Bedload transport and abrasion monitoring at the Koshibu Dam sediment bypass tunnel and proposing countermeasures against the abrasion problem

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ABSTRACT:

Sediment bypass tunnels (SBTs) is a leading technique, mainly operated in Japan, Switzerland and Taiwan, to mitigate sedimentation problems in reservoirs. SBT reduces sedimentation by diverting sediment laden flood to a tunnel and draining directly to the downstream reach. A major issue in operating SBT is hydro-abrasion on the tunnel invert caused by a combination of high sediment transport rate and high flow velocity, whereas the countermeasure is not well established because the relation between sediment transport rate and the abrasion is not clear. Accordingly, at the Koshibu dam SBT in Japan, sediment transport is being monitored with a surrogate bedload monitoring system called an impact plate during all the SBT operations since the SBT completion in 2016. In addition, the abrasion of the entire tunnel invert is measured once a year using mobile mapping system (MMS) with a three-dimensional laser scanner. In this paper, monitoring results including grain size and transport dynamics, i.e. velocity, transport rate, spatiotemporal distribution of bypassed sediment, and current progress of abrasion are reported. On the basis of those observation, design and operation of SBTs that may reduce invert abrasion with maintaining the suitable bypass efficiency is proposed.

1 INTRODUCTION

1.1 *Sediment Bypass Tunnels*

Sediment bypass tunnels (SBTs) is a promising choice to mitigate reservoir sedimentation (Auel and Boes 2012, Kashiwai et al. 2015, Sumi et al. 2004, Vischer et al. 1997). In general, an SBT consists of a tunnel, inlet gate, outlet, and weirs located at the upstream of a dam to divert flood into the tunnel. The terminology of SBTs is still not clearly defined, it is understood that SBTs are mainly operated in Japan, Switzerland and Taiwan.

Note that the first SBT in the world was built at the Nunobiki reservoir in 1900. Just eight years after the dam was completed the SBT was constructed, and this still works effectively. It is estimated that without the SBT, the reservoir would have been filled with sediment by 1925. Another case, the Asahi SBT in Japan reported by Fukuroi (2012), where a large part of incoming sediment was bypassed by Asahi SBT, hence the accumulated sedimentation volume is lowered. The use of SBT would redistribute approximately 77 to 94% of incoming sediment (Auel et al. 2016).

There are technical and ecological benefits in using SBTs over other methods. Technically, we can use SBTs without drawdown thus the economic loss of water users is limited. Although the high initial cost cannot be ignored, the technology might be regarded as semi-permanent mitigation of the sedimentation. Furthermore, if a new dam is designed with an SBT from the stage of planning, economic efficiency and equability would be better (Auel et al. 2017, Facchini et al. 2015, Martín et al. 2015). SBTs are also favorable to downstream ecology because they do not incur sudden change in sediment concentration unlike that by flushing: the downstream reaches receive flood water that presents more natural characteristics. For promoting SBTs and sharing the exiting problems with dam owners and researchers, International Workshop on Sediment Bypass Tunnels is held every two years since 2015.

1.2 *Invert abrasion*

Despite the advantages of SBTs, there are still few applications in the world. The primal reason for that are lack of knowledge for designing, operating, and maintaining SBTs properly, and the consequent unclear cost effectiveness. In particular, hydro-abrasion on the tunnel invert caused by a combination of high sediment transport rate and high flow velocity is a serious problem on which maintenance cost depend. Figure 1 shows measured abrasion distribution in the Asahi SBT, Japan. The owner, Kansai Electric Power Co., Inc., is required annual rehabilitation works to fix it (Nakajima et al., 2015). However, countermeasures are not well established because the relation between sediment transport distribution and the consequent abrasion is not clear.

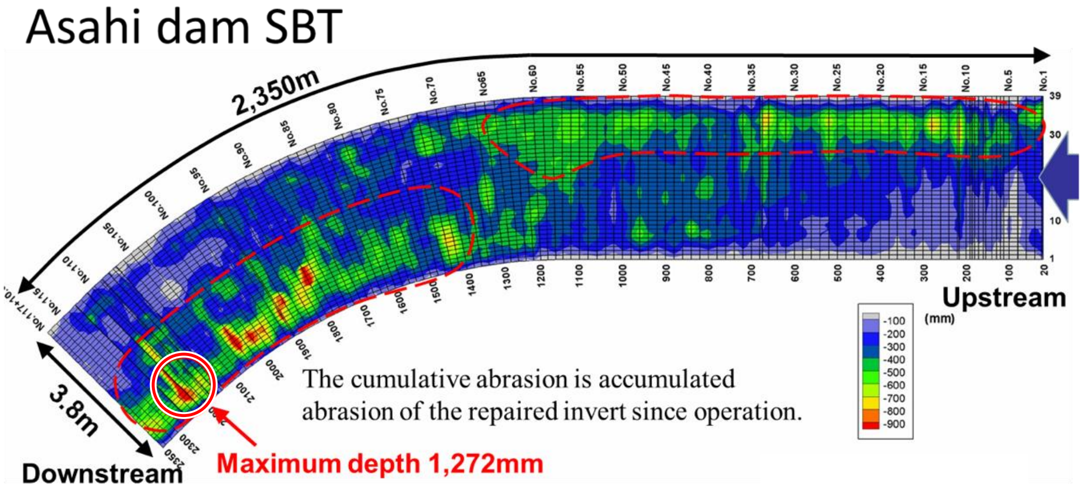

Figure 1. Accumulated abrasion depth (1998 to Nov.2011) at the Asahi dam SBT (adapted from Nakajima 2015).

It is reported that most existing SBTs are affected by invert abrasions. Indeed, in the 2^{nd} International Workshop on SBT held in Kyoto, Japan, the three tasks which should be elucidated for addressing the abrasion problem were identified:

- **task1** How bedload is transported in SBTs.
- **task2** How bedload gives an impact on inverts.
- **task3** What kind of countermeasures are effective.

To elucidate them, first of all, bedload monitoring in SBTs is important because the volume of abrasion is highly related with the invert strength and bedload transport rate. We are working to clarify **task1** by developing bedload transport monitoring system and apply it for the Koshibu dam SBTs in Japan to investigate the relation between the bedload observation and the invert abrasion measured to know **task2**.

In this paper, we present our observation results of spatiotemporal transient of grain size and bedload transport rate during a the Koshibu Dam SBT operation.

2 MONITORING METHODOLOGY

2.1 *Impact plate*

The Impact Plate (IP), manufactured by Hydrotech Co., Ltd. (Japan) was employed for the Koshibu Dam SBT monitoring (Koshiba et al. 2018) (Fig. 2). IPs consist of four parts: a steel plate, a microphone, an acceleration sensor (GH-313A, which serves as a sensor, and GA-223, which functions as a converter; manufactured by KEYENCE, Japan), and a data logger. The steel plate is 49.2 cm in width, 35.8 cm in length in the flow direction and 1.5 cm in depth. The microphone and acceleration sensor register signals produced by the impact of sediment particles on the plate. IPs are expected to record the impact of small gravel particles with diameters of approximately 2 mm. A computer records the signals detected by the acceleration sensor and microphone sensor of the steel plate during the SBT operation with a sampling frequency *fs* 50 kHz.

The obtained signals are analyzed to extract information on bedload, i.e. grain size and bedload transport rate.

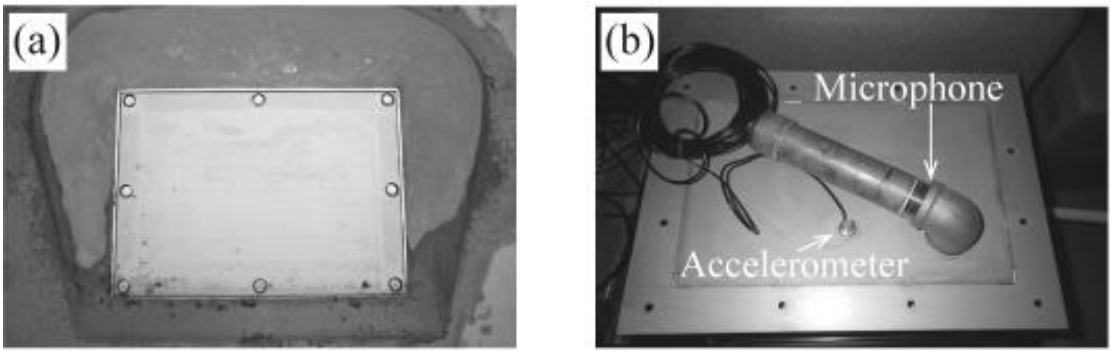

Figure 2. The Impact Plate. (a) top view of an IP, (b) the back side of an IP with a microphone and accelerometer.

2.2 ***Analyses method***

In general, signal analysis is conducted following three steps: signal cleaning, feature extraction, and modeling. Many studies have been published for estimating bedload transport rate using surrogate monitoring techniques and some of them are practically used. We are using various techniques to obtain grain size and bedload transport rate. Because of the limited pages, in this section, the concept of analysis is briefly explained. The detail can be found in Koshiba and Sumi (2018) and Koshiba (2020).

For signal cleaning, many studies skip this step or just apply simple low-pass filter based on Fourier transform. In my approach, considering particular properties of signals obtained from impact plates, i.e. non-periodicity and abrupt change appearance, Discrete Wavelet Transform was exploited for denoising. As the result, it was confirmed that noise was removed better than that done with conventional low-pass filter, consequently the distinguishability of grain size improved.

For the modeling, most of the studies are along deductive approach where simple regression and physical parameters are used. This approach provides high interpretability of models but often restricts the prediction accuracy and general applicability. Therefore, we attempted to use a more inductive, in other word data driven, method. Although neural networks and deep learning are popular data driven methods giving high expressive power today, their black box property does not allow us to incorporate physical a posteriori knowledge into the models. Therefore, we decided to use non-parametric Gaussian process regression, which has both high expressive power and high interpretability by designing kernels that determines the form of regression function (Rasmussen & Williams 2006).

Essentially, application of models based on flume experiments to real field data involves extrapolation. In order to cope with this weak point, our models were created only using flume experiment data with integrating background knowledge into kernels, for instance: the magnitude of signal increases as bedload increases; the high flow velocity causes gravels to jump over the plate which invites bedload transport rate underestimation; gravels with the smaller grain size tend to jump over the plate more. Then, the models were evaluated by their prediction accuracy for on-site experiment data where the application also presents extrapolation. At last, we were able to make a model which provides good prediction accuracy for on-site experimental data albeit the model was optimized only from flume experimental data.

3 BEDLOAD MONITORING AT THE KOSHIBU SBT

3.1 *Field data*

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 crest length of 293.3 m. The catchment area is 288 km^2 and mostly covered by forest and sediment supply prone area. Moreover, the reservoir received enormous severe floods and thus rapid sedimentation rate has been an issue for the dam management. Indeed, in 2015, the sedimentation volume exceeds 15.6 Million m^3 (MCM) almost reaching to the original designed sedimentation capacity 20.0 MCM.

Considering the proceeding Koshibu reservoir sedimentation, MLIT initiated the construction of the Koshibu dam SBT and the first operation was successfully achieved between 21st and 23rd of September 2016. 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 = 1000 m). The plan view of the Koshibu dam and SBT is shown in Fig. 3. 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 are reinforced with rubber-steel and steel-lining material respectively. The impact plates are installed at the outlet and started observation from the first SBT operation.

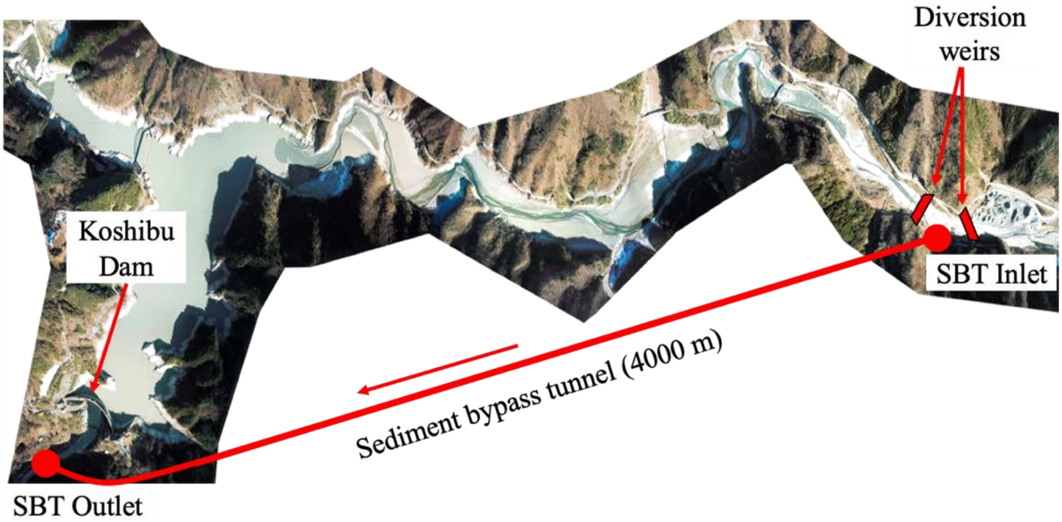

Figure 3. The plan view of the Koshibu dam and SBT.

3.2 *Impact plate deployment*

Figure 4 shows the arrangement of measurement devices at the outlet. Five IPs (named IP1 – IP5 from the orographic right side) are mounted in order to measure the cross sectional distribution of transported sediment. In addition, to compare the robustness with other surrogate monitoring system, a conventional system Japanese Pipe Microphones (JPMs) were also employed for the observation.

Every monitoring system works only during bypassing periods. Two kinds of data are output, raw signal and impulses. Impulses are conventional summary value used in Japan (Mizuyama et al. 2010) which reduce the data volume significantly. Although it is desirable to store raw signals at every operation, only impulses were recorded at some of the operations due to a technical reason.

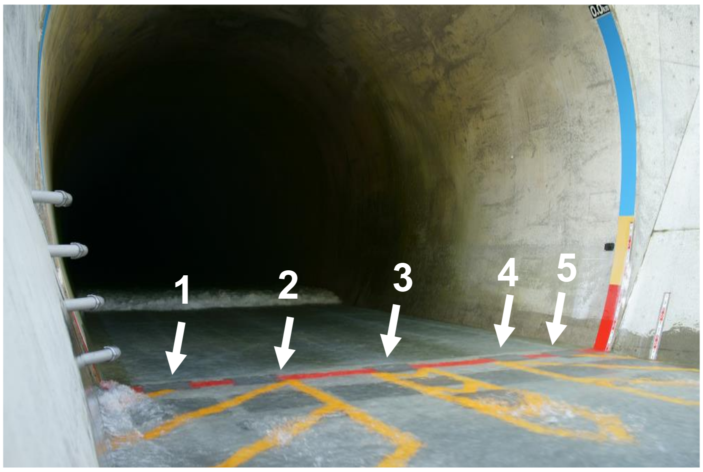

Figure 4. The Koshibu Dam SBT outlet with five IPs installed. White arrows show the impact plates.

3.3 *The Koshibu SBT operations in 2016 - 2019*

Since the first operation in September 2016, the Koshibu SBT was operated for eight times as a testing period. Table 1 shows the list of operation in the period, operation duration, and maximum bypass discharge $Q_{bypass,\ max}$. The consequent maximum flow velocity V_{max} and water depth h_{max} were given assuming uniform flow and a roughness length of 0.013 $m^{1/3}s^{-1}$. As of present, the SBT is operated 2-3 times in a year. Also, the inflow discharge in the three years and the bypass discharge are shown in Figure 5. In the first several operations were relatively small scale because their main purpose was to see the impacts on downstream environment and SBT structurers. Contrary, recent bypassed discharges are as large as inflow discharges, thus the sediment might have been effectively bypassed. In particular, the operation 5, 7, and 8 completely include the flood peak periods. Overall, bypass operations did not last until the end of a flood event in order to mitigate sediment deposition inside the tunnel and to start storing water in the reservoir.

Some of the sediment monitoring apparatuses were damaged or not able to record data well. Table 2 summarizes the condition of all sediment monitoring devises. JPMs were completely destroyed during the first operation. In general, JPMs are not robust against strong impacts, having high sensitivity though, because the half of the pipe is out of bed surface. According to the fact that four IPs are still working after experiencing large bypass operations such as 6, 7, and 8, IPs are much more robust than JPMs.

Table 1. The Koshibu SBT operations in 2016 – 2018.

Operation No.	Date [-]	Duration [hours]	$Q_{bypass,\ max}$ [m^3/s]	V_{max} [m/s]	h_{max} [m]
Op1	21-22/09/2016	16	80	9.14	1.28
Op2	23/09/2016	5.8	60	8.31	1.06
Op3	04-05/07/2017	3.1	120	10.39	1.67
Op4	22-23/10/2017	9.7	180	11.75	2.18
Op5	29-30/10/2017	48.8	90	9.49	1.83
Op6	04-05/07/2018	10.7	150	11.13	1.93
Op7	04-05/09/2018	44.2	175	11.65	2.14
Op8	01-02/10/2018	69.5	200	12.11	2.34

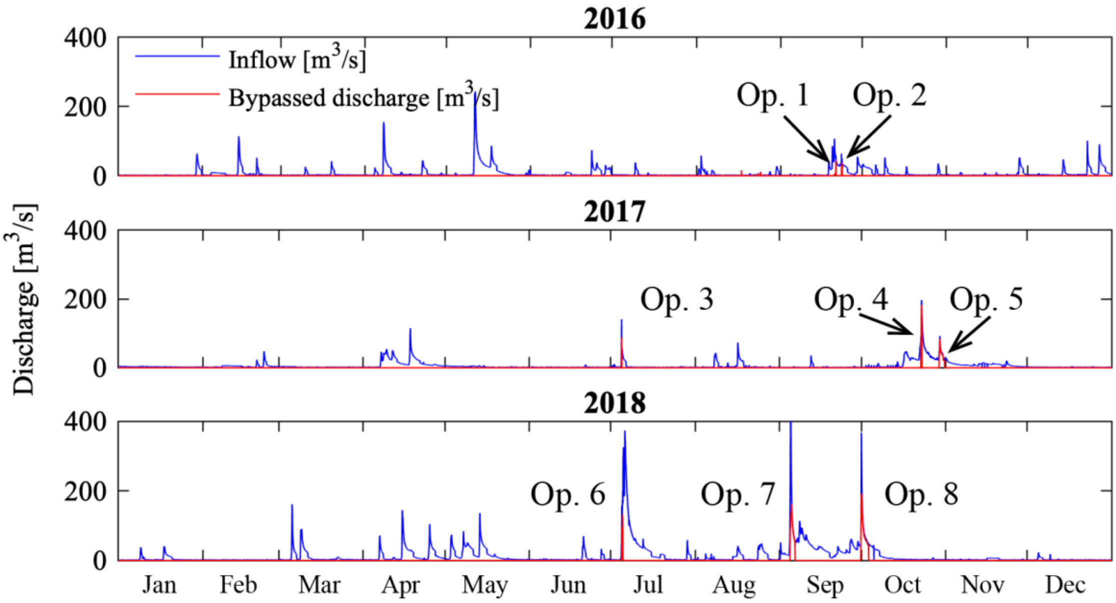

Figure 5. The inflow discharge into the Koshibu reservoir, and the bypassed discharge by the Koshibu SBT in 2016 – 2019.

Table 2. Condition of bedload monitoring apparatuses at the Koshibu SBT.

Operation	IP1	IP2	IP3	IP4	IP5	JPM1	JPM2
Op1	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Op2	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓*	✓✓*
Op3	✓	✓	✓	✓	✓	×	×
Op4	✓	✓	✓	✓	✓	×	×
Op5	✓	✓	✓	✓	✓	×	×
Op6	✓✓	✓✓	✓✓	✓✓	✓✓	×	×
Op7	✓	✓	✓	✓	✓	×	×
Op8	✓✓	✓✓	✓✓*	✓✓	✓✓	×	×

✓✓ : Both impulses and raw signals were recorded.
✓ : Only impulses were recorded.
× : Neither impulses nor raw signals were recorded.
* : Broken during the operation

3.4 ***Monitoring results***

The signal analysis method introduced in Section 2.2 was applied for Op1, Op2, Op6, and Op8, which raw signals were recorded, to obtain spatiotemporal information of grain size and bedload transport rate. Result of Op2 is in Figure 6. The figure consists of five plots with time in abscissa. The figure contains five plots and their details are below.

- *Top row*: Bypassed discharge Q [m^3/s] and accumulated estimated bedload volume $V_{s,acc}$ [m^3]. The blue shaded area stands for the range of the mean estimate $\pm 1\sigma$ (standard deviation).
- *Second row*: Estimated D_{50} [mm]. The blue shaded area stands for the range of the mean estimate $\pm 1\sigma$.
- *Middle row*: Mean of estimated D_{50} [mm] for each plate (IP1 - IP5, see Fig. 3).
- *Forth row*: Bedload transport rate BTR per V_s [m^3/s]. The blue shaded area stands for the range of the mean estimate $\pm 1\sigma$.

– *Bottom row*: Bedload transport rate *BTR* per a plate width V_s [m^3/s/plate width] for each plate (IP1 - IP5, see Fig. 3).

The discharge presents bimodal shape. This was to test complicated operations with frequent gate open and close because the operation was in testing period of the SBT.

In general, the results are provided with mean and standard deviation. This is one advantage of using Gaussian Processes introduced in Section 2.2. The method outputs prediction with a probability distribution, thus we can know the uncertainty of the results. Overall, bedload transport was output with higher variance than D_{50}. This is because the D_{50} observed in the field was the same order as that used in laboratory experiments conducted for making the model. In contrast, the bedload transport rate observed in the field was sometimes much higher than that in experiments, thus the variance for bedload transport rate tends to be relatively large.

Estimated D_{50} was less than 100 mm. To consider that the maximum designed sediment grain size to be bypassed at the Koshibu Dam SBT is 100 – 200 mm, this result is reasonable. Evidently, larger grain sizes were observed when discharge was not the maximum value. It might be caused by the condition at the SBT inlet. In the rising limb of the bypass discharge, the inlet gate was opened gradually and flow state was not in open channel. Contrary, the decreasing part of bypass discharge might be open channel, hence larger drag force occurred to induce larger grain sizes to flow. For the aspect of abrasion mitigation, it is reported that saltating gravels damage inverts much higher than sliding and rolling gravels. Accordingly, it is favorable that larger grain size sediment flowed under relatively low discharge period where flow velocity was also low.

Bedload transport was constant in both operations despite of the drastic change of D_{50}. This might be because large grain size was observed in lower discharge and vice versa. It should be note that bedload concentrated on IP1 – IP3 in the first half of each operation. This is caused by secondary flow (secondary flows of Prandtl’s second kind) occurred due to the tunnel curvature. Also, this result is consistent with abrasion observation at the Asahi Dam SBT in Japan (Fig. 1) where abrasion concentrated on tunnel curve inner side. However, the concentration was not as significant as that of abrasion at the Asahi Dam SBT. Even in other operations with the maximum discharge 200 m^3/s recorded, significant concentration was not confirmed. Considering the secondary flow is proportional to flow velocity/curvature, it might be possible that the large curvature of the Koshibu Dam SBT would not make severe abrasion in tunnel curve inner side. Moreover, sediment transport concentrated on the middle in the tunnel width direction in the latter half of each operation. According to the large grain sizes in these periods, the force of secondary flow was not enough large to move large sediment to be moved. Therefore, at least in the Koshibu Dam SBT or larger SBTs, it might be important to carry out abrasion mitigation measures on the center of tunnels.

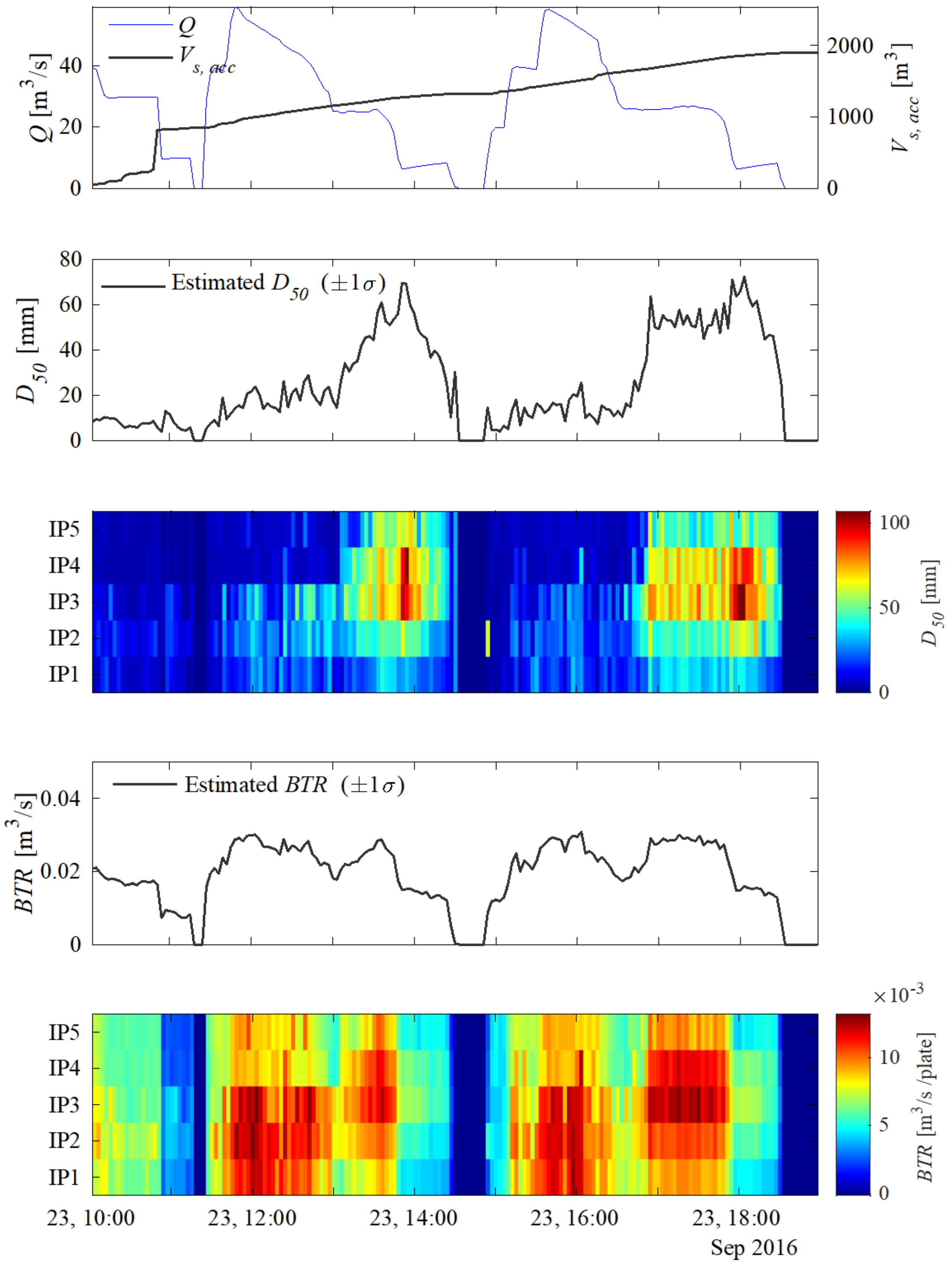

Figure 6. Estimated grain size and bedload transport rate in Op2.

4 CONCLUSIONS

In this paper, sediment transport monitoring at the Koshibu Dam sediment bypass tunnel with impact plates was introduced. Impact plates can indirectly observe bedload that cannot be observed by collecting water or turbidimeter. Furthermore, it was revealed that the system has enough robustness to work in SBT.

Our analysis made it possible to unveil the spatiotemporal bedload movement inside SBTs with actual grain size and bedload transport rate for the first time. We believe that this technique and analysis method help in optimizing SBT design, operation, and management with considering both abrasion mitigation and bypass efficiency. In addition, the technique enables dam operators to monitor real time sediment transport in SBTs. We expect active installation and utilization of this monitoring technique at SBTs to improve their operation.

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