Bedload monitoring with impact plates at Koshibu sediment bypass tunnel

Takahiro Koshiba and Tetsuya Sumi

Abstract

Sediment Bypass Tunnels (SBTs) are leading technologies to mitigate reservoir sedimentation that operated in some countries as Japan, Switzerland, and Taiwan. Although their high efficiency are confirmed, the design and maintenance criteria are not well clarified yet. In particular, invert abrasion is one of the severest problems on it and requires high maintenance cost. Measuring bedload transport rate in SBTs is an important step to predict the amount of invert abrasion and bypass efficiency hence improve SBTs management. In this study, we conduct field experiment for bedload measurement with using impact plates at Koshibu SBT, Japan. Grain size and bedload transport rate of the bypassed sediment are described as the function of their output. Finally, the outcomes are validated and applied for the actual flood monitoring.

Keywords: sediment bypass tunnels, reservoir sedimentation, impact plate, bedload monitoring, field experiment

1 Introduction

Reservoir sedimentation is one of the severest problems affecting the sustainable usage of dams and reservoirs. Therefore, taking countermeasure against the problem is a topical issue in managing dams hence various methods are proposed and operated (Kondolf *et al.* 2014, Morris and Fan 1998). Sediment Bypass Tunnels (SBTs) are implemented to reduce suspended and bedload deposition in reservoirs by routing the incoming sediment around the dam (Auel and Boes 2011b, Sumi *et al.* 2004, Vischer 1997). On the operation of SBTs, the hydroabrasion on the tunnel invert cause by the combination of high flow velocity and high sediment flux is non negligible problem because it requires high and regularly maintenance costs. For an optimized design and operation of SBTs with considering expected abrasion and bypass efficiency, it is important to establish a sediment transport measurement system because abrasion prediction model is basically depending on actual bedload flux in the SBTs (Auel *et al.* 2016b, Ishibashi 1983). In the study field of Sabo works, a few number of studies on bedload monitoring are conducted (e.g. Rickenmann 2017, Gray *et al.* 2010). Based on the studies, we developed one surrogate bedload monitoring system called impact plate specific for SBTs where the flow condition is intense. This system was calibrated at laboratory flume and employed for bedload monitoring at Koshibu SBT in Japan from 2016 (Koshiba *et al.* 2017). In prior to the first operation of the Koshibu SBT, in-situ calibration experiment was carried out with the impact plate.

In this study, we particularly focus on the bedload transport rate and grain sizes because these are important factors for computation of the invert abrasion. Additionally, their validity is investigated with applying the data collected during the actual first SBT operation in September 2016. The results and analyses of the experiments are shown in the following sections.

2 Bedload monitoring at Koshibu dam SBT

2.1 Field information

The Koshibu dam is located at the Koshibu river catchment in Nagano prefecture, Japan, and is operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for flood prevention, water supply and hydropower generation. The dam was built on 1969, and is 105 m high with a width of 293.3 m. The catchment area is 288 km^2. Moreover, the reservoir received enormous severe floods and thus rapid sedimentation rate has been a critical issue for the dam management. Indeed, on 2015, the sedimentation volume exceeds 15.6 Million m^3 (MCM) almost reaching to 20.0 MCM of original designed sedimentation capacity. Therefore, MLIT initiated the construction of Koshibu SBT (Fig. 1). The length of the SBT is 3,982 m with a cross section of circular shape and a plain invert with a slope of 2%. The width and height are 5.5 m and 7.9 m, respectively. Most of the parts are rectilinear tunnel but the last approximately 600 m from the outlet is curved on the orographic right direction (Radius (R) = 1000 m). Most of the tunnel invert is paved with the high strength concrete (50 N/mm^2), particularly in the first 20 m where is in the inlet facility and the next 30 m where the tunnel inclination is relatively high for accelerating incoming flow which are reinforced with rubber-steel and steel-lining material respectively.

Figure 1: Outlet of the Koshibu dam SBT

2.2 Impact plate

Accurate measurement of sediment transport rate in the SBTs can fairly contribute to the sound management of the tunnel. Accordingly, impact plates were developed and calibrated at laboratory flumes (Koshiba *et al*. 2016). As a consequence, in the Koshibu SBTs, seven impact plates (Fig. 2) manufactured by Hydrotech Co., Ltd. (Japan), were employed for bedload monitoring. The impact plate consists of four units as: a steel plate, microphone, acceleration sensor (GH-313A as a sensor and GA-223 as a converter; manufactured by KEYENCE, Japan) and data-logger. The steel plate is 49.2 cm in width, 35.8 cm in length in flow direction and 1.5 cm in thickness. Both microphone and acceleration sensor record the acoustic energy and vibration of the sediment particle impacts transmitted to the sensor through the plate as a voltage [V] at 50 kHz of sampling frequency. Even though such raw waveform data are useful in analyzing transported sediment attributions, i.e. volume, grain size and particle transport mode (sliding, rolling, and saltation), a significant volume of its data amount doesn't allow to continuously collect raw data. Therefore, a data processing method for decreasing data amount with remaining the characteristics of transported particle were developed namely the number of impulse I_{ps}. In the monitoring, raw signal waveform data is collected intermittently while, I_{ps} is registered continuously.

The number of impulses I_{ps} is obtained through analog signal processing in a data logger in accordance with the previous observations by the JPM (Mizuyama *et al*. 2008) and thus calculated simultaneously with the recording of the raw waveform data. Due to the technical limitation, i.e. the limited memory of PC and electricity power supply, these variables were computed only for the microphone signal. This parameter works to significantly decrease the accumulated data amount compared to collecting all signal raw waveform data while maintaining some extend of information about the frequency and amplitude fractions of the signal of particle impacts. To compute I_{ps}, as in the Figure 3, the following steps (i) - (iv) are conducted with the data logger: (i) the raw waveform is collected, (ii) the waveform is proceeded through a band-path filter to extract the frequency of approximately 4.6 kHz which is previously computed as the most effective frequency for distinguishing particle impacts on the plate, (iii) the filtered waveform is transformed into an absolute value, and the envelope curve is generated, (iv) the enveloped data are exported to 10 different channels, in which the wave is amplified with amplification factor *Amp* of 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 times, finally, I_{ps} for each amplification factor is defined as the number of impulses, grouping the distributed signals above a predefined threshold of 2 V (iv). In Figure 3 (iv), the envelope curve and the amplified curves with $Amp = 4$, 16 are exemplified. When $Amp = 4$ is considered, no peak of the amplified curve reaches the threshold hence $I_{ps} = 0$, in contrast, the amplified curve with $Amp = 16$ touch the threshold 4 times hence $I_{ps} = 4$.

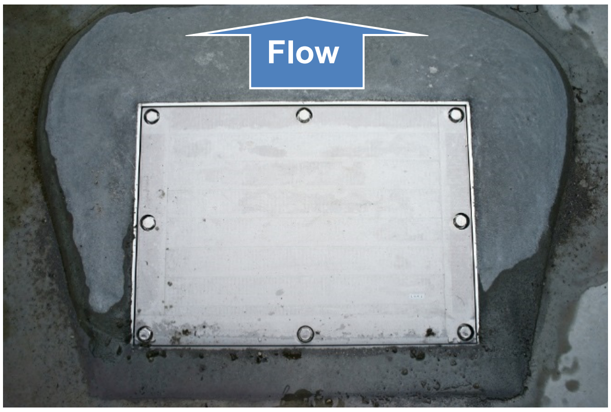

Figure 2: Impact plate system installed on the Koshibu SBT outlet, an acceleration sensor and a microphone is mounted on the back side.

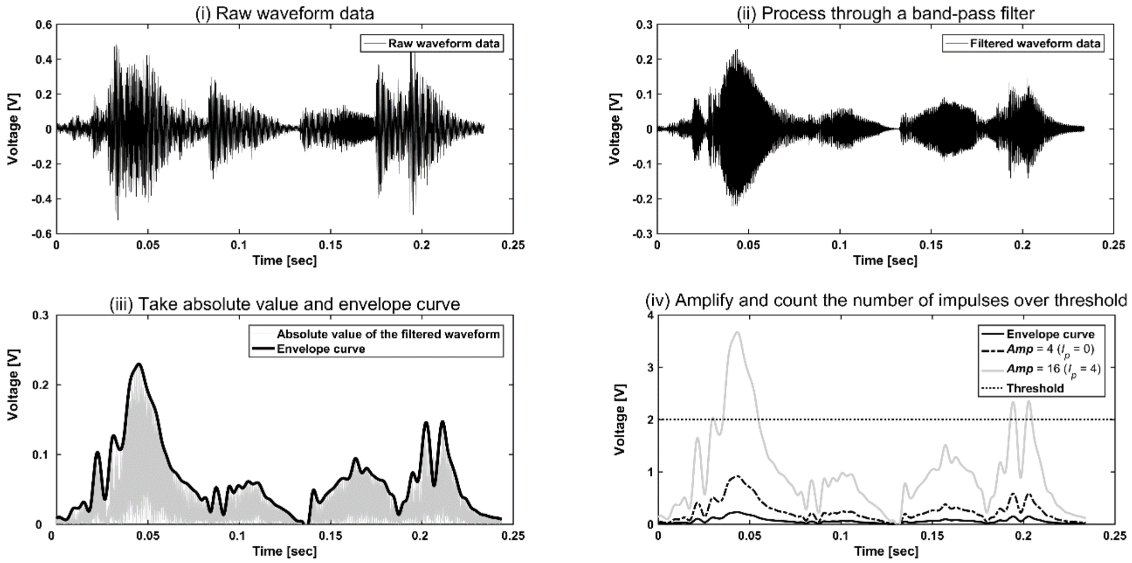

Figure 3: Illustration of the signal processing for counting the number of impulses (I_{ps}). (i) Raw waveform data collected by a microphone. (ii) Filtered raw waveform data through band-pass filter, (iii) Filtered waveform data transformed to the absolute value and envelope curve is extracted. (iv) Envelope curve is amplified with the amplification factor (*Amp*) ranging from 2 to 1024 times and the number of impulses (I_{ps}) over the threshold is counted. (*Amp* = 4 and 16 are exemplified).

2.3 The deployment design of the impact plates

The design of the impact plates deployment at Koshibu SBT outlet is shown in Figure 4. Five impact plates named t15 are mounted in order to measure the cross sectional distribution of transported sediment. Moreover, two additional impact plates are mounted namely, t12 and t15 inclined. Original impact plate (t15) has the thickness of 15 mm, but t12 is an impact plate with the thickness of 12 mm. On the other hand, t15 inclined is an original impact plate but the plate is inclined with 10 degrees. These are employed for investigating the difference of detection efficiency due to the different thickness and inclination. In particular, the increase of sensitivity by inclining a plate is confirmed in the previous study by Auel and Boes (2011b). We chose the inclination angle of 10 degrees according to the study where the value showed the highest detection efficiency.

Two JPMs were also embeded at the outlet for the comparative study with the impact plates. However, both JPMs were completely destroyed due to the first Koshibu SBT operation in September 2016 and already removed. Moreover, five pipe pits are also built at the outlet vertically to collect bypassed water with the five fractions of height to measure vertical turbidity distribution because the impact plates are not good at gaining the vertical sediment flow profiles. Figure 5a is the outlet taken from the outside

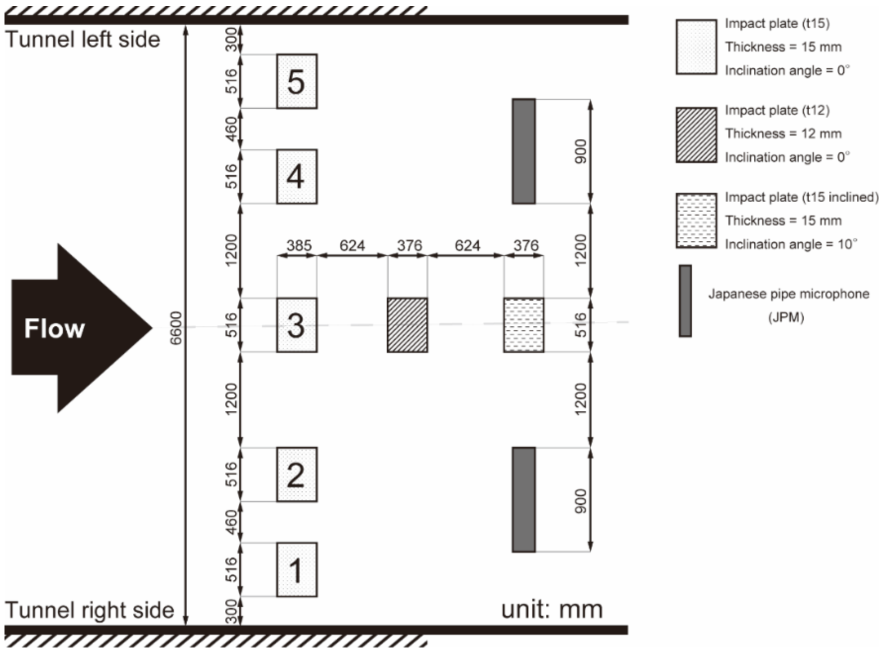

Figure 4: Plan view of the bedload measurement apparatuses on the outlet part of the Koshibu dam SBT

3 Full scale experiment with impact plates

3.1 Experimental setup

When surrogate bedload monitoring systems such as the impact plate are transferred to the field-site measurements, it is usual that they show the different behavior from the laboratory experiment (Rickenmann 2017). Therefore, field-site calibration assures the higher accuracy of the measurement and bedload estimation, as a consequence, we carried out a calibration experiments in prior to the first operation of the Koshibu SBT. For that, a series of field experiments were conducted at Koshibu SBT by artificially flush sediment over the devices through the tunnel. As in the Table 1, 10 cases of experimental conditions were selected varying the grain sizes (D_s = 5, 10, 50 mm), sediment volumes (V = 1, 3, 5, 9 m^3), and water discharges (Q = 5, 10, 50 m^3/s). At Case 8 and 10, mixed grain size sediment were tried so that all D_s are included with V = 3 m^3 for each. The test sediment was collected from the quarrying area in the immediate downstream of the SBT and carried by a dump truck into the SBT just before every runs.

For observing the effect of the tunnel section where SBT makes a turn in the last 600 m, the sediment was placed 800 m upstream from the outlet (Fig. 5b). Then, the designated amount of water was drawn by opening the gate at the tunnel inlet for 20 minutes (T_{flush}) in each run. The natural riverine water stored in a pool impounded by diversion equipment was used for the experiment. All impact plates continuously registered the I_{ps} throughout the each experimental flushing while, raw waveforms were started recording when the incipient of the sediment flow reaches the outlet and stopped when all sediment is passed the outlet completely, with five seconds of recording and ten seconds of interval.

Table 1: Experimental conditions

Case	Date	D_s [mm]	V_s [m^3]	Q [m^3/s]	V_w [m/s]	T_{flush} [min]
1	22/8	10	1	10	2.60	20
2	22/8	10	3	5	1.98	20
3	22/8	50	3	5	1.85	20
4	22/8	5	3	5	1.67	20
5	23/8	10	5	5	2.03	20
6	23/8	10	9	5	1.87	20
7	23/8	10	9	20	3.66	20
8	23/8	5/10/50	3/3/3	5	1.89	20
9	24/8	50	9	20	3.34	20
10	24/8	5/10/50	3/3/3	20	3.98	20

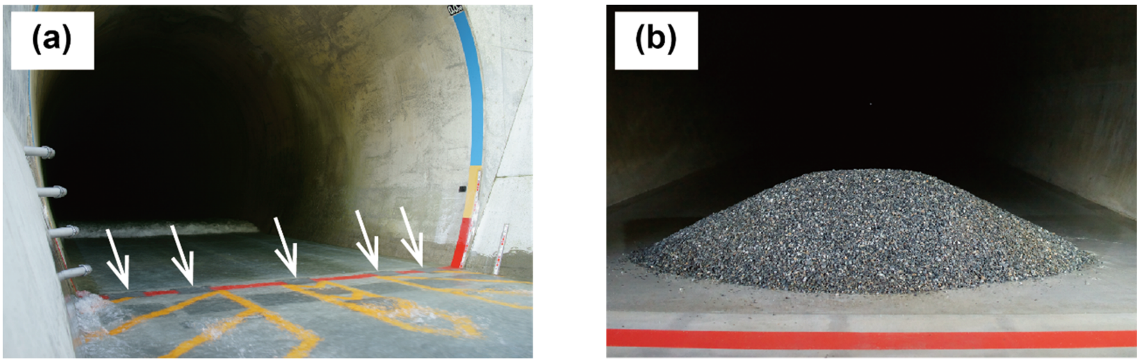

Figure 5: (a) Koshibu SBT outlet. White arrows show the location of the impact plates. (b) test sediment (D_s = 10 mm, V = 5 m^3/s)

3.2 Result

3.2.1 Grain size analysis

The difference of grain size significantly influences the signal of impact plates especially on the amplitude of the waveform (Koshiba *et al*. 2016). The tendency was also found in this experiment that larger gravel causes the larger impact signal amplitude, and vice versa. As a consequence, I_{ps} with high *Amp* was counted for both small and large D_s gravels in contrast I_{ps} with low *Amp* was counted only when large D_s gravels hit on the plate. This indicates that the grain size distribution at each time point might be explained by the degree of I_{ps} increase against the *Amp*. For visualize grain size of the bypassed sediment, a coefficient called amplification centroid $Amp_{centroid}$ is suggested and defined as formulated in Eq.[1]. This coefficient means the centroidal *Amp* value in a graph with x-axis of *Amp* and y-axis of I_{ps}.

$$Amp_{centroid} = 10 - \frac{\sum I_{ps(i)} \cdot \log_2 Amp(i)}{\sum I_{ps}} \quad [1]$$

Where, $I_{ps(i)}$ is I_{ps} with $Amp = i$, and $Amp(i)$ is amplification factor of i times.

The result applying the $Amp_{centroid}$ to all cases and plates is shown in Figure 6. These show the computation results at first 250 seconds from just before the time when sediment flow incipient reaches the outlet. The vertical ticks indicate the Plate 1 to 5 as written in the result of Case 1, thus the bottom side of each figure corresponds to the inner side of the SBT curve. Apparently, the results can be classified into three groups based on the magnitude of $Amp_{centroid}$. The lowest group includes only Case 4, the intermediate group includes Case 1, 2, 5, 6, and 7, and the highest group includes Case 3, 8, 9 ,and 10. This classification matches the maximum grain size in the transported sediment, in turn the lowest with D_s = 5 mm, the intermediate with D_s = 10 mm, and the highest with D_s = 50 mm (see Table 1). Especially, Case 8 (Mixed grain sizes test) shows the tendency that $Amp_{centroid}$ gradually goes down which implicates the larger D_s gravels flowed faster and the smaller D_s gravels later. This hypothesis is supported by confirming the time series signal of raw waveforms (Koshiba *et al*. 2017). Even though this coefficient does not describe the grain size distribution, it is meaningful that the predominant grain size of bypassed sediment can be seen as time series data.

This computational result also describes the spanwise concentration of sediment transportation. In all cases, sediment flows longer at the tunnel inner side (Plate 1 side) than the other side. The analogous phenomenon is discovered in the bedload monitoring at Solis dam SBT, Switzerland (Albayrak *et al*. 2015), and the hydroabrasion depth measurement at Asahi dam SBT, Japan (Nakajima *et al*. 2015).

3.2.2 Bedload transport rate analysis

In this section, we examine bedload transport rate with the function of the impact plate outputs. In flume experiment with the impact plates, the relevance of sediment concentration and particle jump length with sediment transport rate was investigated (Koshiba *et al*. 2016). Based on the investigation, the observed sediment transport rate v_s [m^3/s] was found to be described in Eq.[2] with R^2 = 0.88. Here v_s is the V_s divided by the duration of sediment flow T_s [sec]. Considering $I_{ps(1024)}$ has very high sensitivity that gravels of D_s = 5 mm can be detected, the summed value of $I_{ps(1024)}$ over time can implicate the summed length of the moment when gravels hit on the plate. Therefore, the

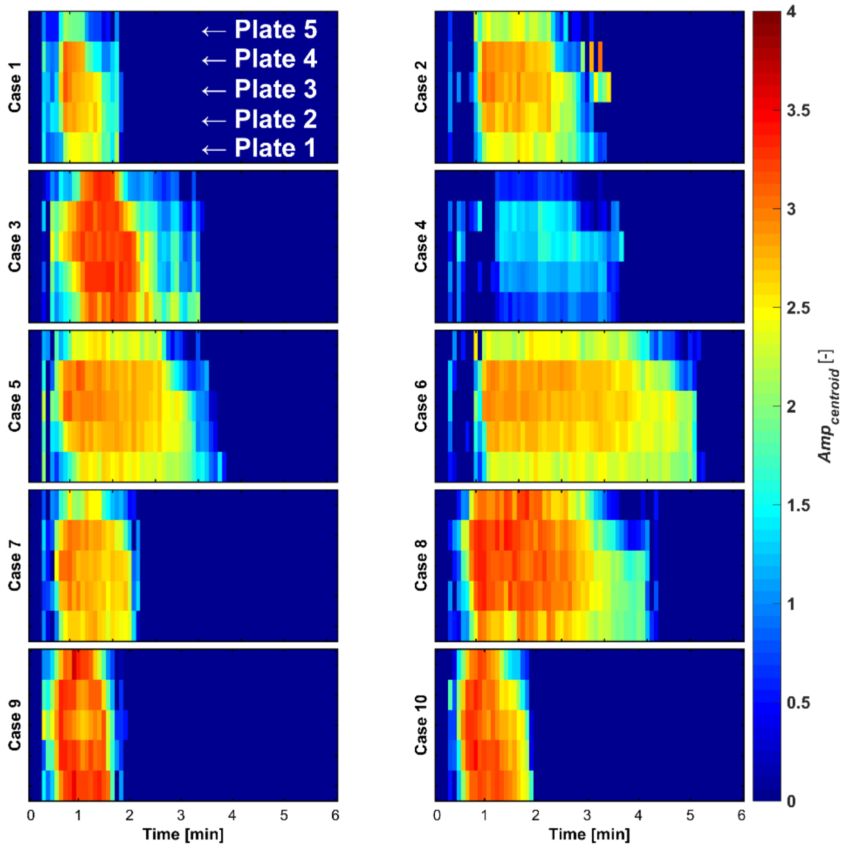

Figure 6: Computational results of the $Amp_{centroid}$ over time at all plates (Case 1 - 10)

summed value of $I_{ps(1024)}$ is included in the equation to represent the sediment flow concentration. Because $I_{ps(1024)}$ only indicates the sediment concentration at the tunnel bed, $I_{ps(1024)}$ is multiplied by the Q for considering the flow depth.

$$V_s = 2.0310^{-5} \frac{\sum_{T_s} Q \cdot I_{ps(1024)}}{T_s} r_p \qquad (R^2 = 0.88) \qquad [2]$$

Where, $\sum_{T_s} I_{ps(1024)}$ is the summed I_{p1024} for all plates during T_s, r_p is the ratio of summed impact plate width in the spanwise direction to the tunnel width ($r_p = 2.56$ at Koshibu SBT).

In this equation, the impact of sediment particle jump length was not incorporated. It was because the ten cases of experiments were not adequate to incorporate the impact of jump length which varies with D_s.

4 Bedload measurement at the first Koshibu SBT operation

The first Koshibu SBT operation was conducted during flood event of Typhoon No. 16 on 21 – 22 September 2016. The overall basics on the SBTs operation including dam inflow, dam discharge through conduit, bypass tunnel outflow, reservoir water level, and diversion weir water level are shown in Figure 7 (Takeuchi *et al.* 2017). The sediment transportation during the SBT operation was monitored by the impact plates without any visible failure on the plates and the information about grain sizes and sediment transport rate was analyzed based on the theories discussed above. For that, the operation was grouped into eight stages as indicated in the Figure 7 and 8 shows the bypassed flow discharge and registered I_{ps} for each stage. In the figure, I_{ps} with Amp = 1024, 256, 64, 16 and 4 are exemplified.

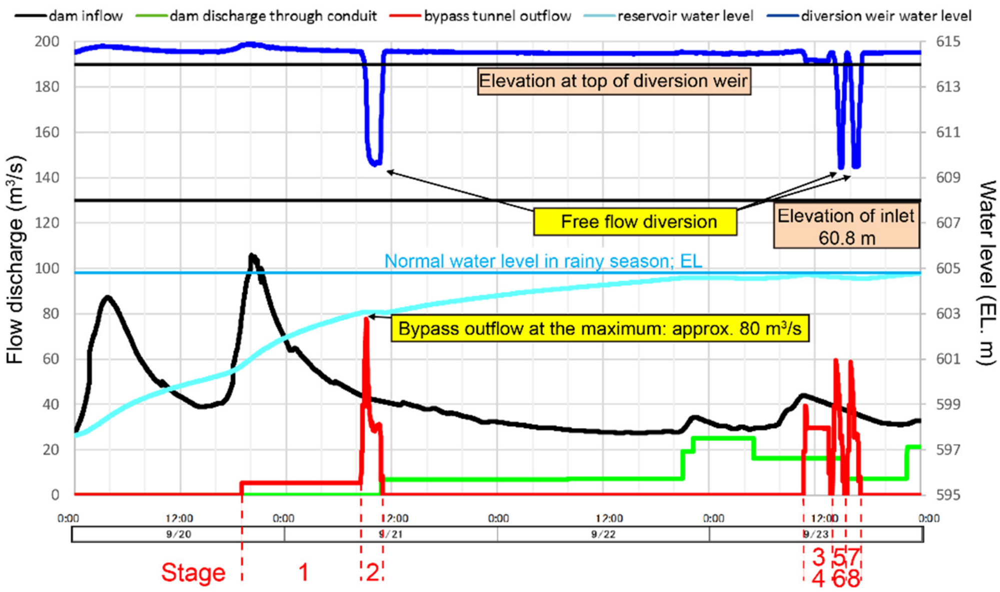

Figure 7: Operational data during the first Koshibu SBT operation in 20-23 September 2016 (Takeuchi *et al.* 2017)

Figure 9 shows the result of the Eq.[1] and Eq.[2] application to the measured data. V_{cal} means the estimated bypassed sediment volume in each stage with Eq.[2]. Comparing $Amp_{centroid}$ with the experimental result (Fig. 6), the values are in the same range of the experimental values hence the grain sizes of the bypassed sediment can be at most D_s = 100 mm. This result exhibits a good agreement with the measured grain size at the downstream area. The summed V_{cal} throughout the operation is around 2,700 m^3. The volume of bypassed sediment was also computed by Tenryu River Integrated Dam Management Office with sediment volume measurement at the immediate downstream are of the SBT outlet and 1-D riverbed fluctuation analysis as 1,300 m^3. Although it was found that both values are not so far each other, more monitorings and analyses are expected to enhance the accuracy of the computation.

5 Conclusions

For the sake of SBT maintenance improvement in the respect of the invert hydroabrasion, we developed a novel surrogate monitoring system namely impact plates. The system has been already deployed at Koshibu SBT and, in prior to the actual operation, field based

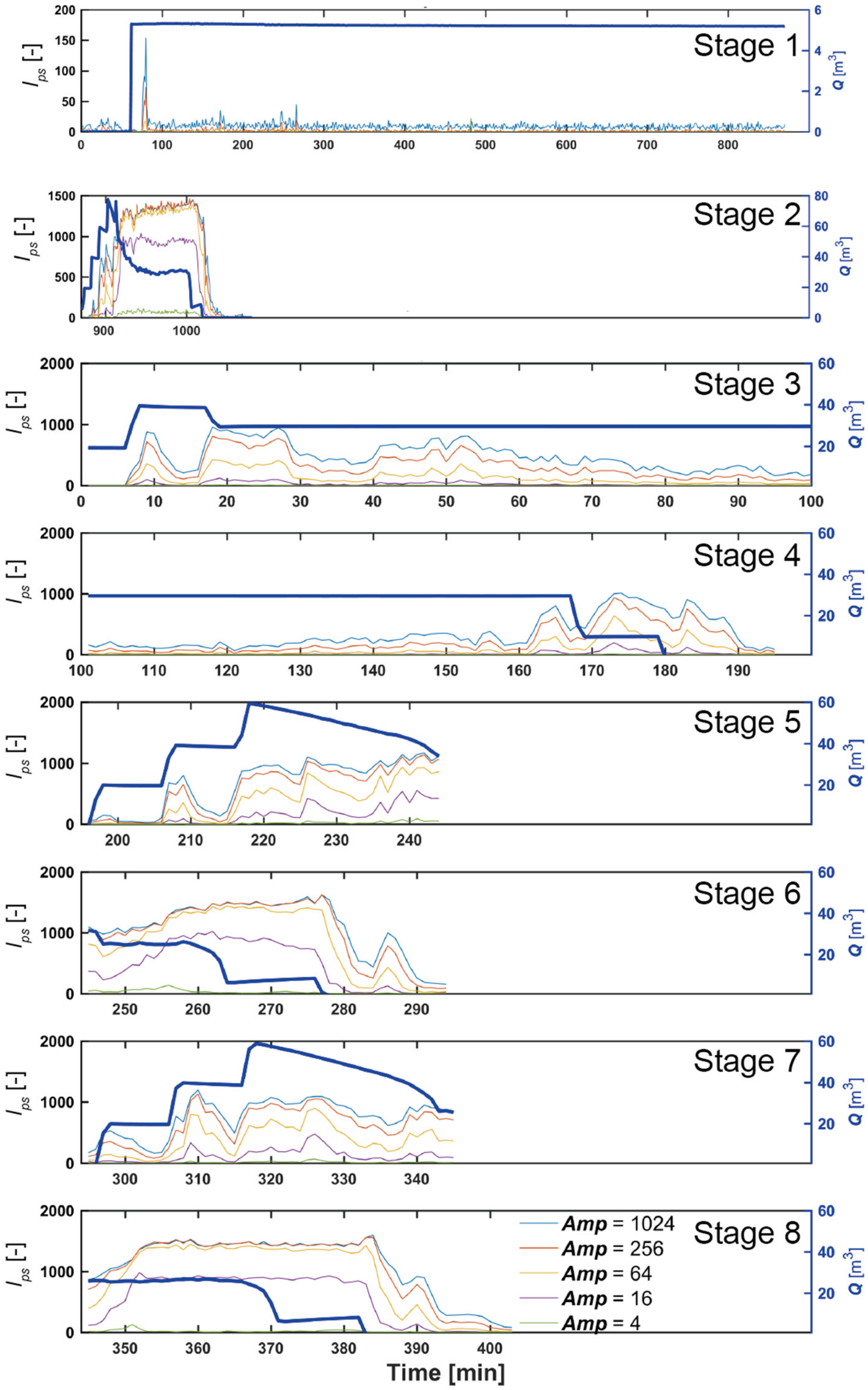

Figure 8: Flow discharge Q and I_{ps} with $Amp = 1024$, 256, 64, 16 and 4 during the first Koshibu SBT operation in each stage

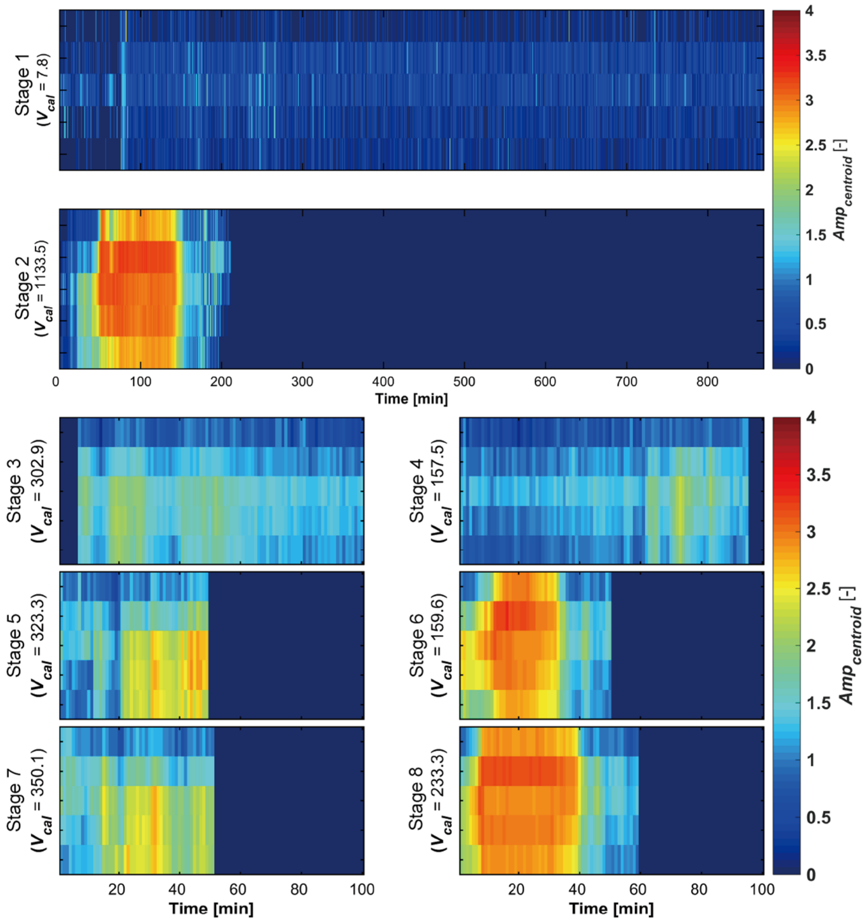

Figure 9: $Amp_{centroid}$ and estimated total bypassed sediment volume V_{cal} [m^3] in each stage calculated from the Eq. [1] and Eq. [2] respectively.

experiment was conducted. Through the experiment, the method to estimate the predominant grain size and the bedload transport rate of the bypassed sediment was developed with using the number of impulses. Although their validity was investigated by applying the sediment monitoring result collected at the first SBT operation, the accuracy should be enhanced through more SBT operations. We believe that the developed new technique of impact plates can visualize the time variation and spatial distribution of the intense bypassed sediment flow in the tunnel

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References

Albayrak, I., Felix, D., Hagmann, M., and Boes, R.M. (2015). Suspended Sediment and Bed Load Transport Monitoring Techniques. *Dresdner Wasserbauliche Mitteilungen*, 53, 405-414.

Auel, C., and Boes, R.M. (2011b). Sediment bypass tunnel design–hydraulic model tests. *Proc. Hydro 2011 - Practical solutions for a sustainable future*, No.29.03. Aqua-Media International Ltd. Prague, Czech Republic.

Gray, J. R., Laronne, J. B., & Marr, J. D. (2010). Bedload-surrogate monitoring technologies. *US Department of the Interior, US Geological Survey*.

Ishibashi, T. (1983). Hydraulic study on protection for erosion of sediment flush equipments of dams. Civil *Soc Proc.* 334(6):103–112 (in Japanese).

Kondolf, M., Gao, Y., Annandale, G., Morris, G., Jiang, E., Zhang, J., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, HW., Wang, Z., Wei, Z., Wu, B., and Yang, C.T. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future* 2(5): 256-280.

Koshiba, T., Sumi, T., Takemon, Y., and Tsutsumi, D. (2016). Flume Experiment on Bedload Measurement with a Plate Microphone. *Annuals of Disaster Prevention Research Institute*, Kyoto University, No.58 B.

Koshiba, T., Kantoush, S.A., and Sumi, T (2017). Field experiment of bedload transport rate measurement at sediment bypass tunnel. *85th Annual Meeting of ICOLD,* Prague, Czech Republic. (Submitted)

Mizuyama, T., Matsuoka, M., and Nonaka, M. (2008). Bedload measurement by acoustic energy with Hydrophone for high sediment transport rate. *Journal of the Japan Society of Erosion Control Engineering*, 61(1), 35-38 (In Japanese).

Morris, G.L., and Fan, J. (1998). Reservoir sedimentation handbook: design and management of dams, reservoirs, and watersheds for sustainable use. *McGraw Hill Professional*.

Nakajima, H., Otsubo, Y., and Omoto, Y. (2015). *A*brasion and corrective measures of a sediment bypass system at Asahi Dam, *Proc. Int. Workshop on Sediment Bypass Tunnels*, VAW-Mitteilung 232 (Boes, R.M, ed.), ETH Zurich, Switzerland, 21-32.

Rickenmann, D. (2017). *Bed-Load Transport Measurements with Geophones and Other Passive Acoustic Methods* (Doctoral dissertation, American Society of Civil Engineers).

Sumi, T., Okano, M., and Takata, Y. (2004). Reservoir sedimentation management with bypass tunnels in Japan. *Proc. 9th International Symposium on River Sedimentation*, Yichang, China: 1036-1043.

Vischer, D.L., Hager, W.H., Casanova, C., Joos, B., Lier, P., and Martini, O. (1997). Bypass tunnels to prevent reservoir sedimentation. *In Transactions of the international congress on large dams*, Vol. 3: 605-624.

Authors

Takahiro Koshiba (corresponding Author)
Tetsuya Sumi
Water Resources Research Center, Disaster Prevention Research Institute, Kyoto University, Japan
Email: kobeline2@gmail.com