events since the last phreatic explosion of this volcano in 1962. Those observations, which continued until the 2000s, resulted in the collection of vast amounts of data on phenomena such as the longitudinal spreading velocity of the frontal part, temporal changes of surges, the relationship between the flow peak discharge rate and the volume, and other factors.

At Sakurajima Island, debris flow observations were carried out from the 1970s to monitor the debris flow occurrences that followed volcanic eruptions [e.g., Osaka et al., 2014], as well as at Kamikamihorizawa Creek, where sediment-water mixture measurements of debris flow bodies were carried out manually with a sampling box to evaluate sediment concentrations. However, little information regarding sediment
concentrations, pressure, and stress has been collected by previous debris flow observations because it is still difficult to measure pressure, shear stress, and sediment concentrations in moving debris flow bodies via field observations.

As part of efforts to rectify this, modified debris flow measurement tools based on a system equipped with load cells and pressure sensors (hereafter referred to as a DFLP system) that were initially developed by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) [McArdell et al., 2007] were first installed along the Arimura River on Sakurajima Island, Kagoshima Prefecture [Osaka et al., 2014]. This is a location where volcanic activity is severe and where numerous debris flows take place. This DFLP system collects data on debris flow characteristics such as specific weights and volumetric sediment concentrations [Osaka et al., 2014].

Following the Sakurajima Island system installation, another DFLP system was installed in Kamikamihorizawa Creek, which is located on the eastern side of Mt. Yakedake, Nagano Prefecture, in November 2014. This installation took place seven years after the last phreatic explosion of this volcano, at a location where heavy rainfall often causes debris flow events and which has been closely monitored since 1970 [e.g., Okuda et al., 1980].

Unlike debris flow observation systems that monitor surges using loadcells installed in small boxes [Scott et al., 2011], DFLP systems measure bed force and bed surface pore water pressure over wide areas, which is why current observations using DFLP systems are more suited for evaluating changes to the force balance on a bed surface caused by moving debris flow surges. Accordingly, this paper introduces examples of bed force measurements and the related sediment concentration calculations that were measured and calculated using the DFLP system at Kamikamihorizawa Creek.
2. KAMIKAMIHORIZAWA CREEK DFLP SYSTEM

2.1 DFLP system

As stated above, the Kamikamihorizawa Creek DFLP system was installed in November 2014, even though Mt. Yakedake’s volcanic activity was quiescent at that time, because it is a site where a significant number of debris flows and large amounts of sediment deposition have been reported previously. After completion of static on-site weight tests, active measurements began on July 14, 2015. Figure 1 shows the location of Kamikamihorizawa Creek and installed sensors.

Figure 2 shows a schematic layout of the DFLP site, which was installed at the Kamikamihorizawa No. 6 Weir (See Fig. 1) at a location where an 8° bed slope was fabricated by the installation of a gabion just upstream. Longitudinal bed profiles are shown below (Fig. 8 in 3.2). The force plate (which was 4 m wide and 2 m long) and load cells used were identical to those used in the Sakurajima Island system. In this DFLP system, a pin-type load cell (JFE Advantech Co., Ltd.) was used to measure weight while the vertical force component was measured by a force plate, thus allowing both the vertical and horizontal components of force on the bed to be measured at the site. The load cell and pressure meter data were collected at a sampling rate of 100 Hz. An NR 600 data logger (Keyence Co., Ltd., Osaka, Japan) was set at the observation station near the right bank of the Kamikamihorizawa No. 6 Weir. The sensors were then inspected, and the outputs of the pressure meters were modified by field tests to calibrate the relative zero used for measurement purposes.

2.2 Other sensors

2.2.1 CCTV video camera and ultrasonic level sensors

In addition to the DFLP system components, the other sensors installed at the site include closed-circuit television (CCTV) video cameras, an ultrasonic level sensor, and a velocity meter, as shown in Fig. 1.

The CCTV video camera is used to evaluate flow conditions and flow velocity on the DFLP plate, while the ultrasonic level and velocity meters measure the flow depth and surface velocity of debris flow surges, respectively. Digital images captured by the CCTV system at 10-second intervals are recorded at the Matsumoto Sabo Office.

The ultrasonic sensors, which are produced by Koito Electric Industries, Ltd. (Shizuoka, Japan), capture data at a resolution of 1.0 m/s and 0.01 m, and the measured data are recorded at the observation station at one-minute intervals without time-averaged processing.

The measurement areas on the bed surface are approximately 0.32 m² and 0.6 m² for flow depth and velocity, respectively. However, the areas become smaller when debris is flowing, and measurements can be usually affected by splashes near the free surface of debris flows.

To calculate the surface velocity, CCTV-captured images are analyzed manually, primarily by visual inspections, because observers can more easily pick
out objects in the debris flow and are uninfluenced by splashes near the free surface.

2.2.2 Rainfall measurement
Rainfall intensity is mainly measured by a telemeter based on radar observations. The telemeter is installed at Yakedake Station, which is shown in Figs. 1 and 4. Radar rainfall intensity is calculated for a 1 km$^2$ area around Kami-kochi using a C-band polarimetric radar, as shown in Fig. 4.

3. DEBRIS FLOWS ON AUGUST 29, 2019

3.1 Rainfall
During the massive rainfall that took place from August 27 to 30, 2019, Yakedake Station recorded an accumulated rainfall depth of 217 mm and a maximum rainfall intensity of 35 mm/h at 06:00 on August 29, as shown in Fig. 3. In Fig. 4, which shows rainfall intensity based on radar measurements, it can be seen that a heavy magnitude of rainfall was observed at 04:00. Figure 5 shows the rainfall intensity at 04:40 that same day when 12 mm of rain fell at Yakedake Station during a 10-minute period.

3.2 Debris flows
On August 29, 2019, the DFLP system observed and measured several debris flow surges resulting from a short period of rainfall. The rainfall intensity was measured at 12 mm in a 10-minute period (Fig. 5).

![Fig.6 Bed condition around the DFLP installed before and after the debris flow events recorded on August 29, 2019, at Kamikamihorizawa Creek](image)

![Fig.7 Temporal changes of flow depth, surface velocity, loads, and pressure on the bed measured by several sensors and DFLP system](image)
Fig. 8 Longitudinal bed profiles along Kamikamihorizawa Creek.

Fig. 9 Temporal changes of flow depth, surface velocity, discharge, loads on the bed and calculated sediment concentration & specific weight of debris flow by DFLP system.

Fig. 10 Relationship between relative depth and velocity factor.
resulting in an accumulated depth of 56 mm, and triggering seven debris flow events within a 20-minute period shortly thereafter. Figure 6 shows two views of the installation site. The left- and right-side images were taken before and after the debris flow events recorded on August 29, 2019, respectively. Debris flow surges also transported numerous boulders.

**Figure 7** shows the temporal changes in various quantities observed on August 29, 2019, including flow depth and velocity measurements obtained by ultrasonic sensors, the vertical and horizontal weight components obtained by load cell measurements, and the bed water pressure as measured by the pressure meter. Flow depth and surface velocity values based on CCTV image analyses are also shown. However, due to variations in the original values, the measured values using the pressure meter are shown by a solid line, while the modified values are shown by a dashed line. The modification relationship is as follows: head (m) = 0.557 × (measured head : m) + 0.051 by field tests.

Due to the large velocity changes at Kamikamihorizawa Creek, measured data were plotted as follows: flow depth, velocity by the ultrasonic sensor, load, and pressure on the bed were plotted every 10 s during after 5-s time-average. The CCTV image analyses were plotted every 10 s.

The abovementioned seven debris flow surges were observed during the 20-min period beginning around 04 : 32, and peaks of these surges were recorded at (a) 04 : 33 : 40, (b) 04 : 35 : 00, (c) 04 : 37 : 00, (d) 04 : 38 : 40, (e) 04 : 39 : 40, (f) 04 : 41 : 30 and (g) 04 : 48 : 00. While all of the surges were detected by the DFLP system and the CCTV camera, surges (a) to (d) were also detected by ultrasonic level meters and ultrasonic velocity meters.

**Figure 8** shows longitudinal bed profiles along Kamikamihorizawa Creek. Averaged bed slope is 5.9° around and downstream reach of the No. 6 Weir where the DFLP system is installed, and the deposition is dominant for debris flow surges. Herein, the bed slope is 8.0° just upstream of the No. 6 weir as described in 2.1. **Figure 9** shows the sediment concentration and relative mass density as calculated by the previous method [Osaka et al., 2014], which uses the flow depth, bed pore water pressure, and surface velocity. The free surface velocity was compared with calculations based on the Manning resistance equation to evaluate the flow resistance of the bulk debris flow body because seven debris flow surges took place during the above-mentioned 20-min period. More specifically, the velocity for each peak was estimated using a Manning coefficient of 0.05 m 1/3 s for the ultrasonic sensor and 0.06 m 1/3 s for CCTV images. The measured velocity is for the free surface, and the depth-averaged velocity is 3/5 times as large as the surface velocity if the vertical profile of velocity follows the 3/2 power law, which is a well-known value for debris flow resistance. However, the depth-averaged velocity is somewhat faster when the Manning resistance law is used.

**Figure 10** shows the relative depth versus velocity factor using data collected for this event. In this figure, h is the flow depth, d is the representative diameter of the debris flow, U is the depth-averaged velocity, u* is the shear velocity (defined as $\sqrt{gh \sin \theta}$), g is the acceleration due to gravity, and $\theta$ is the bed slope. The value of d was supposed as 0.1m and the diameter was specified as $d_{oa}$. Herein, $d_{oa}$ is representative value for grain size distribution and the value means sixty percent on the accumulated line of the distribution. The value of $d_{oa}$ was supposed by photographic analysis after the event. Some flow resistances, such as the minimum value of logarithmic flow resistance of clear water, $U/u_{*}=6.0$ applying that $\lambda=8.5$ and $\kappa=0.4$, and empirical formula [Takahashi, 2007], are also shown in the figure. Previously observed data [Suwa et al., 2019] is indicated in **Fig. 10**. Here, it should be noted that those values are smaller than usual for debris flow resistance.

Next, we will discuss the calculated data for sediment concentrations and relative mass density levels. At the peaks of the debris flow surges from (e) to (g), which followed the (a) to (d) surges, it was possible to estimate the sediment concentration.

In **Fig. 9**, it appears that the time-averaged sediment concentration and relative mass density during the 20-min period beginning at 04 : 33 : 00 were 0.470 and 1.73, respectively, for CCTV measurements; and 0.323 and 1.53, respectively, for ultrasonic sensor measurements. The depth-averaged sediment concentration, $c_{oa}$, was calculated at 0.160 for coarse debris component particles using Takahashi’s formula
The depth-averaged sediment concentration, which means the equilibrium sediment concentration, is defined as

\[ c_\text{eq} = \frac{\tan \theta}{(\sigma/\rho - 1)(\tan \phi - \tan \theta)} \]

in which \( \theta \) is the bed slope, \( \sigma \) is the mass density of sediment particles, \( \rho \) is the mass density of clear water, and \( \phi \) is the interparticle friction angle. Values for calculation of Eq. (1) are used as follows: \( \sigma/\rho = 2.65 \), \( \phi = 34^\circ \), and \( \theta = 8^\circ \).

It should be noted that the sediment concentration calculated using the DFLP system was much larger than \( c_\text{eq} \) because the component consisting of fine sediment particles (mud phase) becomes extremely condensed due to the rapid velocity of the debris flow and other factors. Sediment concentration takes zero to unity, and influences of air on debris flow body and noises due to sensors during debris flowing could appear in case that the value takes over \( c_\text{eq} \) which is sediment concentration in the non-flowing layer.

Figure 11 shows the temporal changes in debris flow characteristics such as the discharge of the water and sediment mixture, sediment discharge, debris flow body sediment concentration, and coarse phase sediment concentration. Sediment concentration was calculated for the debris flow and the coarse phase by the DFLP system. In the figure, the origin is 04:30, and the temporal changes in the discharge and concentration cover the next 20 minutes.

The sediment concentration of 0.470 was calculated by a time average over a 20-min period, as shown in Fig. 11. A previous study [Osaka et al., 2014] showed that sediment concentrations could be divided into two components: coarse-particle and mud phases, with the sediment concentration of the mud phase calculated by the pressure sensor. Hence, using the DFLP system, the time-averaged value of 0.458 in Fig. 11 can be divided by 0.201 for the coarse phase and by 0.257 for the mud phase. The sediment runoff volume was calculated as 17,017 m³ without pore by the DFLP system analysis.

Figure 12 shows the temporal changes in the ratio of the horizontal to normal force exerted on the bed slope just upstream of the DFLP system where the debris flows were running. The bed slope value is 0.141 (= tan 8°). In the figure, (A) to (G) refer to the times when the peak surges occurred. The horizontal force component is also shown. If the debris flows satisfy the fully-laden condition of a water and sediment mixture, the ratio of the horizontal to the normal components of the bed force must be equal to the bed slope, tangent (θ). The ratio near the peak stage is almost 0.141 (tan 8°); and the effects of sediment deposition on the vertical weight measurement on the force plate could appear in the decreasing stage of the flow, except for (A) to (G). This indicates that both bed force components can be measured using the DFLP system and that the ratio of these components can be confirmed by measurements of debris flow surges. The measured components of force on the bed could lead to shear stress in debris surges flowing, and data collection is needed via continuous field observation by observed data in several magnitude of debris flow surges.

4. CONCLUSIONS

The DFLP system that was installed at Kamikamihorizawa Creek in November 2014 was used to measure debris flow events on August 29, 2019. The results obtained in the present research are as follows:

1. Seven surges corresponding to debris flow events were monitored during the 20-min period using the DFLP system. Rainfall intensity during a 10-min period just before the surges was measured at 12 mm, and the accumulated depth was estimated at 56 mm. The time before those events was 4.5 hours.

2. The DFLP system measured multiple debris flow surges, and sediment concentrations were calculated continuously. The time-averaged sediment concentration and relative mass density were estimated to be 0.470 and 1.73, respectively, via CCTV, and 0.323 and 1.53, respectively, via ultrasonic meters. The equilibrium sediment concentration was estimated to be 0.160 for coarse sediment particles, and it was found that the equilibrium value calculated using the DFLP exceeded the value obtained using the previous
calculation method due to the inclusion of fine sediment particles in the mud phase.

(3) The DFLP system can measure the normal bed and flow direction components independently, and the validity of the measured values can be confirmed by considering the force balance in a uniform flow field.

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REFERENCES
Arattano M., Marchi L., Genevois R., Berti M., Simoni A., Tecca P. R. and Bonte M. (1999) : Field monitoring and real time management of debris flows, European Project “Debris Flow Risk” (N. ENV 4960253), Final Report (1999 : 30).
Daido, A. (1971) : On the Occurrence of mud-debris flow, Bulletin of the Disaster Prevention Research Institute, 21(2), pp. 109-135.
McArdell, B. W., Bartelt, P. and Kowalski, J. (2007) : Field observations of basal forces and fluid pore pressure in a debris flow, Geophysical Research Letters, Vol. 34, L 07406.
Okuda, S., Suwa, H., Okunishi, K., Yokoyama, K. and Nakano, M. (1980) : Observation of the motion of debris flow and its geomorphological effects, Zeitschrift fur Geomorphology, Suppl. -Bd. 35, pp. 142-163.
Osaka, T., Utsunomiya, R., Tagata, S., Itoh, T. and Mizuyama, T. (2014) : Debris Flow Monitoring using Load Cells in Sakurajima Island, Proceedings of the Interpraevent 2014 in the Pacific Rim (edited by Fujita, M. et al.), Nov. 25-28, Nara, Japan, 2014, O-14. pdf in DVD.
Rickenmann, D. (1999) : Empirical Relationships for Debris Flows, Natural Hazards 19, pp. 47-77.
Scott, W. M., Jeffrey, A. C., Jason, W. K., Greg, E. T., Dennis, M. S. and Thad, A. W. (2011) : Observations of debris flows at Chalk Cliffs, Colorado, USA : Part 1, In Situ Measurements of flow dynamics, tracer particles movement and video imagery from the summer of 2009, Italian Journal of Engineering Geology and Environment, 1, pp. 65-75.
Suwa, H., Okuda, S, and Yokoyama, K. (1973) : Observation system on rocky mudflow, Bulletin of the Disaster Prevention Research Institute, Kyoto University, No. 23(3-4), pp. 59-73.
Suwa, H., Okano, K. and Kanno, T. (2019) : Forty years of debris-flow monitoring at Kamikamihorizawa Creek, Mount Yakedake, Japan, Proceedings of 7th international Conference on Debris-flow Hazards Mitigation (by Genevois, Hamilton & Prestinzi), Golden, Colorado, USA, June 10-13, 2019, pp. 605-613.
Takahashi, T. (1980) : Debris flow on prismatic open channel, J. Hyd. Div., New York : ASCE, 106(3), pp. 381-396.
Takahashi, T. (2007) : Debris Flow : Mechanics, Prediction and Countermeasures, Taylor & Francis Group, London, UK, 448 p (Referred Equation (128) in p. 75).

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