Continuous debris flow monitoring using DFLP and LVP on Sakura-jima Island

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Abstract. Since 2010, numerous debris flows have occurred on Sakura-jima Island due to rainfall events that occurred after extensive ash deposition associated with volcanic activity. The study area included the Nojiri and Arimura rivers in the southwestern and southeastern parts of Sakura-jima, respectively. Debris flow monitoring systems consisting of loadcell and pressure sensor (DFLP) were installed to evaluate characteristics of moving weight and so on during debris flows. The systems were installed at the Arimura River No. 3 sabo dam in June in 2012 and at the Nojiri River No. 1 sabo dam in 2014. In addition, LVP (Load, Vibration and Pressure) sensors consisting of loadcells and accelerometers for measuring vibration and pressure were installed on the riverbed for debris flow detection. Modified LVP systems were installed at the Nojiri River No. 7 sabo dam in February in 2015, and at the Arimura River No. 3 sabo dam in October in 2016. Interesting characteristics of debris flows were obtained by the DFLP and LVP systems. The findings showed that the sediment concentrations of both the coarse and the suspended and liquid phases could be estimated by the DFLP systems, and several patterns of debris flows were observed by the LVP systems.

1 Introduction

Numerous debris flows have occurred on Sakura-jima Island in southwestern Japan due to rainfall events that followed extensive ash deposition due to the volcanic eruptions that have occurred on the island since 2010. Debris monitoring using a variety of sensors has been carried out at the sabo dams along the Nojiri River and Arimura River. The monitoring stations and catchments have the following characteristics. The Nojiri River drains a catchment measuring 2.99 km^2, has a bed slope of 4.5% and a flow width of 13.2 m at the Nojiri No. 1 sabo dam. The Arimura River drains a catchment measuring 1.35 km^2, has a bed slope of 19% and a flow width of 20.5 m at the Arimura No. 3 sabo dam. In addition, the average bed slope of the storage area of the Nojiri No. 1 and Arimura No. 3 sabo dams is 4.5% and 6.5%, respectively.

A DFLP is continuous measurement system comprising loadcells and pressure sensors [1]. A modified DFLP [2] was installed at Arimura No. 3 sabo dam in 2012. In the Nojiri river, three newly developed DFLP systems employing an iron plate (1 m^2) for measuring moving weight were installed at the No. 1 sabo dam in 2014 [3]. The sensors, which were evenly spaced in the transverse direction, were maintained during monitoring because of impacts with boulders due to debris flows. In addition, maintenance was required for the loadcells on three occasions (26th April, 9th June and 9th September) and the pressure sensor (9th June and 9th September) at the Nojiri No. 1 sabo dam in 2021

An LVP, that is a sensor for load, vibration and pressure, system and wires were installed on the river bed for debris flow detection. The system consisted of pressure meter, loadcells and an accelerometer for measuring vibration [2, 3]. The sensor has been maintained mainly for the detection of debris flows on an event-to-event basis [2, 3].

In the present study, temporal changes in the specific weight and sediment concentration of coarse/fine components of the debris flows were investigated using DFLP systems installed in the Nojiri and Arimura Rivers. Data obtained by a LVP system also showed temporal changes in flow depth, load and vibration during debris flows. As a result, threshold values were proposed for debris flow detection. Those could be used in near future looking ahead application of online tools for debris flow detection using a LVP system.

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2 Estimates of sediment concentration by DFLP

A variety of sensors have been employed to measure the occurrence and runoff characteristics of debris flows along the Arimura and Nojiri Rivers, including rain gauges, X-band multi-parameter (MP) radar, ultrasonic water level meters, wire sensors, falling ash gauges, acceleration vibrographs (only in the Arimura River) and closed-circuit television (CCTV) cameras [3, 4]. On Sakura-jima Island, the number of debris flows are counted by the number of wires that become disconnected from wire sensors during events. Also, to determine the magnitude of debris flows, wires are installed vertically on the bed surface at distances of 60, 120 and 180 cm. DFLP data are recorded at a sampling rate of 100 Hz using a pulse measurement unit (NR6000, Keyence Corp., Osaka, Japan). Sediment concentration is calculated using time-averaged data at 1 min intervals, as described previously [2-4].

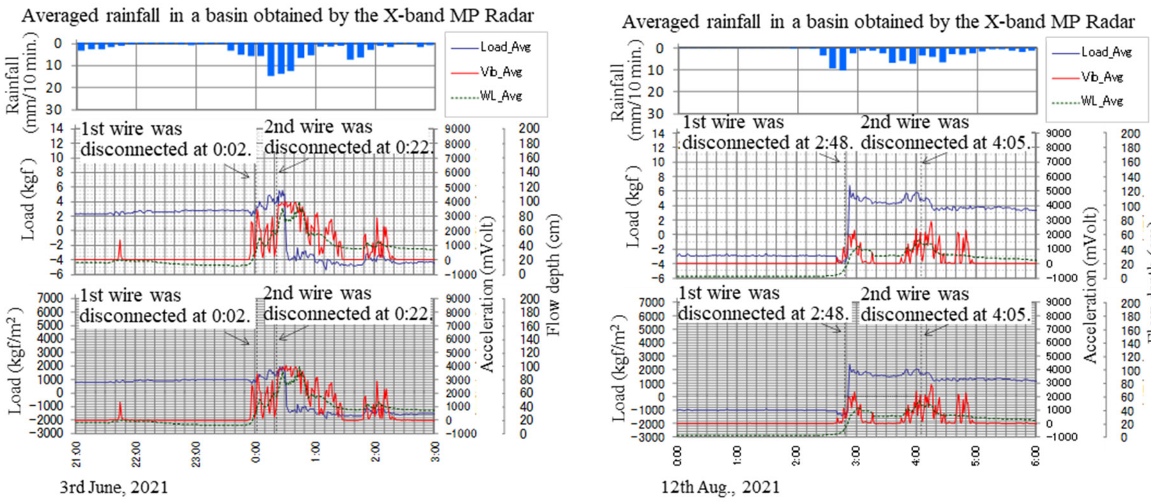
Tables 1 and 2 show the estimated sediment concentration of debris flows measured using a DFLP at Arimura No. 3 sabo dam and Nojiri No. 1 sabo dam, respectively. The parameters in the tables are as follows: Wire: number of disconnected wires, c: time-averaged volumetric sediment concentration near the peak stage, C: coarse sediment concentration, F: fine sediment concentration, R: accumulated rainfall depth before debris flow (mm), r_{10}: maximum rainfall depth during 10 min before debris flow (mm), Q_p: peak discharge (m^3/s). In Table 2, the asterisk indicates peak discharge of debris flow for data collected at Nojirigawa No. 1

Table 1. Sediment concentration of debris flows calculated by a DFLP at Arimura No. 3 sabo dam.

No.	Y/M/D	Wire	c	R, r_{10}	Q_p
1	2016/9/20	2	0.402 (C: 0.0679, F: 0.334)	74.0 (-)	132
2	2017/5/13	1	0.545 (C: 0.293, F: 0.252)	30.0 (-)	103
3	2017/7/4	1	0.323 (C: 0.222, F: 0.101)	11.0 (-)	106
4	2017/8/15	1	0.303 (C: 0.174, F: 0.129)	5.0 (-)	44.0
5	2018/5/2	2	0.306 (C: 0.164, F: 0.143)	18.0 (4.0)	137
6	2018/12/3	2	0.247 (C: 0.155, F: 0.0915)	5.0 (2.0)	124
7	2019/3/3	1	0.386 (C: 0.00, F: 0.386)	11.0 (5.0)	42.4
8	2019/3/10	1	0.356 (C: 0.286, F: 0.148)	18.0 (4.0)	78.0
9	2019/9/6	1	0.346 (C: 0.00, F: 0.346)	36.0 (12.0)	98.5
10	2020/3/27	1	0.510 (C: 0.246, F: 0.264)	11.0 (2.00)	51.6
11	2020/6/11	2	0.478 (C: 0.477, F: 0.01)	8.00 (4.00)	180
12	2020/7/24	1	0.254 (C: 0.253, F: 0.01)	42.0 (12.0)	99.0
13	2021/5/15	3	0.314 (C: 0.314, F: 0.00)	34.0 (18.0)	178
14	2021/6/4	2	0.322 (C: 0.322, F: 0.00)	135 (16.0)	272
Average			0.364 (C: 0.213, F: 0.151)		

Table 2. Sediment concentration of debris flow calculated by DFLP at Nojiri No. 1 sabo dam.

No.	Y/M/D	Wire	c				R, r_{10}	Q_p
			Averaged	Left	Center	Right		
1	2016/7/11	2	0.288 (C: 0.245, F: 0.0398)	0.257 (C: 0.211, F: 0.0346)	0.285 (C: 0.217, F: 0.0680)	0.323 (C: 0.306, F: 0.0168)	14.5 (-)	31.9
2	2017/6/20	2	Outliers	—	—	—	40.0 (6.00)	28.4
3	2017/6/24	2	Outliers	—	—	—	46.0 (8.00)	112
4	2018/5/2	3	0.539 (C: 0.488, F: 0.0510)	0.369 (C: 0.230, F: 0.139)	0.766 (C: 0.753, F: 0.0122)	0.482 (C: 0.482, F: 0.00)	19.0 (7.00)	128
5	2018/8/24	3	0.347 (C: 0.346, F: 0.001)	0.159 (C: 0.159, F: 0.00)	0.518 (C: 0.514, F: 0.00453)	0.364 (C: 0.364, F: 0.00)	5.00 (4.00)	62.3
6	2018/12/3	3	0.440 (C: 0.435, F: 0.005)	0.223 (C: 0.222, F: 0.00118)	0.622 (C: 0.609, F: 0.0132)	0.475 (C: 0.475, F: 0.0000106)	12.0 (9.00)	93.5
7	2019/3/3	2	0.129 (C: 0.0493, F: 0.0793)	0.0157 (C: 0.0137, F: 0.00200)	0.149 (C: 0.0307, F: 0.118)	0.221 (C: 0.104, F: 0.118)	5.00 (2.00)	213
8	2019/3/6	2	0.309 (C: 0.108, F: 0.201)	0.122 (C: 0.122, F: 0.00)	0.379 (C: 0.00, F: 0.379)	0.426 (C: 0.203, F: 0.223)	23.0 (7.00)	152
9	2019/10/2	2	0.382 (C: 0.0480, F: 0.335)	0.0757 (C: 0.0757, F: 0.00)	0.688 (C: 0.00, F: 0.688)	0.383 (C: 0.0669, F: 0.316)	6.00 (6.00)	265
10	2019/10/23	2	0.173 (C: 0.0197, F: 0.153)	0.259 (C: 0.0410, F: 0.218)	0.221 (C: 0.00, F: 0.221)	0.0378 (C: 0.0179, F: 0.0199)	7.00 (2.00)	46.7
11	2019/11/24	2	0.239 (C: 0.178, F: 0.0615)	0.310 (C: 0.310, F: 0.00)	0.142 (C: 0.00, F: 0.142)	0.226 (C: 0.224, F: 0.0422)	3.00 (1.00)	60.9
12	2020/6/11	3	0.214 (C: 0.0610, F: 0.153)	0.220 (C: 6.00×10^{-5}, F: 0.220)	0.289 (C: 0.0512, F: 0.237)	0.132 (C: 0.132, F: 0.00)	4.00 (1.00)	107
13	2020/6/25	2	0.313 (C: 0.115, F: 0.199)	0.473 (C: 0.150, F: 0.323)	0.367 (C: 0.153, F: 0.214)	0.100 (C: 0.0409, F: 0.0592)	6.00 (6.00)	56.1
14	2021/5/15	3	0.388 (C: 0.175, F: 0.213)	0.435 (C: 0.363, F: 0.0726)	0.00 (C: 0.00, F: 0.00)	0.728 (C: 0.163, F: 0.565)	9.00 (8.00)	221*
Average			0.314 (C: 0.188, F: 0.125)	0.206 (C: 0.157, F: 0.0480)	0.370 (C: 0.194, F: 0.176)	0. 324 (C: 0.214, F: 011)		



(a) Debris flow events on 3rd to 4th June, 2021 (b) Debris flow events on 12th August, 2021

Fig. 1. Several patterns of debris flow events observed by LVP.

karyu, which is a channel with a trapezium shaped flow area.

The depth-averaged sediment concentration can be calculated using Takahashi's formula [5, 6]; the values were 0.0643 (6.5% bed slope) at Arimura No. 3 and 0.0437 (4.5% bed slope) at Nojiri No. 1 sabo dam, assuming that the specific weight of the bed sediment is 2.65. The coarse sediment concentration can be compared with the values and estimates shown in the tables. The sediment concentration observed at Nojiri No. 1 sabo dam was occasionally close to that estimated using Takahashi's formula [6]. The monitored value was greater than that estimated by Takahashi's formula at the Arimura No. 3 sabo dam because the bed slope at Arimura No. 3 sabo dam changes from 18.9% to 7.1% and the sediment concentration could be affected by several factors such as nonstationary of debris flow. In addition, there are few clear correlations between the sediment concentration of the combined coarse sediment, suspended sediment and liquid phases and the peak discharge, rainfall intensity and accumulated rainfall depth. More monitoring data are required to clarify the reason for this.

3 Detection of debris flow occurrence by LVP

LVP systems installed on the river bed are mainly used to detect continuous debris flows. The sensor can capture information on passing debris flows [3, 4], especially when used in conjunction with wires.

Modified LVP sensors were installed at Nojiri No. 7 sabo dam in February, 2015. The sensors and a stainless steel plate required maintenance in February, 2019 and March, 2022, respectively. In comparison with disconnected wires, the LVP can detect almost all occurrences of debris flow events, except debris flows associated with transverse channel shifting (one event). The LVP data were recorded at a 10 Hz sampling rate using an data logger (CR1000, Campbell Scientific Inc., Logan, USA). The measured data were averaged at one-minute intervals as shown in Fig. 1.

At Arimura No. 3 sabo dam, maintenance of sensors was performed on several occasions in December, 2017, electric issues were resolved in May, 2021, and a new LVP was installed in February, 2022 to replace the

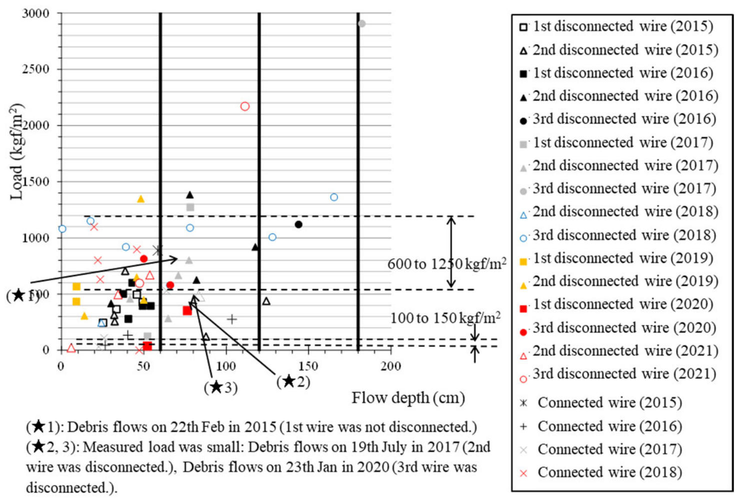


Fig. 2. Relation between flow depth and load at time of debris flow occurrence measured using LVP system and disconnected wires.

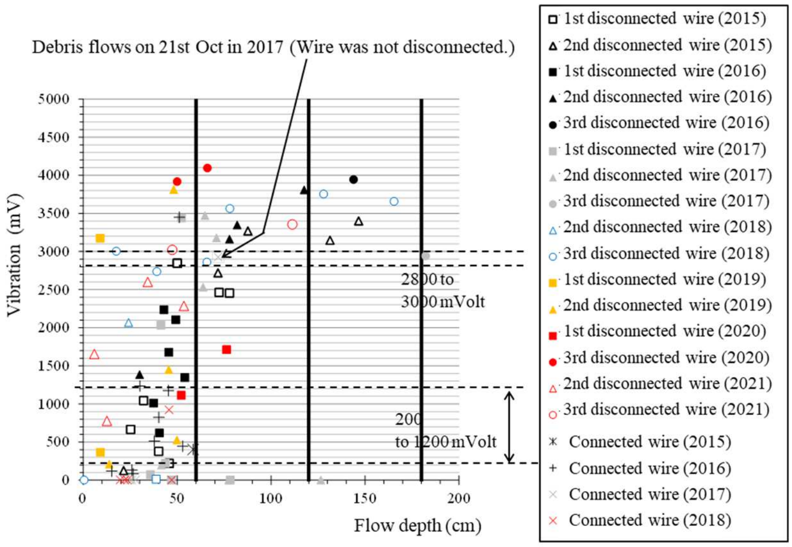


Fig. 3. Relation between flow depth and acceleration due to vibration at time of debris flow inferred by disconnected wires.

original system which was installed in October, 2016. Monitoring has continued, focusing on correlations with DFLP data.

Figures 1(a) and 1(b) show typical debris flow data; the occurrence of wires becoming disconnected is also shown. In the figure, 'Load', 'Vb' and 'WL' refer to the load, acceleration due to vibration, and flow depth for the LVP measurements. Two surges of debris flows were detected by the wires and the LVP. If a debris flow occurs, vibration and flow depth are registered by the sensor, and typical debris flows can be identified by the measured load. Deposited sediment that is present before the debris flow is eroded during such events (Fig. 1(a)). On the other hand, sediment deposition that occurs can remain on the bed during and after debris flow events (Fig. 1(b)).

An LVP detects the flow depth, load and acceleration of vibration, in order, and the data can be used to distinguish the kind of debris flow, i.e., whether it is associated with storny, muddy and other types of debris flows. Figure 2 shows the relation between flow depth and load at the time a wire is disconnected. In addition, the relation between flow depth and acceleration of vibration at the time a wire becomes disconnected has been evaluated since 2016. Figure 3 shows the relation between flow depth and acceleration due to vibration at the time a wire is disconnected. There may be a threshold value for debris flow occurrence and for the magnitude of debris flow. As shown in Figs. 2 and 3, the threshold is measured to determine whether the load is 100-150 kgf/m^2 or 200-1200 mV. For debris flows over 60 cm in depth, the threshold can be 600-1,250 kgf/m^2 or 2,800-3,000 mV.

4 Conclusions

On Sakura-jima, which is still volcanically active, the sediment concentration in two rivers was estimated continuously by a DFLP system, and debris flows were detected using wires in conjunction with an LVP system. Online tools could be used for real-time detection of debris flow occurrences using the LVP. The effects of rainfall intensity on debris flow characteristics, devastation in the sediment yielding area after debris flow occurrence, and the magnitude of such events remain to be clarified using DFLP monitoring data.

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References

1. B. W. McArdell, P. Bartelt, J. Kowalski, *Field observations of basal forces and fluid pore pressure in a debris flow*, Geophysical Research Letters, **34,** L07406 (2007)
2. T. Osaka, R. Utsunomiya, S. Tagata, T. Itoh, T. Mizuyama, *Debris Flow Monitoring using Load Cells in Sakurajima Island*, in Proceedings of the Interpraevent 2014 Pacific Rim (edited by Fujita, M. et al.), 25-28 November 2014, Nara, Japan, O-14.pdf in DVD (2014)
3. T. Itoh, T. Mizuyama, S. Tagata, *Direct debris flow monitoring using load cell systems in Sakurajima Island*, in Proceedings of the 37th IAHR World Congress, 13-18 August 2017, Kuala Lumpur, Malaysia, pp. 1142-1150 (2017)
4. T. Itoh, N. Fujimura, H. Katou, S. Tagata, T. Mizuyama, *Debris Flow Monitoring using load cells and pressure sensors on Sakura-jima Island*, in Proceedings of 7th international Conference on Debris-flow Hazards Mitigation, 10-13 June 2019, Golden, Colorado, USA, pp. 138-145 (2019)
5. T. Itoh, T. Nagayama, S. Matsuda, T. Mizuyama, International Journal of Erosion Control Engineering, **14, 2**, pp.12-19 (2021)
6. T. Takahashi, Journal of the Hydraulics Division, New York: ASCE, **106**(3), pp. 381-396 (1980)