Estimation of Temporal Change of River Bed Elevation Upstream of a Check Dam During Debris Flow

Naoki FUJIMURA[1*], Yuya TAKAHASHI[1] and Hideaki MIZUNO[2]

[1] Erosion and Sediment Control Research Group, Public works Research Institute (1-6 Minamihara, Tsukuba, Ibaraki, 3058516, Japan)

[2] Faculty of Agriculture, Kyusyu University (6-10-1 Hakozaki, Higashi-ku, Fukuoka, Fukuoka, 8128581, Japan)

*Corresponding author. E-mail: n-fujimura@pwri.go.jp

A check dam has various functions, which includes sediment control. In the past, the effects of the sediment control function were assessed either by obtaining measurements upstream of a check dam or by performing numerical simulations based on information after flooding. Therefore, the purpose of this study is to clarify the temporal change of the river bed elevation upstream of a check dam during flooding along with sediment transportation. The authors estimated the river bed elevation based on data continuously measured by a laser profile scanner (LPS). Similarly, the sediment concentration was altogether estimated. The longitudinal profile measurement of the check dam’s sedimentation area, which was obtained using the LPS, made it possible to estimate the temporal change of the river bed elevation, as well as the erosion and deposition processes. Sediment accumulation in the decay phase was confirmed in either case of all the debris flows that were observed under the decay phase conditions, such as the lower flow velocity and higher sediment concentration during the peak flow.

Key words: sediment control function, debris flow, laser profile scanner

1. INTRODUCTION

A check dam has various functions, particularly in sediment-related disaster prevention. Sediment control is one of those functions. Through this function, the upstream runoff sediment during a large flood is temporarily stored. Thereafter, this sediment is carried downstream through a transport medium, or when small floods occur after several years or even decades after the large flood [*Nishimoto*, 2011].

In the past, the effects of the sediment control function were assessed by measuring the longitudinal gradient upstream of a check dam or by numerical simulations.

For example, a study on the sediment gradient included a case where the longitudinal profile of the sedimentary layer was evaluated through the survey of check dams filled with sediments after flooding through sediment transportation [*Murano*, 1962]. The longitudinal profiles of the sediments were approximately represented by a quadratic curve, although it varied according the amount of sediments and flow rate.

In the case of measuring the sediment gradient through a hydraulic experiment [*Yoshida et al.*, 1964], it was found that water and sediments are continuously supplied to the flume. Moreover, when the temporal change of the sediment profile of the dam is tracked, it gradually approached the straight line from the quadratic curve. This shows that the coefficient of the curve equation varies according to the supplied amounts of sediments and water.

Similarly, succeeding studies were conducted to evaluate sediment control effects and functions of check dams through observations, which focused on the type of check dams [*Mizuyama et al.*, 1990; *Satou* et al., 2000 etc.], and through numerical simulations [*Fujita et al.*, 2001; *Honda* and *Okumura*, 2005].

The effect of the sediment control function is determined by the amount of sediments and water supplied to the check dam, and not where the installed check dam is located. The amount of upstream sediment supply and flow rate of sediment-carrying water can fluctuate during actual events. However, past studies were analyzed based exclusively on the information after flooding either by performing a survey or numerical simulation. Thus, the actual fluctuation of the river bed as the process of the appearance of the sediment control function during flooding is not clarified.

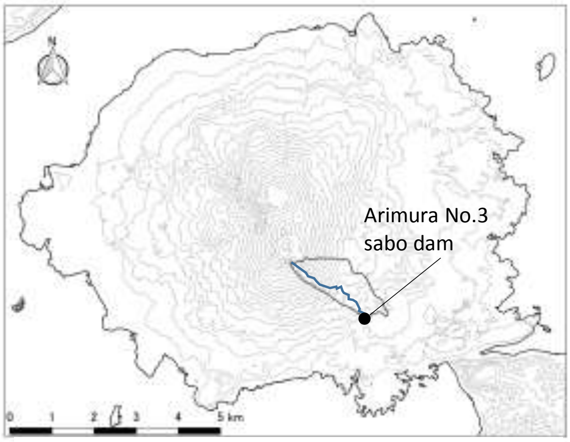


Fig. 1 Observation site

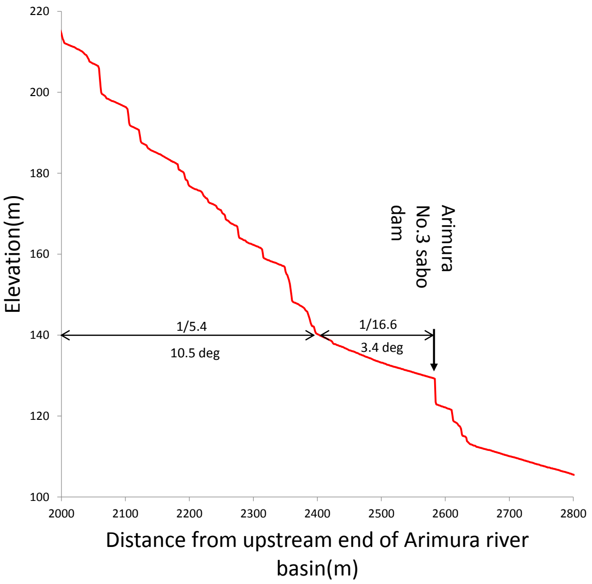


Fig. 2 Gradient of Arimura river

In this regard, the purpose of this study is to clarify the temporal change of the river bed elevation upstream of a check dam during flooding with sediment transportation. The authors estimated the river bed elevation with data that are continuously measured by the laser profile scanner (LPS). The sediment concentration was estimated altogether. The events that indicate when the sediment control function appears cannot be expected only in a few years. Thus, in this paper, we will report the result of the conducted observation of the debris flow in the river, where several sediment transportations are expected.

2. METHOD

2.1 Observation site

The study site is the Arimura River located in the southeastern area in Sakurajima, Japan (**Fig. 1**). It is a debris-flow prone river where several check dams are installed. Through an observation system, the authors and the MLIT Osumi Office of River and National Highway observed the debris flow system on the spillway of the Arimura No. 3 Sabo dam. The catchment in the upstream area of the dam is 1.55 km^2 and the slope gradient above the dam is 3.4° (**Fig. 2**).

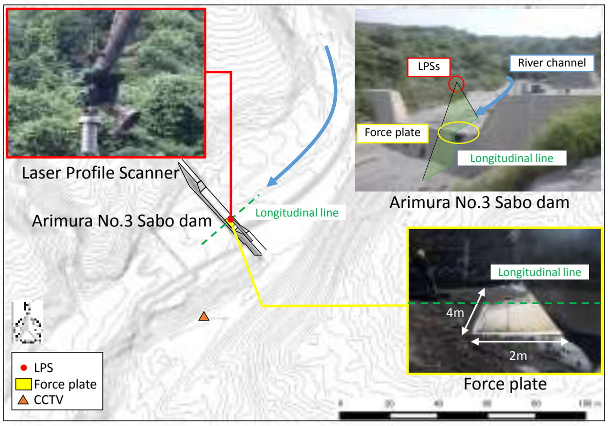


Fig. 3 Image of installed LSP and force plate

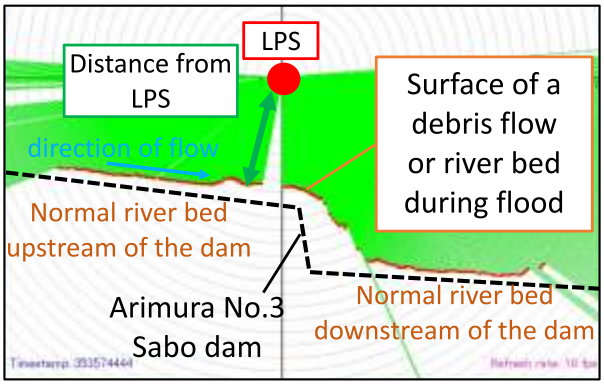


Fig. 4 Longitudinal elevation measured by LPS

2.2 Observation devices

The observation system is mainly composed of LPSs, a force plate, and closed-circuit television (CCTV), etc. (**Fig. 3**).

A force plate installed by MLIT measures unit weight of debris flow. It is located on the spillway of the dam to the left bank because flow tends to biased to the side due to river curvature.

The Public Works Research Institute installed two LPSs (UXM-30LX-EW, Hokuyo Co., Ltd.) approximately 9 m above the dam, which continuously measure the profiles of the river bed within a 30-m radius. Thus, the LPSs longitudinally measure 15 m of the upstream area and 15 m of the downstream area of the dam. Measurements are performed 20 times per second, and the average values per second are used as profiles. One LPS measures the temporal change of the longitudinal elevation of the river bed surface or the debris flow (**Fig. 4**), whereas the other LPS makes measurement in the transverse direction.

The force plate installed by MLIT measures the

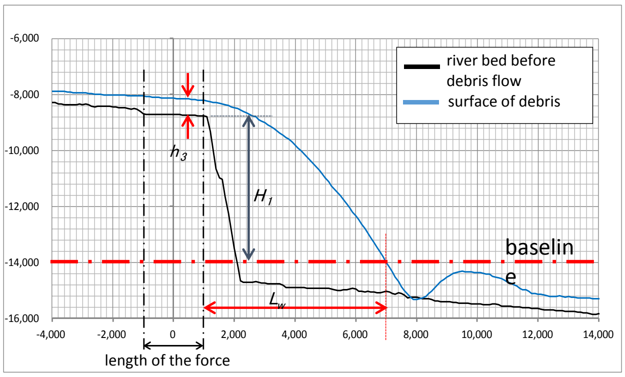


Fig. 5 Measured values for semi－theoretical equation

unit weight of the debris flow. It is located at the spillway of the dam, on the left bank. The flow tends to be biased to that side because of the river curvature.

The CCTV records a video of the debris flow. It was installed by MLIT on the left side and at approximately 30 m downstream from the check dam.

2.3 Calculation of hydraulic quantity of debris flow

2.3.1 Flow velocity of debris flow

Ultrasonic velocity sensors are often used to measure the debris flow velocity. Ultrasonic velocity sensors installed by MLIT at the observation site measure the flow velocity per minute. Consequently, the flow velocity per minute data cannot be compared with the flow velocity per second data. In order to obtain the flow velocity per second data, the velocity was calculated with a semi-theoretical equation using the nappe distance [*Yoshinaga*, 2017] obtained from the longitudinal profile of the flow surface, which is measured every second downstream of the dam.

The velocity is calculated with Eq. (1) shown below [*River bureau, Ministry of Construction*, 1997].

$$V = L_w \times \left\{\frac{2\times(H_1+0.5\times h_3)}{g}\right\}^{-0.5} \qquad (1)$$

Where V is the debris flow velocity on the spillway of the check dam (m/s); L_w is the nappe distance (m); H_1 is the vertical distance from the crown of the check dam (m); h_3 is the overflow water depth on the spillway of the check dam; g is the gravitational acceleration (m/s^2).

The baseline for H_1 was set vertically downward at 14 m from the sensor to avoid the influence of bounding water and splash (**Fig. 5**). The values of h_3 are calculated as average depths between 2 m from the downstream edge of the dam, so as to eliminate the influence of the error caused by a splash or huge boulder.

Table 1 Measured data of debris flows

Date	Data of LPS	Data of Force plate
2015/12/10	✓	✓
2016/5/9	✓	
2016/6/19	✓	✓
2016/9/20	✓	

2.3.2 Sediment concentration of debris flow

The sediment concentration of the debris flow is estimated using Eqs. (2) and (3) [*Osaka*, 2013]:

$$\gamma_d = PA_{FP}/AL \qquad (2)$$

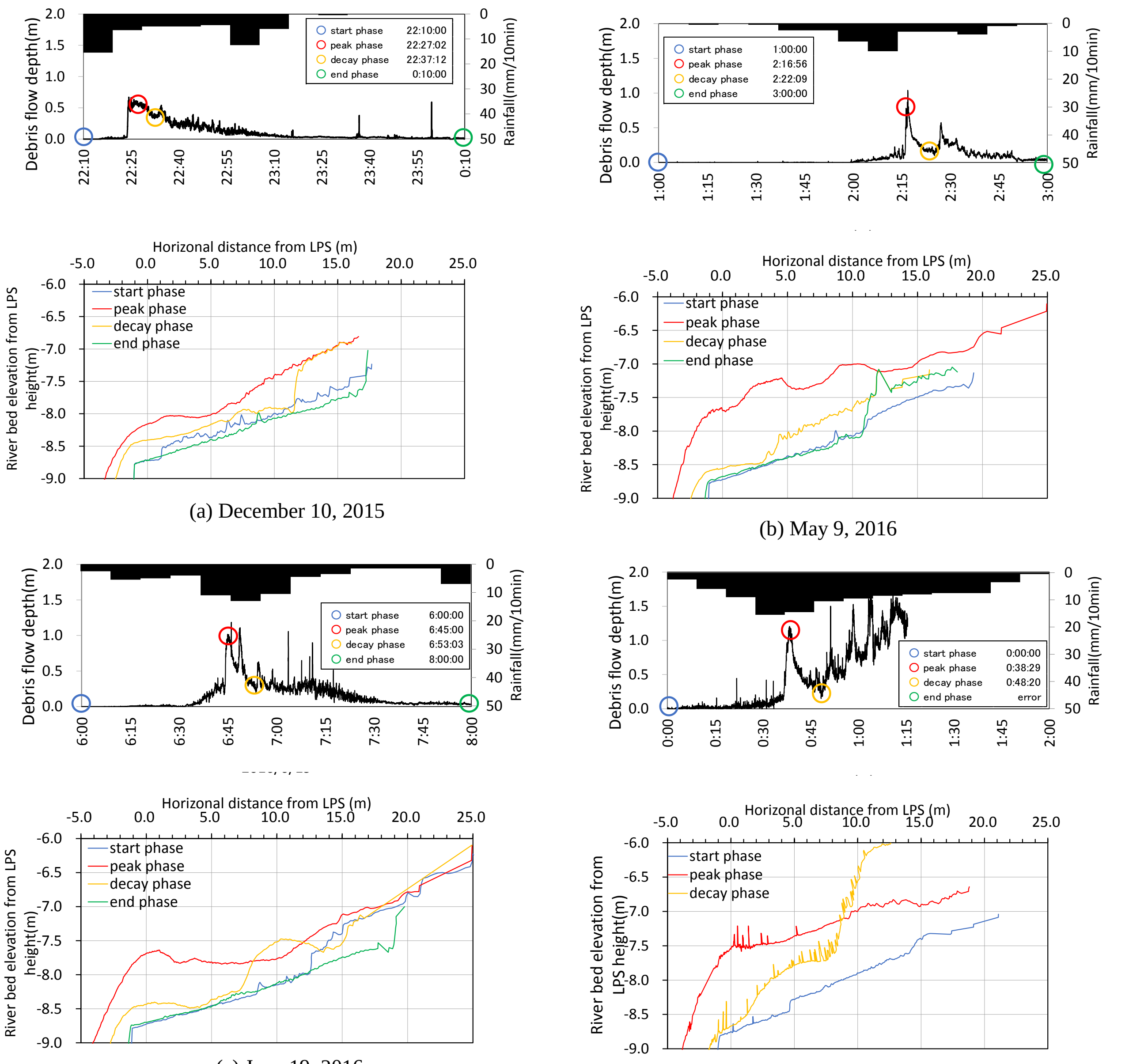
$$C_v = (\gamma_d - \gamma_\sigma)/(\gamma_\sigma - \gamma_\rho) \qquad (3)$$

where γ_d is the unit weight of the debris flow (kN/m^3); P is the basal normal stress (kPa); A_{FP} is the plane area of the force plate (m^2); A is the cross-sectional area of the debris flow (m^2); L is the longitudinal length of the force plate (m); C_v is the sediment concentration; γ_σ is the unit weight of grains (kN/m^3); and γ_ρ is the unit weight of water (kN/m^3).

3. RESULT

The list of measured data since December 2015 when the LPS started to measure the longitudinal profiles of the river bed on the check dam are summarized in **Table 1**. Similarly, **Fig. 6** shows the temporal change of the debris flow depth with rainfall intensity observed at Kagoshima rainfall observatory near the Arimura river and the river bed elevation expressed by the distance from the LPS. The situations of the river bed elevation are focused on the start, peak, decay, and end phases. To be precise, the elevation of the peak and decay phases did not show an accurate state of the river bed, since LPS scanned one part of the flow surface during these phase. The debris flow that occurred on (a) December 10, 2015, (b) May 9, 2016, (c) June 19, 2016, and (d) September 26, 2016 are presented in **Fig. 6**.

The depths of each event, including the debris flow, are shown within 2 h. The start phase is the situation before the debris flow. The peak phase is the first peak of the depth of the debris flow. The decay phase is the time immediately before the depth increased after the first peak. Concerning (c) June 19, although second peak appeared right after the first peak depth tended to decrease. Thus, in this case the



(a) December 10, 2015

(b) May 9, 2016

(c) June 19, 2016

(d) September 20, 2016

Fig. 6 Depth of debris flow and river bed elevation

moment after the second peak was regarded as decay phase. Concerning (d) September 26, decay phase was not clear since depth increased after the first peak continuously. Thus, in this case the moment after the first peak was regarded as decay phase even though depth tended to increase.

3.1 Elevation of river bed surface or debris flow

3.1.1 Debris flow at December 10, 2015

The debris flow occurred at approximately 22:23 and peaked 4 min later, at 22:27. Thereafter, the depth gradually lowered at approximately 23:15. The accuracy of that change, which occurred at 00:00, is difficult to confirm. In the longitudinal direction of the decay phase, although most of the profiles were lower than those during the peak phase, the elevation above upstream, 12 m from the LPS was almost the same as that of the peak. In the end phase, the high elevation range, which was confirmed in the decay phase, disappeared. Additionally, the elevation of the entirety of the river bed generally decreased compared to that during the start phase. In this case, it is seen that sediment was temporarily deposited upstream of the check dam during debris flow even though it was finally eroded.

3.1.2 Debris flow at May 9, 2016

The depth of the debris flow started to rise at approximately 2:00 and rapidly peaked at approximately 2:16. Thereafter, the depth decreased for 5 min, then increased again starting at 2:22. At 2:27, the depth attained the second peak, which is lower than the first peak. The change in elevation at 3:00 is difficult to confirm.

In the measured range during the decay phase, the elevation was lower than the peak. On the other hand, the elevation above upstream, 12 m from the LPS, was almost the same as that in the end phase.

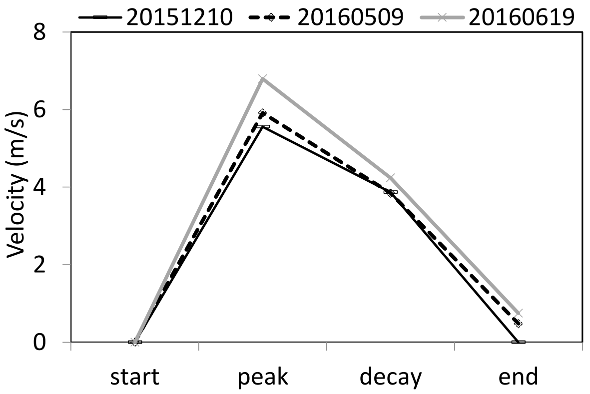


Fig. 7 Flow velocity on each phase

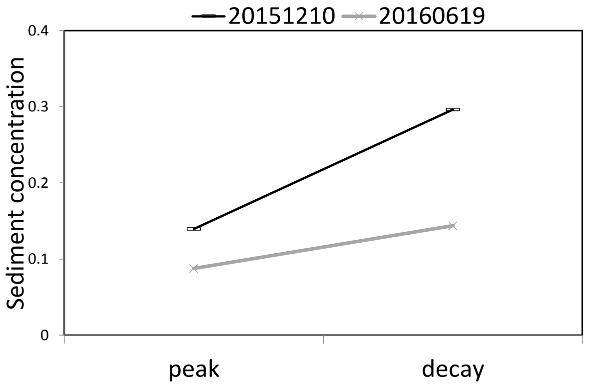


Fig. 8 Sediment concentration on each phase

As a result, the elevation above upstream, 11 m from the dam, at the end phase was higher than that in the start phase. The sediment is approximately 30 cm deep and accumulated at a maximum of approximately 80 cm after the debris flow, which was higher compared with that of the previous. In this case, it is seen that sediment was temporarily deposited upstream of the check dam and one part of it was stored after debris flow.

3.1.3 Debris flow at June 19, 2016

The depth of the debris flow started to rise at approximately 6:30, and then peaked at 6:45 to a height of 1 m. The depth decreased for 8 min until 6:53, across the second peak. The sedimentation, confirmed at this time, was at a point above upstream 7 m from the LPS. The sediment accumulated at a maximum of approximately 80 cm at a point above upstream 10 m from the LPS.

Ultimately, the elevation in the end phase, compared with that in the start phase, was approximately of the same height up to a section 12 m upstream in the longitudinal direction from the LPS. However, it decreased from 18 to 12 m. In this case, it is seen that sediment was temporarily deposited upstream of the check dam during debris flow even though it was finally eroded.

3.1.4 Debris flow at September 20, 2016

Approximately, the depth of the debris flow started to rise gradually at 00:00 and peaked at 00:35. After that, the depth decreased for over 10 min. In the range above upstream, 10 to 14 m from the LPS, the depth was higher than that in the start phase at approximately 2 m. In this case, it is seen that sediment was temporarily deposited upstream of the check dam after the peak of debris flow.

3.2 Calculated hydraulic quantity of debris flow

The flow velocity and sediment concentration shown in **Fig. 7** and **8** are based on Eqs. (1) and (2), respectively. The flow velocities are shown in three cases, from which all the phase data were obtained. Two of the three cases had basal normal stress data.

The velocity during the peak phase was the fastest in all cases, with values of approximately 5–7 m/s, whereas the velocity in the decay phase in all cases was approximately 4 m/s. On the other hand, the sediment concentration in the decay phase was higher than that in the peak phase.

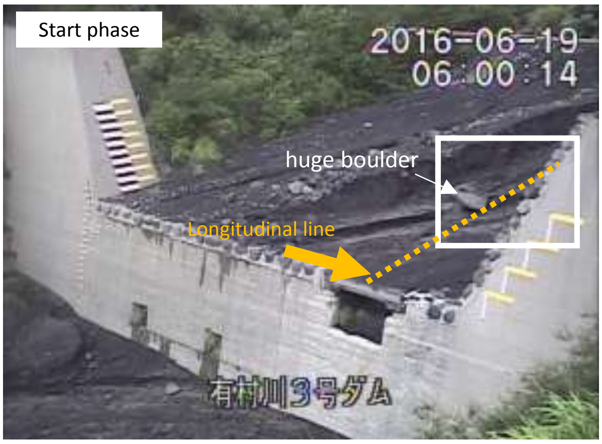
4. DISCUSSION

4.1 Accuracy of the temporal change of river bed elevation measured by LPS

The status of the river bed, which was indicated by the measured data, was confirmed through the CCTV recording of debris flow at June 19 which was clear enough to observe since the flow occurred in the daytime and was not influenced by the noise caused by heavy rains. As shown in **Fig. 9,** the change in the sedimentary condition from the start to the end phase was able to be seen clearly.

The yellow line represents the longitudinal line, which was measured by the LPS, whereas the white line is the range where the sediments were deposited during the decay phase.

At 6:00, a boulder was confirmed to be at the legs of the sediment, which was deposited at the center of the river channel of the area surrounded by a white rectangle. At the peak of the debris flow at 6:45, the boulder was almost invisible. At 6:52, it was confirmed that there was a flow towards the bank in a direction perpendicular to the debris flow. Thereby, the progress of the sediment deposition was confirmed by the intermittent occurrence of sediment-containing flow at the legs of the sediments deposited at the center of the river channel. As a result, the sediments were accumulated upstream where the boulder was located. At approximately 6:53, the depth of the debris flow decreased near the



(1) Start phase at 6:00

(2) Peak phase at 6:45

(3) Decay phase at 6:52

(4) Decay phase at 6:53

(5) Decay phase at 6:54

(6) End phase at 8:00

Fig. 9 Temporal change of condition of river bed during debris flow, June 19, 2016

spillway of the dam. At 6:54, the accumulated sediments started to erode. At approximately 8:00, the sediment that accumulated at the right side of the upstream of the boulder disappeared.

Based on **Fig. 9**, it was confirmed that the sedimentary condition in the debris flow shown by CCTV images and the transformation of the longitudinal course measured by the LPS are substantially the same.

4.2 Sedimentation when debris flow occurred

Comparing debris flow elevations in the start phase with those in the end phase of the three cases, which were measured over the entire event, the river bed elevation fell after the debris flow two of the cases. On the other hand, temporal sedimentation was confirmed after the peak in all cases. This was particularly true in the May 9 case, during which the sediments deposited in the decay phase were retained. Consequently, the sediments had already accumulated before the debris flow.

4.3 Condition that sedimentation appeared

As shown in **Fig. 7**, the flow velocity in the decay phase is lower than that in the peak. Moreover, **Fig. 9** shows that in the decay phase, where the sedimentation occurred, the flow caused not only a downward flow direction, but also one in a direction perpendicular to the main flow. As shown in Fig. 8, the debris flow in the decay phase has a high sediment concentration. Accordingly, when the flow velocity is low and flow with high sediment concentration occurs, the sedimentation in the check dam is assumed to progress.

In two of the three cases that were observed until the end phase, the sediments, which accumulated in the decay phase, disappeared. However, after the peak, the debris flow is assumed to have a low-velocity condition with high sediment concentration. Thus, sedimentation, although temporary, is expected during the debris flow.

5. CONCLUSION

The measurement of the longitudinal profile of the check dam's sedimentation area, which was obtained through the LPS, made it possible to estimate the temporal change in the river bed elevation, as well as the sediment erosion and deposition processes. Sediment accumulation in the decay phase was confirmed in either case of all the debris flow observed. This indicated that sediments had accumulated upstream of the check dam for a brief period during the debris flows. During that time, the flow velocity was lower than the velocity in the peak phase. Moreover, the sediment concentration was higher. This implied that sedimentation occurs when the debris flow rate with high sediment concentration decreases. From these results, it is assumed that the sediment amount deposited may be larger than the measurements given in this report, if the debris flow rate with high sediment concentration decreases and if the subsequent flow does not continue for an extended time.

In the future, it is necessary to gather cases that will consider other observation sites and study the conditions when the sediment control function is expected to occur.

ACKNOWLEDGMENT: The authors thank the Osumi Office of Rivers and Highways for cooperating with us in performing our observation and for providing the data of the debris flow unit weight at the Arimura River.

REFERENCES

Fujita, M, Mizuyama, T and Musashi, Y (2001): Sediment runoff control by a series of sabo dams, Annual Journal of Hydraulic Engineering Vol. 45.

Honda, N and Okumura, T (2005): Estimation of debris flow control with sabo facilities based on numerical simulation, Annual Journal of Hydraulic Engineering Vol. 49.

Mizuyama, T, Irasawa, M, Fukumoto, A and Kobayashi, M (1990): Sediment Control Effect of a Sabo Dam with Large Drainage Condits, Journal of Japan Society of Erosion Control, Vol. 43, No. 2, pp. 29–34.

Murano, Y (1962): On the Longitudinal Profile of Sabo Dam Accumulation, Journal of Japan Society of Erosion Control, No. 47, pp. 21–28.

Nishimoto, H (2011): Discussion on the transition of idea about sediment control effect functioned by check dam, Journal of Japan Society of Erosion Control, Vol. 64, No. 4, pp. 46–51.

Osaka,T, Takahashi, E, Kunitomo, M, Yamakoshi, T, Nowa, Y, Kisa, H, Ishizuka, T, Utsunomiya, R, Yokoyama, K and Mizuyama, T (2013): Field observation of unit weight of flowing debris flows by force plate in Sakurajima, Japan", Journal of Japan Society of Erosion Control, Vol. 65, No. 6, pp. 46–50.

River bureau, Ministry of Construction (1997): Ministry of Construction Technical criteria for river works for research

Satou, K, Hongou, K, Uehara, S and Mizuyama, T (2000): Case study on sediment control by a slit sabo dam, Journal of Japan Society of Erosion Control, Vol. 53, No. 2, pp. 43–47.

Yoshida, Y, Matsuyama, K, Murano and Y, Izumi, I (1964): On the Longitudinal Profile of Sabo Dam Accumulation, Journal of Japan Society of Erosion Control, No. 55, pp. 23–29.

Yoshinaga, S, Shimizu, T, Mizutani, T, Takahashi, Y, Fujimura, N, Izumiyama, H and Ishizuka, T (2017): A method for measuring nappe distance and depth of debris flow using laser range finder and application to estimate debris flow velocity, Journal of the Japan Society of Erosion Control Engineering, Vol. 70, No. 1, pp. 46–53.