Field experiment of bedload transport rate measurement at sediment bypass tunnel

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ABSTRACT

For advanced maintenance of sediment bypass tunnels (SBTs), particularly concerning on the abrasion of the tunnel invert, a monitoring of sediment through tunnel is essential. We developed new bedload measurement systems, namely a plate microphone and a plate vibration sensor. After confirming the high sensitivity and robustness of these systems by flume experiments, these systems were installed at the outlet of Koshibu SBT, which started operation in 2016, in Japan. Prior to its commencement of the SBT, on-site calibration experiment was conducted. In the experiment, sediment is input in the SBT artificially by truck beforehand and flushed them out with clear water from the upstream. The experiment is repeated for 10 times with different grain size (5, 10 and 50 mm), volume (1, 3, 5 and 9 m3) and water discharge (5, 10 and 50 m3). Seven sensors of the measurement systems, which installed evenly along the width, successfully recorded the signals of passing sediment. In this paper, practical calibration formula of predicting sediment transport rate by recorded data are developed by analyzing the pattern of the 10 experiment cases. Finally, a method to quantify sediment transport rate and a desirable operation of those measurement systems on-site are discussed.

1. INTRODUCTION

Reservoir sedimentation has been one of the topical issues throughout the world affecting sustainable use of dams with respect to hydroelectricity production, flood disaster prevention, water supply and irrigation. Generally, the concept of the countermeasures can be classified into broad three categories: (1) sediment yield reduction, (2) removing sediment deposited in the reservoir already, and (3) sediment routing around or through the reservoir (Kantoush & Sumi 2010, Kondolf et al. 2014). In particular, the third category includes one advanced technique of SBTs, which are implemented to reduce suspended and bedload deposition in reservoirs by routing the incoming sediment around the dam (Sumi et al. 2004, Auel & Boes 2011a). SBTs are an effective strategy and can divert around 77% to 94% of the incoming sediments to the downstream reaches (Auel et al. 2016a). Japan and Switzerland are the leading countries where more than five SBTs are operating but also more than two SBTs are constructed and planned in Taiwan. The advantages of SBTs are not only alleviate reservoir sedimentation but also alleviate sediment starvation in the downstream reaches with nearly the same flow conditions (Kondolf et al. 2014). However, SBTs tend to be affected by the combination of high flow velocity and high sediment flux causing invert abrasion, which increase SBTs maintenance costs additionally to the relatively expensive SBTs tunnel construction costs (Auel & Boes 2011b, Baumer & Radogna 2015, Jacobs & Hagmann 2015, Nakajima et al. 2015). Figure 1 shows the Koshibu SBT operating during a flood event and Figure 2 is the current hydroabrasion state in Asahi SBT. Therefore, to realize appropriate invert abrasion management and quantifying the amount of abrasion is the noteworthy research subjects. For that, it is important to establish a sediment transport measurement system because abrasion prediction model is basically depending on actual bedload flux in the SBT (Auel et al. 2016b). Moreover, the sediments transport volumes, which are diverted downstream of the dam during floods, is useful information for comprehensive river basin management and also important regarding environmental aspects, as morphologic variability is enhanced (Facchini et al. 2015).

A numerous volume of studies on bedload transport measurement in the natural rivers has been conducted (Helley & Smith, 1971, Gray et al. 2010, Tsakiris et al. 2014). Although the direct measurement systems such as basket sampler were used for long time, the improved technology has been recently allowing the development of surrogate bedload monitoring devices which is less laborious and invasive than the direct methods (Wyss et al. 2016). Generally, the surrogate monitoring systems consist of steel plate or pipe and some sort of sensor. For instance, Swiss plate geophone (SPG), which is also used for bedload monitoring in Solis SBT in Switzerland, is composed of a steel plate equipped with a geophone sensor underneath the plate and mounted on the river bed. The SPG detects the vibration of sediment particle impacts which are likely to include the information of transported sediment characteristics, e.g. gran size, sediment volume and particle velocity (Auel & Boes 2011b, Rickenmann et al. 2012). Analogous to the SPG, Japanese pipe microphone (JPM) has been also used in many rivers in Japan. The JPM is composed of a microphone mounted in a steel pipe and measures the impact sound caused by particle impinging to the pipe. Even though the JPM has an advantage on its high susceptibility of which minimum detectable grain size is 2 mm, its lack of robustness and short width which causes the particles to jump over the pipe are disadvantages especially in the condition of

Figure 1. Koshibu SBT during operation

Figure 2. SBT invert abrasion (Asahi SBT)

SBTs where the flow velocity is in excess of 10 m/s (Auel & Boes 2011a, Tsutsumi et al. 2014). In contrary, a geophone is shock-resistant but the minimum detectable grain size is 10mm to 40mm (Rickenmann et al. 2012). Based on the characteristics of both devices, we suggested an impact plate for measuring bedload transport in SBTs. The proposed system is consists of a steel plate being robust against particles with high velocity and mounting a microphone underneath the plate to keep the susceptibility as high as the JPM (Koshiba et al. 2016b). Additionally, in the impact plate, an acceleration sensor is also mounted to measure oscillation of the plate. As a result of calibration experiments in a laboratory flume, fundamental characteristics of the impact plate have been proposed. However, it is known that the behaviours of surrogate bedload monitoring systems are field-limited in some extent due to the different field conditions which cause the different motion of bedload particles. It implicates the necessity of the field calibration of the impact plate for more reliable monitoring (Tsakiris et al. 2014, Mao et al. 2016).

Koshibu SBT began operation on September 2016 where various impact plates and JMP were installed to measure the sediment transport capacity. A full scale trail experiment were performed to calibrate the impact plates prior to the real operation during flood season. The paper describes design and results of the trail experiments with a highlight on the implemented technique of impact plate.

2. SEDIMENT MONITORING

In the Koshibu SBTs, seven impact plates (Figure 3) and two JPMs (Figure 4), manufactured by Hydrotech Co., Ltd. (Japan), are installed for measuring spatial distribution of the transported sediment. As noted above, 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. The JPMs has a length of 80 cm and 48.6 mm of diameter, which is the similar to those widely used in Japan. A detailed information about the JPM is reported in the study by Goto et al. 2014. Both microphone and acceleration sensor record the sound and vibration of the sediment particle impacts transmitted to the sensor through the plate respectively as a voltage [V] at 50 kHz of sampling frequency. Figure 5 shows the raw waveform data of their output performed in the laboratory tests where 20 particles of gravels were transported over the plate with the diameter of 50 mm at the water velocity of 4.5 m/s (Koshiba et al. 2016a). Even though such raw waveform data are useful in analysing 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 some data processing methods for decreasing data amount with remaining the characteristics of transported particle were developed for JPMs in Japan and the also employed for observation with using impact plates. During full scale trail experiment, raw waveform data were collected in part, but the following data processing was conducted throughout every runs.

2.1 Data processing

In accordance with the previous observations by the JPM (Mizuyama et al. 2008, Suzuki et al. 2010), the following two parameters were computed by the impact plate during each experiment: the number of impulses I_p and the average value of sound pressure S_p. Both values are obtained through analog signal processing in a data logger, and thus calculated simultaneously with the recording of the raw waveform data (Koshiba et al. 2016a). 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.

The recorded number of impulses I_p represents the number of particles hitting the plate, and the analogous method is employed not only for JPMs but also for SPG as one of the simplest methods for quantifying the Bedload transport rate (Wyss et al. 2016). This parameter works to significantly decrease the accumulated data amount compared to collecting all signal waveform data while maintaining some extend of information about the frequency and amplitude fractions of the signal of particle impacts. To compute I_p, the following steps are conducted with the data logger simultaneously to the raw waveform recording. First, the raw waveform is 20 times amplified and proceeded through a band-path filter to extract the frequency of approximately 4.6 kHz, which was previously computed as the most effective frequency for distinguishing particle impacts on the plate. Subsequently, the filtered waveform is transformed into an absolute value. An envelope curve is generated and amplified 10 times to accentuate the signals caused by the particle impact. Then, the enveloped data are exported to 6 different channels, in which the wave is amplified 2, 4, 16, 64, 256, and 1024 times, and finally, I_p for each amplification factor is defined as the number of impulses, grouping the distributed signals above a predefined threshold of 2 V.

Although I_p is already commonly used for field observations in Japan, it is also reported that I_p can lead to underestimations due to the overlapping of each single impulse when the sediment transport rate is high as well as when several gravel particles hit the plate simultaneously (Mizuyama et al. 2010). To address this shortcoming, bedload measurements were taken using the enveloped data in the process of calculating I_p, as suggested by Suzuki et al. (2010), and also automatically recorded for all runs as S_p, which is referred to as average value of sound pressure in Japan. S_p is defined as the value of the enveloped signal data averaged over every 10-sec duration. S_p can be regarded as a parameter which represents the integrated value of raw waveform which is less affected by the overlapping of particle impacts than I_p.

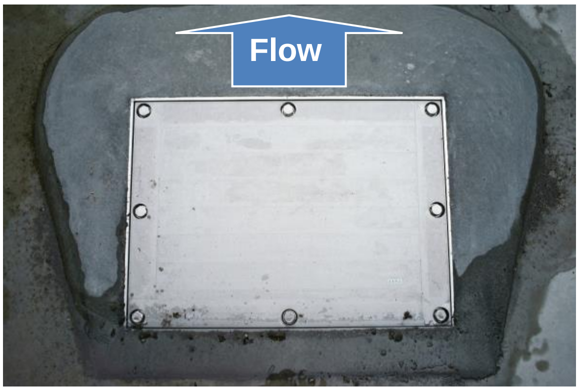

Figure 3. Impact plate

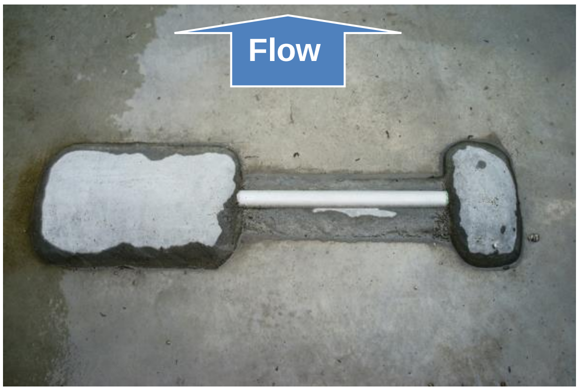

Figure 4. Japanese pipe microphone

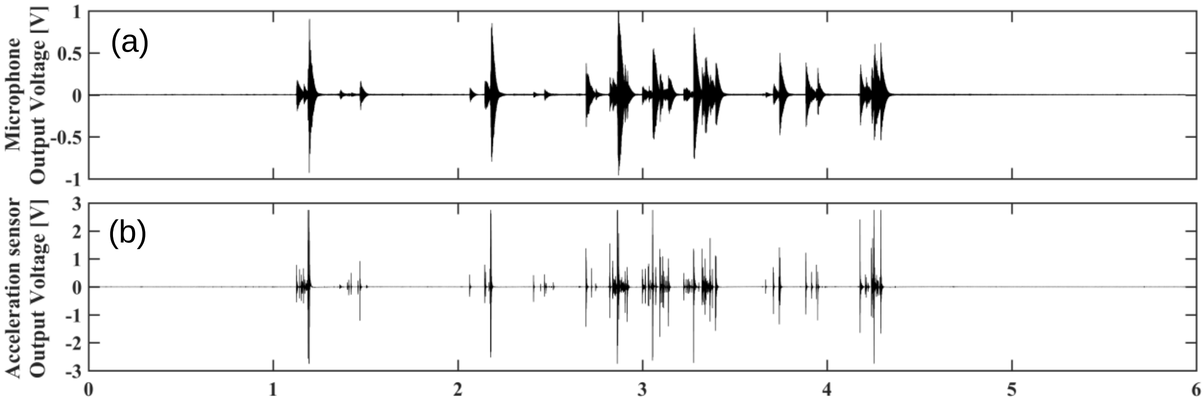

Figure 5. Raw waveform data collected at a flume experiment when 20 particles are transported over the impact plate. (a) Microphone, and (b) Acceleration sensor (D_s = 50mm, V_w = 4.5 m/s)

3. 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, on 2015, the sedimentation volume exceeds 15.6 Million m^3 (MCM) almost reaching to 20.0 MCM of original designed sedimentation capacity. Considering the proceeding Koshibu reservoir sedimentation, MLIT initiated the construction of Koshibu SBT and the first operation was successfully achieved between 21st and 23rd of September 2016 during the typhoon Malakas. 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 are reinforced with rubber-steel and steel-lining material respectively. The impact plates are installed at the outlet (Figure 6) and started observation from the first SBT operation.

3.2 Design of sediment monitoring device deployment

Figure 7 shows the arrangement of measurement devices at the outlet. Five impact plates named t15 are mounted in order to measure the cross sectional distribution of transported sediment. Moreover, as in Figure 7, 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, t15 inclined is an original impact plate but the plate is inclined with 10 degree. These are employed for comparative study with the original impact plates to investigate the difference of detection efficiency due to the different thickness and inclination respectively. In particular, the increase of sensitivity by inclining a plate is confirmed in the past study by Auel & Boes 2011b. We chose the inclination angle of 10 degree according to the study where the value showed the highest detection rate.

Figure 6. Outlet of the Koshibu dam SBT

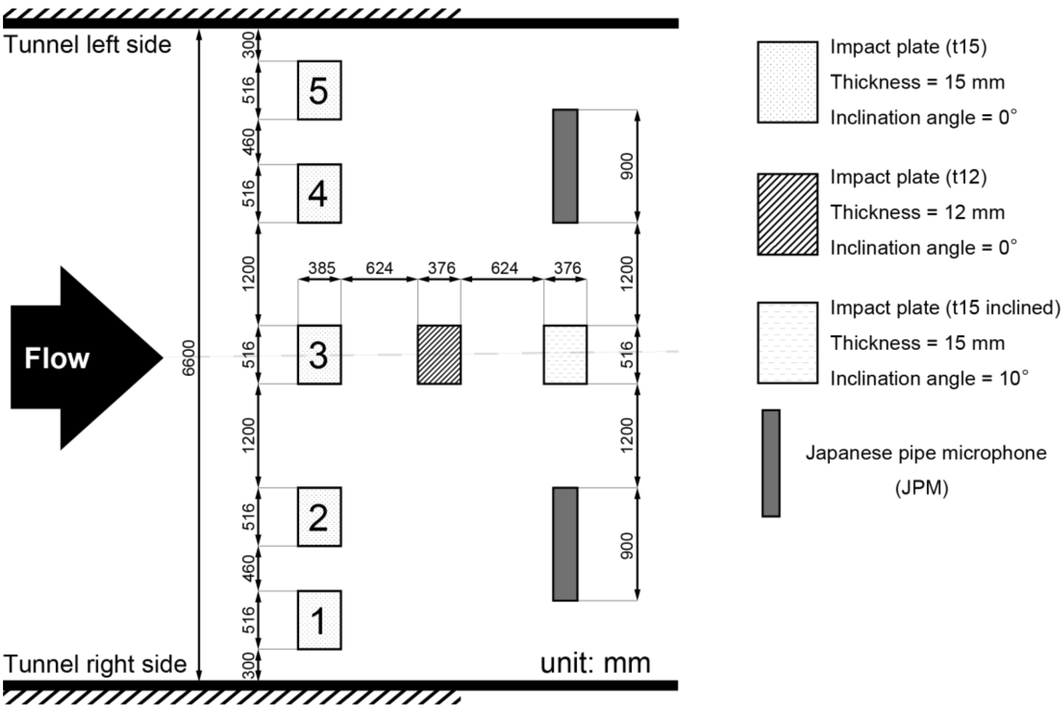

Figure 7. Plan view of bedload measurement apparatuses on the Koshibu dam SBT

To compare the experimental results with existing studies on the JPM and SPG, JPM and the geophone sensor (Geospace GS-20DX, manufactured by Geospace Technologies, Houston, Texas) are also employed for the observation. As in Figure 7, two JPMs are installed both left and right sides and the geophone sensors were mounted underneath the plate 3, 6, and 7 in addition to the microphone and the acceleration sensor. Moreover, five pipe pits are also built at the outlet vertically to collect bypassed water with the five kinds of height fractions to measure vertical turbidity distribution because the impact plates are not good at gaining the vertical sediment profiles.

3.3 Experimental setup

For calibrating the impact plates, a series of field experiments were conducted at Koshibu SBT by artificially flush sediment over the impact plates. The experiments were performed in three sunny days sequentially from 22nd of August in 2016 to 24th. As in Table 1, 10 cases of experimental conditions were selected varying the grain sizes (D_s = 5, 10, 50 mm), sediment volumes (V_s = 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 selected so that all D_s are included with V_s = 3 m^3 for each. The grain sizes are determined based on the Koshibu SBT's design that only sediment of D_s smaller than 100 mm is bypassed by collecting larger sediment particles at a divert equipment nearby the inlet. Although the Q is much smaller than the SBT capacity of 370 m^3/s, it was decided in order to lessen the negative impact of sediment flushing to the downstream reaches as much as possible. The test sediment was derived 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. Indeed, the sediment transport observation of Solis SBT in Switzerland with using the SPGs showed that the tunnel's horizontal curve can cause the sediment concentration on the inner side of the tunnel bend in the cross sectional direction, and the consequential uneven abrasion distribution is also confirmed in Asahi SBT in Japan (Albayrak et al. 2015, Nakajima et al. 2015). After confirming all persons go out of the tunnel, the designated amount of water was drawn by opening the inlet gate 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 and in order not to allow sediment in the pool pass into the tunnel during the experiment, previous gate open operation was conducted for flushing the deposited sediment adequately. All impact plates and JPMs continuously registered the variables throughout the each experimental flushing except for the raw waveform data. Since the raw waveform data volume is extremely high and difficult to be measured continuously with the desirable sampling frequency of 50 kHz, raw waveforms were recorded from just before the incipient of the sediment flow reaches the outlet to the time when all sediment is passed the outlet completely, with five seconds of recording and ten seconds of interval to save the data. Several cameras were also installed at tunnel inside where sediment is placed and the outlet of the tunnel, the flow depth at the outlet was estimated based on the video recorded data of the outlet camera. After every experimental runs, several persons entered into the tunnel and visually observed the condition of the hydroabrasion on the invert.

Table 1. Experimental conditions

Case	Date	D_s [mm]	V_s [m^3]	Q [m^3/s]	V_w [m/s]	T_{flush} [min]	T_{open}	T_{reach}	$T_{reach} - T_{open}$ [min]
1	22/8	10	1	10	2.60	20	10:11:00	10:11:51	11.9
2	22/8	10	3	5	1.98	20	12:30:00	12:45:15	14.3
3	22/8	50	3	5	1.85	20	14:10:00	14:24:50	14.9
4	22/8	5	3	5	1.67	20	16:00:00	16:15:00	15.0
5	23/8	10	5	5	2.03	20	09:10:00	09:25:25	15.4
6	23/8	10	9	5	1.87	20	11:00:00	11:15:15	15.3
7	23/8	10	9	20	3.66	20	13:30:00	13:40:01	10.0
8	23/8	5/10/50	3/3/3	5	1.89	20	15:50:00	16:05:30	15.5
9	24/8	50	9	20	3.34	20	09:00:00	09:10:00	9.2
10	24/8	5/10/50	3/3/3	20	3.98	20	11:00:00	11:10:25	10.4

4. EXPERIMENTAL RESULTS

All experiments were successfully conducted within the planned date and, as shown in Table 1, T_{flush} is the duration between the time when the SBT gate was opened (T_{open}) and the time when the gate was closed being fixed 20 minutes. T_{reach} is the time when the incipient of the water flow reaches to the outlet where the impact plates are installed and thus $T_{reach} – T_{open}$ the time needed for the flow to arrive the outlet from the inlet. $T_{reach} – T_{open}$ has good negative linear correlation with the Q ($R^2 = 0.95$) concurrently with the positive correlation with the average flow velocity V_w calculated by flow measured mean flow depth and Q ($R^2 = 0.96$). However, the water flow in all runs exhibit significant roll-waves thus the water depth undulates in the range of 14 mm to 920 mm. Hence, although the average water velocity V_w calculated from the average water depth is shown in the table, it should be minded that the V_w is also likely to vary with a large range during each run.

Figure 8 shows the one result of the calibration at Case 8 where mixed grain size with V_s = 9 m^3 was flashed with Q = 5 m^3/s of water discharge. The results include S_p (bar chart), I_p with amplification factor of 1024, 256, 64, 16, 4 times, and abscissa notes the time from the impact plates started observation when clear water already reached the outlet. Apparently, it shows the sediment reaches the outlet at T = 0.75 and passed completely around T = 4.5. Throughout the observation, I_p increases as the amplification factor increases in the nature of the I_p's definition. Considering that only clean water flow at T = 5 where all variables detect no signals, the noise of water flow does not affect the accurate measuring of S_p and I_p. The result especially S_p shows the sediment flow is not constant and including some fluctuation. Broadly speaking, the result can be separated into two parts at around T = 3. In the first half, relatively high amount of S_p are recorded. When it comes to I_p, almost same values are recorded for I_p at Amp = 1024 and 256, but the I_p at Amp = 64, 16 gradually decreases in the second half especially I_p at Amp = 4 is almost zero. Since the difference of the impact amplitude affect the profile of I_p in respect of amplification factor, this implicates the difference of grain size distribution casing the difference of particle impact amplitude (Koshiba et al. 2016a). For further investigation, raw waveform data is shown in Figure 9 where left five data are collected by the microphone and others are by the acceleration sensor. In the figure five points in the Figure 8 were selected namely T = 1, 2, 3, 4, and 5 for clarifying the time series variation. Obviously, the wave amplitude increases over time for both sensors, finally at T = 5 no signals are recorded when only water flows. For reference, Figure 10 shows the raw waveform data in Case 3, 5, and 4 thus uniform grain size sediment of D_s = 5, 10,and 50 mm are recorded respectively. According to the Figure 10, the difference of grain sizes are surely arose in the waveform amplitude. By comparing Figure 9 with Figure 10, time series variation of transported particle size can be induced that the large particles reached the outlet first and subsequently rather small particles are arrived. Supposing this process is correct, the difference of I_p between the first and latter half can be reasonably understood. In the first half, only large particles are flushed thus their large amplitudes causes the I_p to be registered for all amplification factors even for Amp = 4 being the lowest sensitivity. On the other hand in the latter half, the D_s of predominant sediment was gradually decrease, accordingly I_ps at low Amp, meaning low sensitivity, also decreases. However, since the much higher number of particles were assumingly flushed in the latte half than the first half part, I_p at higher Amps are relatively high in the latter half (because the amount of the sediment was volume-base, the higher number of particles are flushed in the case of smaller D_s). This finding is meaningful for estimating grain size information, even with only using the number of impulses realizing reduction in data amount.

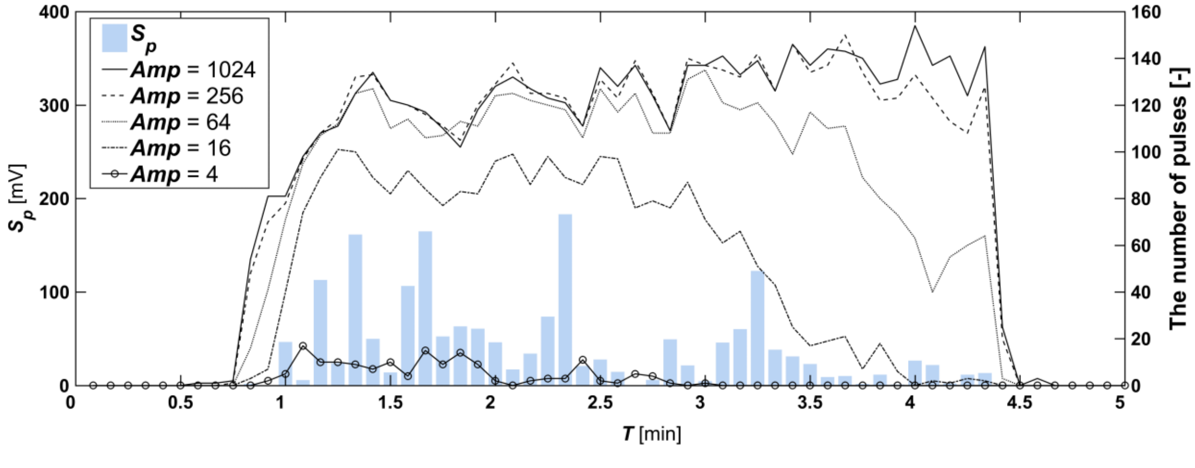

Figure 8. The S_p and I_p (*Amp* = 1024, 256, 64 and 4) registered during the experiment of Case 8

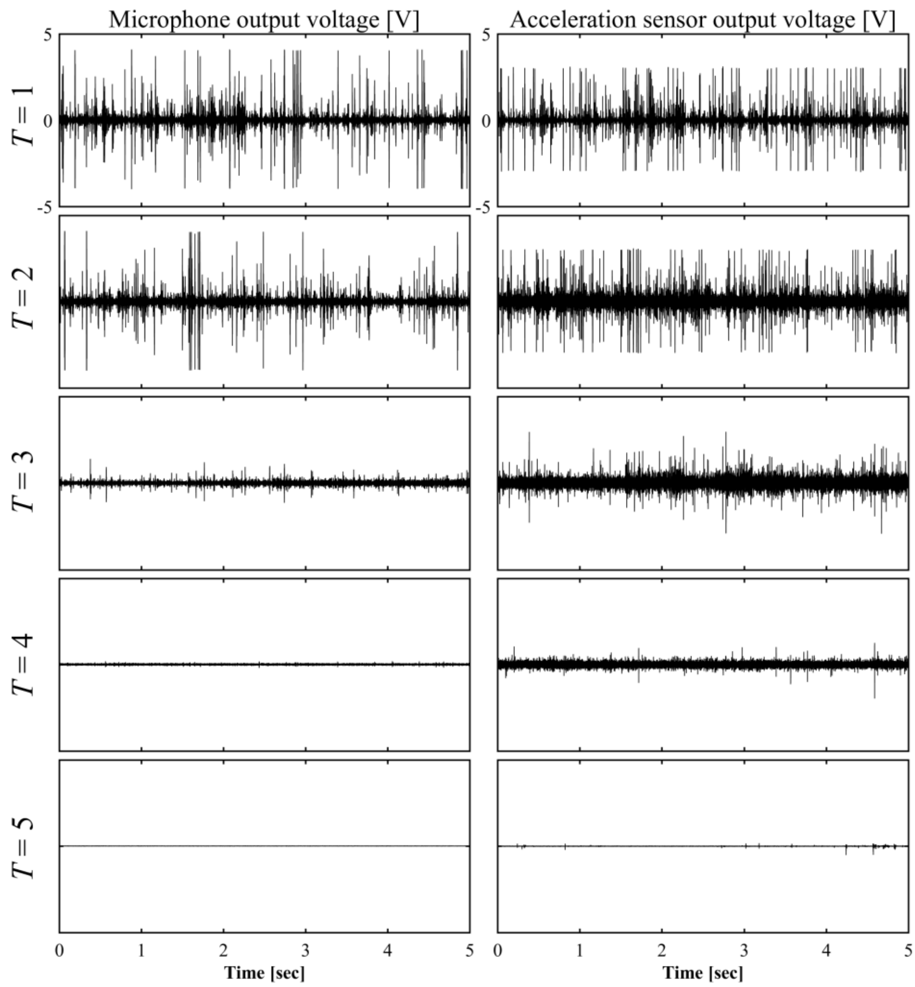

Figure 9. Raw waveform recorded in the experiment of Case 8 by the microphone (left) and the acceleration sensor (right). Each *T* corresponding to the *T* in Figure 8.

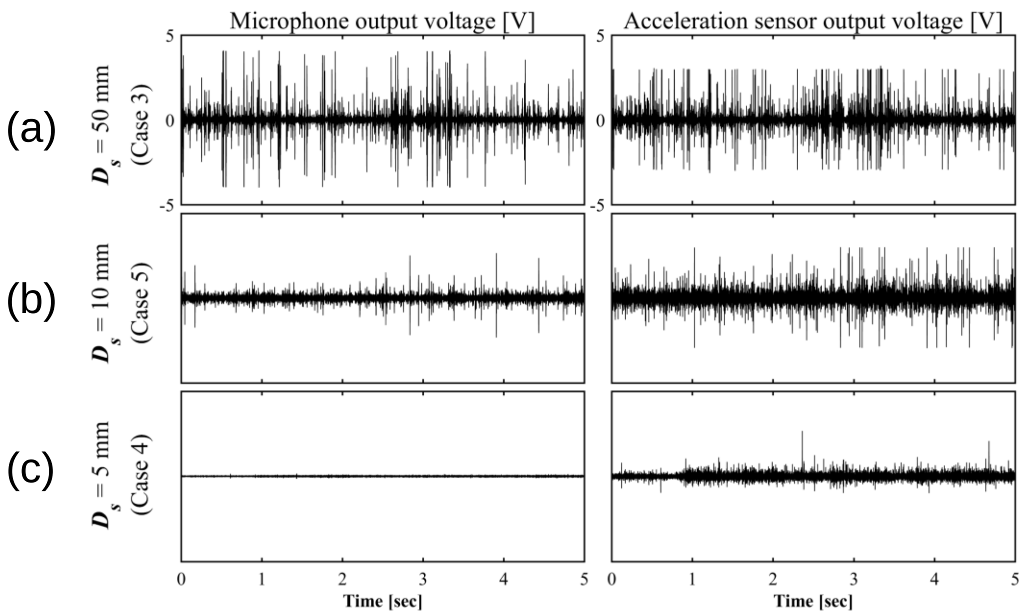

Figure 10. Raw waveform data registered in (a) Case 3 (D_s = 50 mm), (b) Case 5 (D_s = 10 mm), and (c) Case 4 (D_s = 5 mm)

Figure 9 and 10 also show the pros and cons of both sensors in terms of sensitivity. It is serious disadvantage of the acceleration sensor to saturate easily. As in the figures especially in Figure 9 at T = 1 and 2, many waves reach the threshold of the acceleration sensor, meaning not suitable for measuring strong particle impacts. At the same time, the acceleration sensor exhibits the ability to detect small particles at T = 3, 4 and 5 better that the microphone. Therefore it can be said that the acceleration sensor is suitable for measuring small particle and a microphone is for large particles, insisting the coordinated observation with both sensors.

For unveiling the spanwise sediment transport distribution, the summed S_p throughout every runs are depicted in Figure 11 for all plates. As in Figure 7, plate 1 is located at the most inner side of the tunnel curve. Not so obvious sediment deviation to both ends are indicated and it is likely that the plate 3 in the middle show the highest value of summed S_p and thus the peak of the sediment concentration was located at the center in the spanwise direction. However, when focus on all runs except for Case 6 and 8, it can found that the summed S_p slightly deviates to the direction of Plate 1. Therefore sediment presumably concentrate on the Plate 1 side corresponding to the tunnel inner side. This result is in line with the past observation at Solis SBT and the abrasion distribution in Asahi SBT, where the generation of a secondary flow by tunnel curve which transports bedload at the inner side was concluded as the rationale of the phenomenon (Albayrak et al. 2015, Nakajima et al. 2015). The reason why the deviation degree was such slight comparing to other SBTs are that, in this experiments, the flow depth was much lower than the tunnel height (7.2 m) being not enough high for the secondary flow to be formed. Indeed, it is also confirmed that the difference of the number of measured impulses between Plate 1 and Plate 5 increases as Q increases.

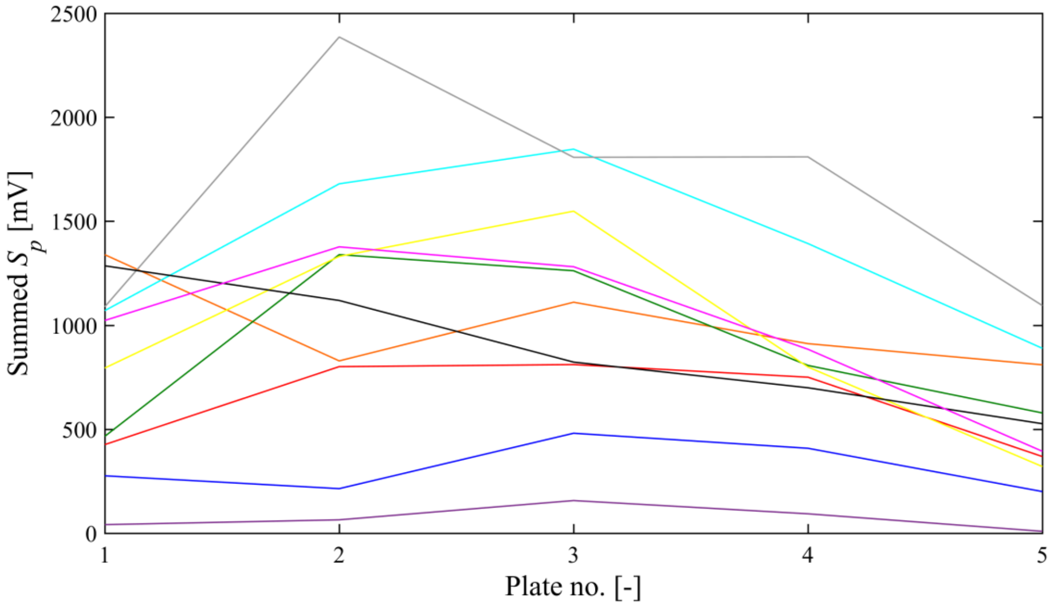

Figure 11. Summed S_p in all Cases for Plate 1 - 5

Because of the limited pages, it's not possible to show all results in this paper but many important outcomes and problems to be solved were gained through the experiment. For example, not so significant difference of the sensitivity was found between normal impact plates and thinner nor inclined impact plates. Even though the effect of D_s difference clearly appeared in the all result, the difference of result by varying Q and V_s were not seen. This might be a topical issue on estimating the amount of abrasion because not only grain size but also the amount of transported sediment is indispensable for the abrasion prediction model application.

5. CONCLUSION

Accurate sediment monitoring in SBTs are necessary for coming up with appropriate maintenance approach and the quantification of bypassing efficiency for promoting SBTs all over the world. The full scale experiment conducted in this study showed that the impact plate is one workable method to indirectly observe bedload transport in SBTs forming intensive flow conditions. We've just revealed the number of pulses might be a useful parameter to estimate transported particle size which is needed to calculate the amount of invert abrasion, still amount of the sediment must be also estimated. For that, more analysis on the raw waveform data is promising especially using signal processing to untangle the bulky raw waveform data into distinct data of each particle impacts. Furthermore, studies incorporating turbidity and suspended load monitoring with the impact plate monitoring are also expectable for gaining vertical profile of sediment flow through Koshibu SBT operations in the future.

In 21st and 23rd of September in 2016, the first Koshibu SBT operation was successfully conducted. Although the JPMs were completely broken and already removed due to the much more intensive sediment flow than this experimental flow, impacts plates registered the sediment impacts clearly. Further studies of both experimental and actual observation are continued for the sound bedload monitoring toward the next typhoon season.

6. ACKNOWLEDGEMENTS

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