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Debris Flow Detection by Combinations of LVP Sensors and Wires: Examples in Sakura-jima Island, Japan

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ABSTRACT Various kinds of sensors for debris flows detection have been proposed such as wire sensor, acceleration sensor, and so on. In Europe, a geophone that is based on a vibration meter is usually used though the applicability is not confirmed for debris flow detection in Japan. A wire sensor is still currently used for debris flow detection in Japan, because of its easy maintenance and measurement principle of disconnected wires. However, there is a drawback in that debris flow cannot be detected until manual maintenance is performed after the wires are disconnected. Sakura-jima is in southwest of Japan. Debris flows occur by rainfall and ash fall after eruption. Many debris flows occur and transport sediment by debris flow events. The number of debris flow occurrences is defined by the number of disconnected wires from a wire sensor, and three wires are set vertically at the height of 60 cm, 120 cm, 180 cm from the bed, respectively, to know magnitude of debris flow height. A LVP sensor has been developed and installed there for continuous detection of debris flows and modified based on technical information obtained by maintenance after debris flow events. The sensor consists of load cell (L), acceleration meter due to vibration (V) and pressure meter (P). The sensor is mainly for debris flow detection, though weight of debris flows on the bed is attempted to be measured using a small box with loadcell. Present studies introduce some examples of debris flow detections using the LVP and emphasize usage of the LVP sensor in combination with wires.

KEYWORDS Debris flow detection; Bed pressure; Vibration; Load; LVP sensor

1 INTRODUCTION

1.1 Necessities in Debris Flow Monitoring

Sakura-jima Island is in the southwestern region of Kyushu in Japan. The rivers around the active volcano Sakura-jima are generally susceptible to debris flows caused by sediments from the large eruptions of Sakura-jima volcano located near the mountain's peak. In addition, the eruptions of Sakura-jima volcano, which produces ash rain in the area around the mountain, cause the land surface to change its properties, namely decreasing the rate of rainwater infiltration into the land surface. As a result, the response of rain to the flow will further increase the potential for surface water runoff and thus will further trigger debris flows (Gonda et al., 2019).

Early detection of debris flow occurrences is important in efforts to mitigate the impact of debris flow disasters. Therefore, the use of debris flow event monitoring sensors, including wire sensors, accelerometers (Osumi Construction Office in the Ministry of Construction, 1988; Osumi Office of River and Highway in the Ministry of Land, 2013) and geophones (e.g., Arattano and Marchi (2008)), is very supportive of these efforts. Wire sensors have been used in Japan because they are inexpensive and easy to maintain. Additionally, efforts to identify debris flow occurrences in rivers on Sakura-jima Island using closed circuit cameras (CCTV) to monitor the cable-cutting process have also been carried out. From this monitoring system, the depth of the debris flow can be determined because the height of the cable from the riverbed is varied, i.e. 60 cm, 120 cm, and 180 cm (Osumi Office of River and Highway in the Ministry of Land, 2013).

1.2 Brief Histories in Debris Flow Monitoring

In Taiwan, the development of debris flow monitoring techniques has reached an advanced level, at least in the era of 2015 (Yin et al., 2015). It is mentioned by Yin et al. that the development began in 2002, coordinated under the Agriculture Assembly of Taiwan Government. Yin et al. introduced the technology of thirteen fixed debris flow monitoring stations and two mobile debris flow monitoring stations. At each monitoring station, several observation instruments, including rain gauges, CCD cameras, wire sensors, geophones, and water level meters, are installed to collect dynamic debris flow information that can be used as references for debris flow disaster mitigation. The framework of the debris flow monitoring system consists of monitoring sensors, an instrumental cabin (vehicle platform for mobile stations), a transmission system, and a web-based display system. The system operates in “normal mode” with a low sampling rate during normal times. When the rainfall exceeds a certain threshold, the entire system will automatically activate and switch to “event mode” with a higher sampling rate. During the typhoon season, the dispatch of mobile stations depends on the typhoon’s predicted route issued by the Taiwan Central Government, thereby increasing the probability of observing debris flow events. By integrating various monitoring sensor modules, the fixed and mobile debris flow monitoring stations can expand the monitoring coverage, especially in remote areas. Debris flow disasters are a serious threat and can cause severe consequences, including losses, injuries, and deaths. With the emergence of current information and communication technology, the application of this technology supports efforts to reduce the negative impacts of debris flow disasters. However, the efficiency of the application of information and communication technology needs to be made more efficient and inexpensive but function effectively. Various efforts have been made to develop equipment to detect debris flow events, and almost all of them strive to create monitoring equipment that is efficient but effective enough to reduce the negative impacts of debris flow disasters (Ye et al., 2019; Itoh et al., 2023; Ersoz and Gonda, 2024). This study was conducted by installing an insitu monitoring system equipment in the form of wireless accelerometer sensors in the Sakura-jima mountainous area. The system was then validated with real data and produced accurate detection. Compared with other debris flow monitoring systems, the proposed solution produces a number of substantive benefits, especially low cost, high accuracy, and less maintenance effort. Several experiences (particularly in developing countries, e.g. Indonesia) have shown that the installation of monitoring systems in remote areas was very prone to vandalism, i.e. some components being stolen with and without any reason. The wires may also be disconnected by natural phenomena, i.e. by high debris flow occurrence. If such a system is intended for issuing alerts of debris flow occurrences, once the wire disconnects, the next debris flow occurrence would not be able to be detected. The re-installation of the new wires requires time that cannot be done right away. The rate of sediment transport in rivers is greatly influenced by the source of sediment flowing in a river section as well as the geometrical characteristics of the river itself. The sediment transport could persist in the form of either bed load, suspended load (including washed load), or even flow with a high concentration of sediment, such as debris flow. The suspended load can be measured by direct sampling. In contrast, bed load is difficult to measure, especially in mountainous rivers where the flow is supercritical, and the flow contains a lot of sediment. As a result, conventional bed load samplers cannot be used. A bed load measurement technique using a hydrophone sensor has begun to be widely used, e.g. in the Jinzu River, Japan (Mizuyama et al., 2003, 2011) and in the Code River, Indonesia (Harsanto et al., 2020). The hydrophone sensor is a steel pipe installed at the bottom of the rapid flow and then emits sound vibrations when sediment particles hit the steel pipe. A microphone records the sound vibrations. The number of pulses and the intensity of the sound vibrations are a function of the amount of bed sediment transport that passes through the hydrophone sensor. The sensor is not appropriate for debris flow measurements because of weakness of the pipe against collisions with boulders in debris flows.

LVP (load, vibration, pressure) sensors consist of load cells, accelerometers, and pressure gauges. The idea of continuous debris flow monitoring using a combination of cable and LVP sensors was first proposed by Itoh et al. (2017). The sensor can detect debris flow surges by distinguishing muddy- and stony-debris flow modes because the loadcell and the vibration sensor could measure continuously. It should be noted that measurement technology using cable sensors cannot detect subsequent debris flow events after the cable breaks, either by debris flow or by other causes (vandalism, animal activity, etc.). This study presents the applications of the LVP sensor, its installation/maintenance on Sakura-jima Island and the results from the field study. The LVP sensor is mainly for debris flow detection and is different from direct measurement using loadcell systems (McArdell et al., 2007; Scott et al., 2011; Osaka et al., 2014). However, some maintenance is needed for the LVP sensor and the related equipment due to unexpected forces by large boulders colliding in debris flows and electric problems from lightning, though the small sensor could be expected to require a few maintenances.

2 METHOD

2.1 Arrangement of Presentation

The arrangement of the article presentation is divided into two major sections. The first section presents the general application of LVP technology and the geometric conditions of the rivers under study, particularly those concerning the longitudinal profile and the location of the hydraulic structures in the river reach under study. The second section presents the necessary data from various types of sensors that have been collected for further analysis.

Figure 1 and Figure 2 show the study sites in the Nojiri and Arimura Rivers on Sakurajima Island. Several types of sensors other than LVP sensors were also in-

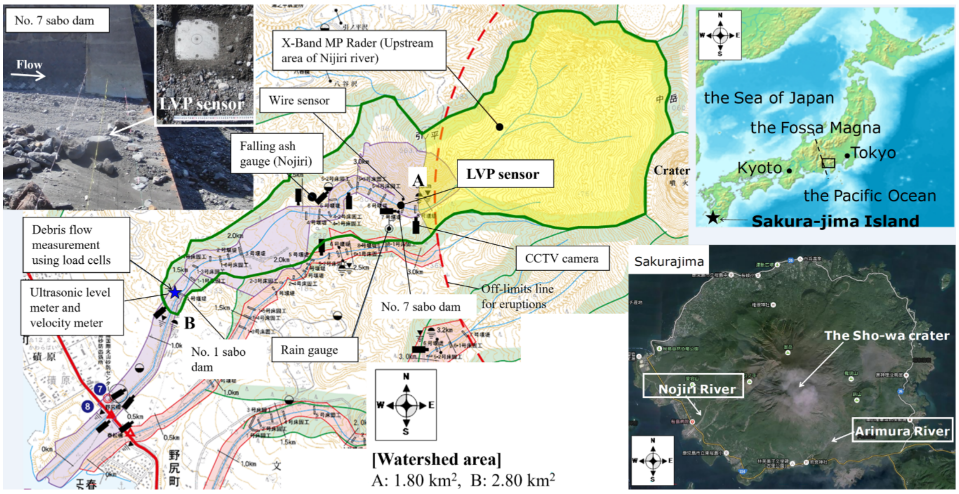

Figure 1 Sensors for debris flow monitoring in Nojiri River

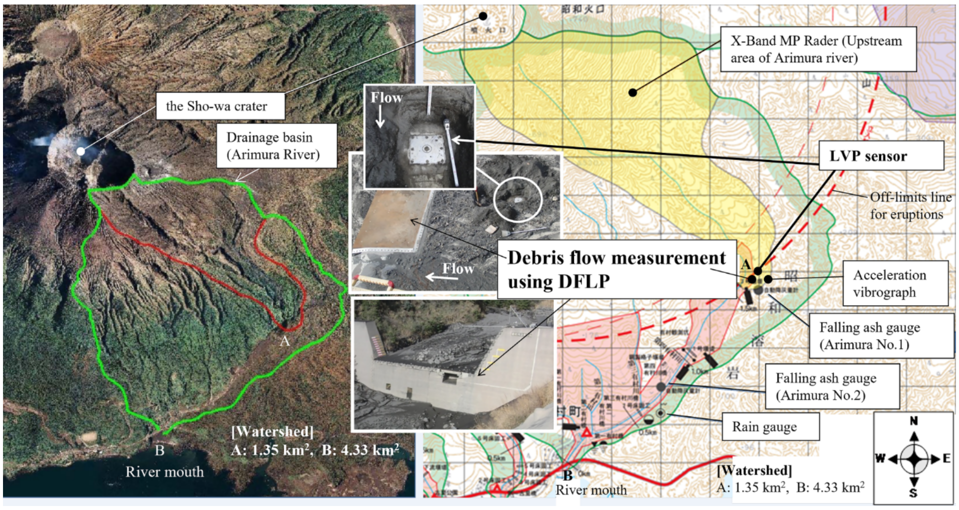

Figure 2 Sensors for debris flow monitoring in Arimura River

stalled, including rain gauges, ashfall gauges, CCTV cameras, wire sensors, ultrasonic level sensors, and velocity meters. Continuous and direct debris flow measurements using load cells and pressure gauges (DFLP) (Osaka et al., 2014) were also conducted to evaluate the mass density and concentration of sediment.

Figure 3 and Figure 4 show the longitudinal profiles of the Nojiri and Arimura riverbeds. The bed slope at the Nojiri No. 7 Sabo Dam test site is 1/7.6 (7.50 degrees), and the expected equilibrium sediment concentration for the bed slope is 0.147 for a specific gravity of 2.65 and an internal friction angle of 34 degrees. In the Arimura River, the bed slope is 1/15.5 (3.7 degrees), and the equilibrium sediment concentration for the bed slope is 0.0643.

2.2 Collected Data of the Debris Flow Monitoring

Table 1 shows debris flow detections by wires and the LVP sensor from 2017 to 2018. In the table, notation "O" indicates debris flow detections by sensors, and the gray-colored line indicates detection of debris flow with depth less than 60 cm, such as small magnitudes of debris flows. The LVP detected 34 of 34 occurrences of debris flow and can also detect small magnitudes of flow that wires cannot detect.

3 RESULTS

3.1 Several Examples for Detections

The present LVP sensor, which was installed on the bed on 6th February 2015, was modified to minimize the risk of damage due to direct impact by boulders in debris flow surges, and measurements were carried out continuously (Itoh et al., 2017). The LVP detected 23 of 24 occurrences of debris flow surges since the installation of the sensor (Kato et al., 2018). The current developments in debris flow detection are now having many challenges. Such detection require not only information on the threshold of the occurrences and magnitudes but also the issuance of the information for early warning purposes (Coviello, 2023; Johnson et al., 2023). Risk mitigation for debris flows has increased significantly, including the need for early warning systems (EWS). Currently, EWS is becoming an interesting topic for advances in information and communication technology. The success story of the development of debris flow detection systems for EWS purposes, however, still needs to be improved. The presence of an EWS, which can operate for a long time and be trusted by local authorities, is considered lacking.

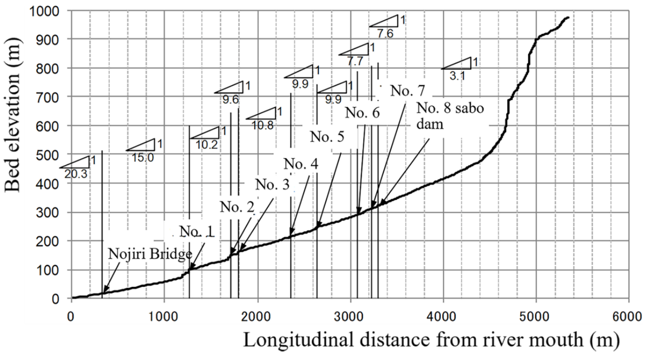

Figure 3 Longitudinal bed profiles of Nojiri River

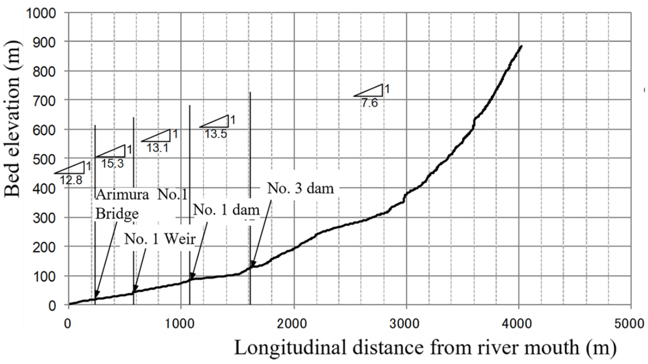

Figure 4 Longitudinal bed profiles of Arimura River

4 DISCUSSION

4.1 Measurements and Maintenances of LVP Sensors in Arimura River

An LVP sensor was installed in October 2016 at the test site of the Arimura No. 3 Sabo dam in the Arimura River. Cables and related facilities were destroyed by debris flow surges on 16th April 2017, and data could not be recorded there. The LVP is located just upstream of the DFLP system used for direct measurements of debris flows (e.g., Osaka et al. (2014)). This is why the correlation of load between an LVP and a DFLP system is expected to help evaluate each other. Figure 5 shows the temporal changes in the output of the LVP sensor in the Arimura River, measured on 20th June 2018. Data

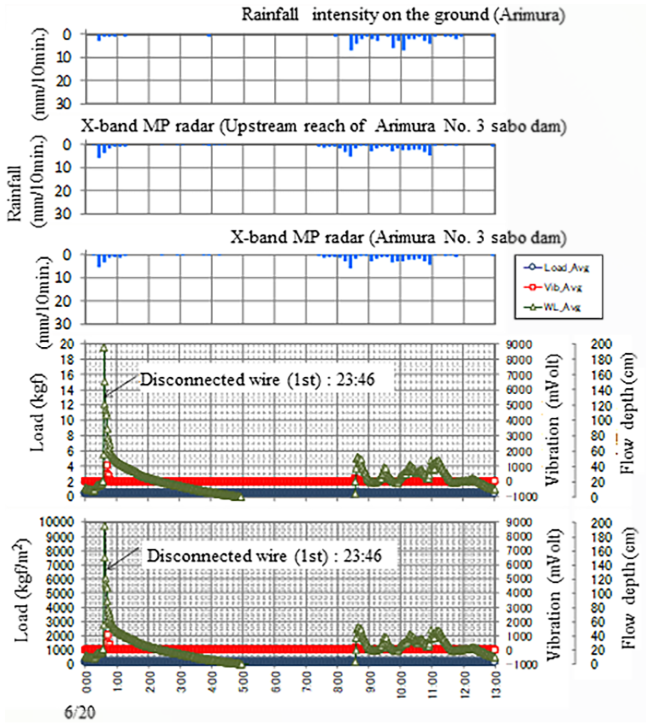

Figure 5 Temporal changes of output of the LVP sensor, measured on 20th June 2018 (Arimura River)

from the continuous time series measurement is also shown (Kato et al., 2018; Itoh et al., 2017). The events in Figure 5 took place at night, with the time of debris flow occurrences recorded at 23:46 on 20th June 2018, though the flow condition could not be clearly identified at the time of the disconnected wires because we could not distinguish whether something other than debris flow passed there. Such a situation would be clearly identified if a reliable video recorder were properly installed at the river cross-section under study. On 7th December 2017, maintenance was carried out for the cable and loadcell, and the cable was repaired. Figure 6 shows the maintenance of the LVP sensor on 7th December 2017. The LVP is installed just upstream of the DFLP system.

4.2 Measurements and Maintenances of LVP Sensors in Nojiri River

An LVP sensor was able to detect debris flow surges, and some issues occurred year to year. Data collection continued through mechanical maintenance of the sensors, and a lot of data for debris flows were detected during debris flow surges since measurement began on 6th February 2015 at Nojiri No.7 Sabo Dam in Nojiri River. Figure 7 and Figure 8 show temporal changes in the output of the LVP on 19th April 2015, and Figure 9 shows measured data on 30th August 2015. Debris flow surges shifted transversely during events and resulted in different flow directions after the event. This knowl-

Table 1. Debris flow detections by wires and the LVP sensor (Nojiri No.7 sabo dam)

No	Date	Disconnected wires			Detection by a LVP sensor		
		1st (60 cm above from the bed)	2nd (120 cm)	3rd (180 cm)	Flow depth	Vibration	Weight
1	April 16th, 2017	-	-	-	○	○	○
2	May 12th, 2017	○	-	-	○	○	○
3	May 13th, 2017	○	○		○	○	○
4	May 13th, 2017	○	○	○	○	○	○
5	June 7th, 2017	○	-	-	○	○	○
6	June 7th, 2017	○	○	-	○	○	○
7	June 20th, 2017	○	-	-	○	○	○
8	June 20th, 2017	○	○	-	○	○	○
9	June 24th, 2017	○	-	-	○	○	○
10	June 24th, 2017	○	○	-	○	○	○
11	July 4th, 2017	-	-	-	○	○	○
12	July 19th, 2017	○	○	-	○	○	○
13	August 15th, 2017	-	-	-	○	○	○
14	September 7th, 2017	-	-	-	○	○	○
15	September 12th, 2017	○	-	-	○	○	○
16	September 22th, 2017	○	-	-	○	○	○
17	September 22th, 2017	○	○	-	○	○	○
18	October 21th, 2017	-	-	-	○	○	○
19	January 17th, 2018	○	○	○	○	○	○
20	February 28th, 2018	-	-	-	○	○	○
21	March 8th, 2018	-	-	-	○	○	○
22	April 6th, 2018	-	-	-	○	○	○
23	May 2nd, 2018	○	-	-	○	○	○
24	May 2nd, 2018	○	○	○	○	○	○
25	May 7th, 2018	-	-	-	○	○	○
26	May 26th, 2018	○	○	○	○	○	○
27	June 5th, 2018	○	○	-	○	○	○
28	June 8th, 2018	-	-	-	○	○	○
29	June 20th, 2018	○	○	○	○	○	○
30	June 22th, 2018	○	○	○	○	○	○
31	July 7th, 2018	○	○	-	○	○	○
32	July 21th, 2018	○	○	○	○	○	○
33	August 24th, 2018	○	○	○	○	○	○
34	September 7th, 2018	○	○	-	○	○	○

edge can help with transverse installations on a wide channel. Increasing the number of devices being installed is highly advisable, although the cost remains a significant constraint (Ikhsan et al., 2010; Hambali et al., 2019).

Data on 30th August 2015 indicates the potential for measurements by the LVP during an eruption sensor In August 2015, the active eruption continued from the middle to the end of August in 2015, and maintenance for a disconnected wire could not be carried out because of restricted access at the monitoring site in the island.

The sensor was able to monitor occurrences of debris flow surges almost automatically. The LVP sensor detected debris flow occurrences during eruptions in the island, as shown in Figure 9.

Figure 10 shows the maintenance of the LVP sensor at Nojiri No. 7 Sabo Dam on 14th February 2019. An inspection was carried out in October 2018, and lightning damaged the vibration sensor. The top plate, as shown in Figure 10, was also worn down by debris flow surges, and the 2 mm clearance between the frames and the top plate disappeared. The top plate and frames

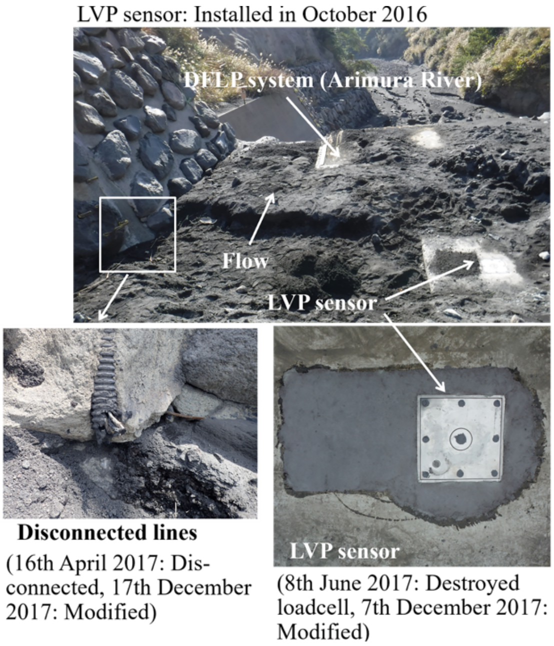

Figure 6 Maintenance of LVP at Arimura No. 3 sabo dam

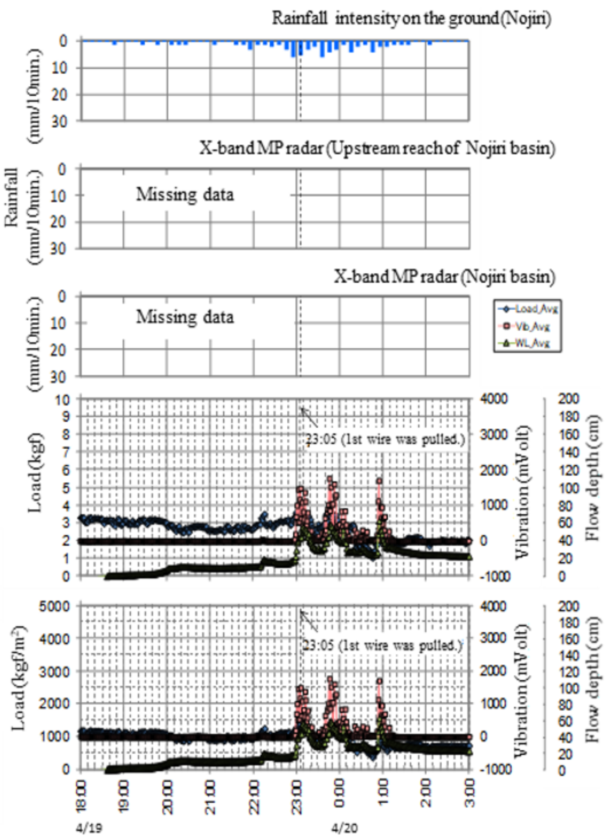

Figure 7 Temporal changes measured by the LVP sensor on 19th April 2015 (Nojiri River)

are made of SUS304 (stainless steel), which has an offset yield strength of 205 N.mm^{-2}, a tensile strength of 520 N.mm^{-2},and Brinell hardness number (HBS) of 187. HBS represents the hardness of metal material. Several adjustments need to be made to the LVP sensor even though SUS304 is used, assuming it has strength

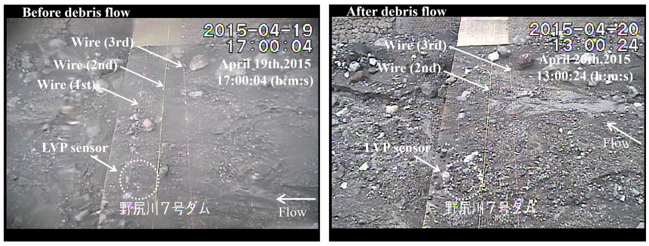

Figure 8 Plan view of bed around the LVP sensor before and after debris flow occurrences on 19th April 2015 (Nojiri River)

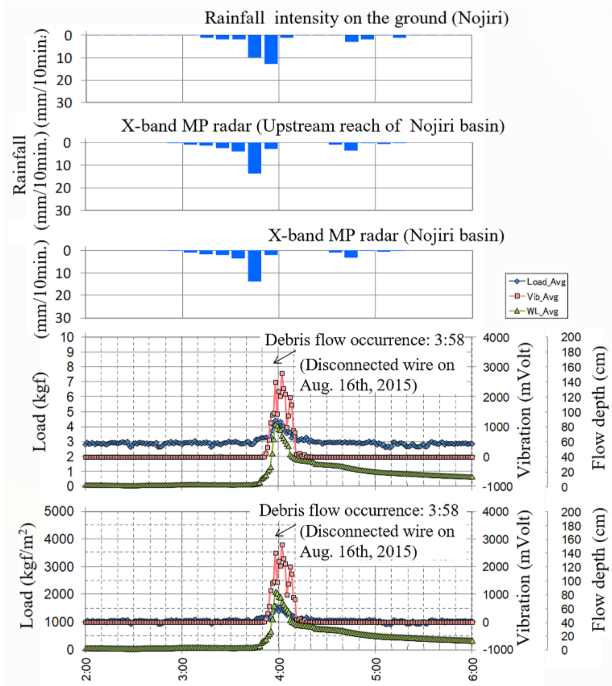

Figure 9 Temporal changes measured by the LVP sensor on 30th August 2015 (Nojiri River)

against friction wear. The top plate has a round force plate with ϕ= 60 mm at center. The differences between the top plate and frames were modified to 5 mm in height to avoid collisions and friction wear from debris flow, and a new vibration meter was re-installed on 14th February 2019.

4.3 Debris Flow Occurrences

Previous research has shown that there is a strong relationship between flow depth and load and between flow depth and vibration at the time when the cable was disconnected (Itoh et al., 2017; Kato et al., 2018). This strong relationship was obtained from the evaluation of debris flow monitoring data in the field.

A further analysis aimed at identifying the minimum threshold value of debris flow load using data from LVP sensors is shown in Figure 11, which ranges from 400 to 600 kgf.m^{-2}. Likewise, further analysis aimed at identi-

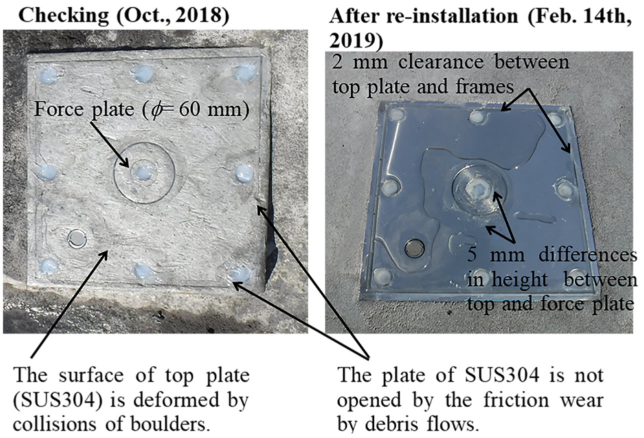

Figure 10 Maintenance of LVP at Nojiri No. 7 sabo dam on 14th February 2019

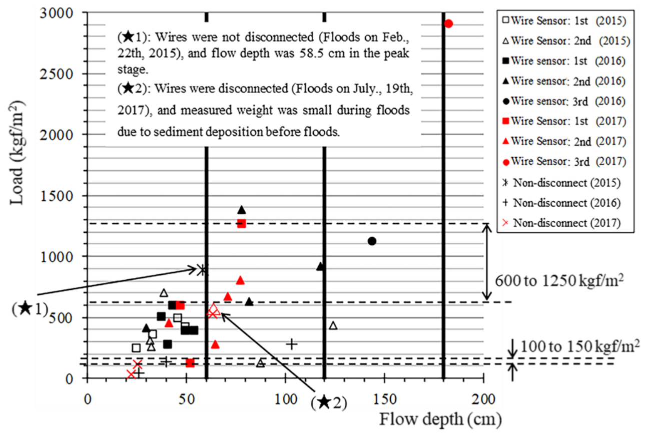

Figure 11 Debris flow occurrences as performed by load of the LVP sensor

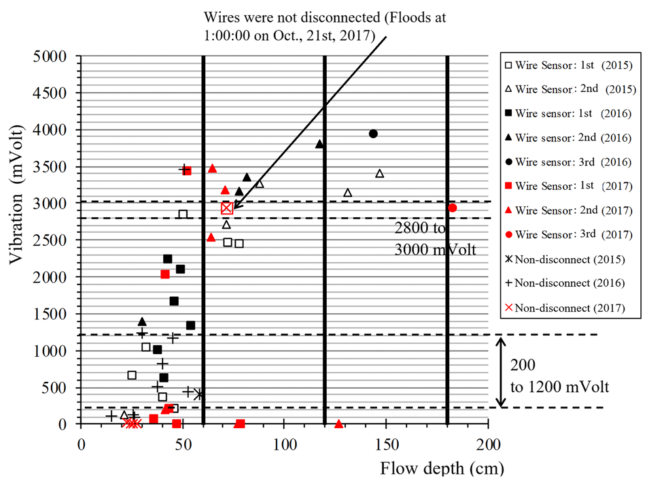

Figure 12 Debris flow occurrences as performed by vibration of the LVP sensor

fying the minimum threshold value of vibration acceleration is shown in Figure 12, which is around 200 mV. However, further data are needed to verify the accuracy of these threshold values.

The measured load only sometimes shows a linear relationship with the depth of flow because the LVP sensor force plate is too small, making the absolute value is difficult to obtain. However, the purpose of detecting debris flow occurrences and their threshold values can still be achieved. Figure 11 and Figure 12 also show that the threshold values are 600 to 1250 kgf.m^{-2} and 2800 to 3000 mV on the second cable (120 cm from the bottom of the river), while the minimum threshold value for debris flow occurrences, as mentioned earlier, ranges between 400 to 600 kgf.m^{-2} and 200 mV. These threshold values were determined empirically by statistical data analyses of the measured LVP sensor including non-disconnected and disconnected wires due to debris flow surges. They are indicated by dotted lines in Figures 11 and 12. These results may indicate that there is a possibility that a debris flow surge has occurred with some estimated magnitude.

5 CONCLUSION

The minimum load and vibration values for debris flow occurrences are 400 to 600kgf.m^{-2} and 200 mV, respectively, through measurements with the LVP and wire sensors for detections for debris flow occurrences. To obtain more accurate information on the threshold of the debris flow occurrences and their magnitudes, further data collection utilizing the adopted technique is essential.

The necessary maintenance was performed during measurement using the LVP sensor, with examples of damage caused by debris flow surges in Nojiri and Arimura Rivers. Information for installation was gathered for cable installation, plate and related structure, through continuous measurements. In addition, measurement taken on 30th August 2015 indicates the possibility of continuous measurements by the LVP during eruption at the site.

An optimal installation method needs to be identified to ensure reliable detection. The number of LVP sensors installed at each site needs to be considered to minimize the effect of transverse flow shifting.

DISCLAIMER

The authors declare no conflict of interest.

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