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DEVELOPMENT OF A BEDLOAD TRANSPORT MEASURING SYSTEM FOR SEDIMENT BYPASS TUNNELS IN JAPAN

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ABSTRACT

Sediment Bypass Tunnels are operated to divert sediment around reservoirs reducing reservoir sedimentation. A major drawback of these tunnels is severe invert abrasion due to high velocity and sediment flows. There is an urgent need to establish innovative measurement systems of sediment transport rates in SBTs. In this paper, three bedload measuring systems, namely hydrophones, geophones, and newly developed plate microphones are introduced and compared. The Koshibu SBT is planned to operate from 2016. Plate microphones combined with geophones and other planned systems are installed in the tunnel. Results of preliminary tests and installation plans of bedload measurement are presented.

1. INTRODUCTION

There are around three thousands dams in Japan for different purposes. Some of these reservoirs are facing severe sedimentation problems and urgent sedimentation management is required. Sedimentation in reservoir causes several problems, namely: (1) Blockage of bottom outlet and intake structures; (2) Losing water storage volume; and (3) Increasing flood risks by aggradation of upstream river bed; (4) Increasing suspended sediment concentration. Moreover, sedimentation also affects the downstream reaches as the lack of sediment downstream leads to river incision, deterioration of the river ecosystem and coastal erosion. Strategies to counteract sedimentation in reservoirs are typically sediment yield reduction, sediment routing, sediment transfer and sediment removal (Morris & Fan 1998, Kondolf et al. 2014). One advanced routing technique is the sediment bypass tunnel (SBT) to reduce suspended and bed load deposition in reservoirs (Sumi et al. 2004, Auel and Boes 2011). A SBT mitigates sedimentation by routing the incoming sediments around the dam into the downstream river directly during flood events. Japan and Switzerland are the leading countries in SBT construction and have the oldest tunnels in operation. However, more SBT exist worldwide, and recently a number of tunnels are planned in Taiwan (Table 1). In the figure, data about section shape includes the section width b_t and height h_t or tunnel diameter D_t. The tunnel length L, tunnel slope S, the reservoir volume V and the catchment are A are also shown respectively. It is confirmed that a SBT works successfully to divert sediments to the downstream reach (Auel et al. 2016). However, measuring and quantifying the sediment transport rate is still one of challenging research subjects (Hagmann et al. 2015). Especially invert abrasion is a severe problem occurring in most SBTs which is directly connected to increasing maintenance cost (Auel and Boes 2011). Figure 1 shows the present abrasion situation of Asahi dam SBT in Nara prefecture, Japan where the abrasion situation is severe (Nakajima et al. 2015). The tunnel invert is abraded largely, and rock and steel reinforcements are exposed.

In order to improve the invert resistance, it is essential to clarify the hydraulic characteristics and sediment transport mechanisms in SBTs. The invert abrasion is caused by a combination of high flow velocities and a high sediment transport rates (Auel and Boes 2011, Auel 2014). The sediment which is routed downstream of the dam during floods is also important regarding river environmental aspects. Various techniques have been developed to monitor suspended sediment, for example by using a turbidity meter or sample bottles. However, there are limited techniques for field observation of bedload sediment transport to understand the mechanisms and to quantify transport rates.

Table 1. List of SBT in Japan and Switzerland (Sumi et al. 2004, Auel & Boes 2011)

Reservoir name	Country	Commissioning year	Section shape	b_t	h_t or D_t	L	S	Run Time	V	A
				[m]	[m]	[m]	[-]	[days/a]	[m^3]	[km2]
Pfaffensprung	Swiss	1922	Horseshoe	4.70	5.23	282	0.03	~200	0.15	390
Runcahez	Swiss	1962	Archway	3.80	4.27	572	0.014	4	0.48	50
Ual da Mulin	Swiss	1963	Circular*	2.50	3.70	268	0.043	~100	0.06	25
Egschi	Swiss	1976	Circular*	1.20	2.80	360	0.026	10	0.4	108
Palagnedra	Swiss	1978	Circular*	3.70	6.20	1760	0.02	2-5	4.26	140
Rempen	Swiss	1986	Circular*	3.45	3.42	450	0.04	1-5	0.5	25
Solis	Swiss	2012	Archway	4.40	4.68	968	0.019	1-5	4.1	900
Nunobiki	Japan	1908	Archway	2.90	2.90	258	0.013		0.76	10
Asahi	Japan	1998	Archway	3.80	3.80	2384	0.029	~100	15.47	39
Miwa	Japan	2004	Horseshoe	7.80	7.00	4300	0.01		29.95	311

Circular: Circular shape with plain invert*

SBTs in the process of construction: Koshibu (Japan), Matsukawa (Japan), Nanhua (Taiwan), Shimen (Taiwan), Zengwen (Taiwan), Rizzanese (France), Nagle (South Africa)

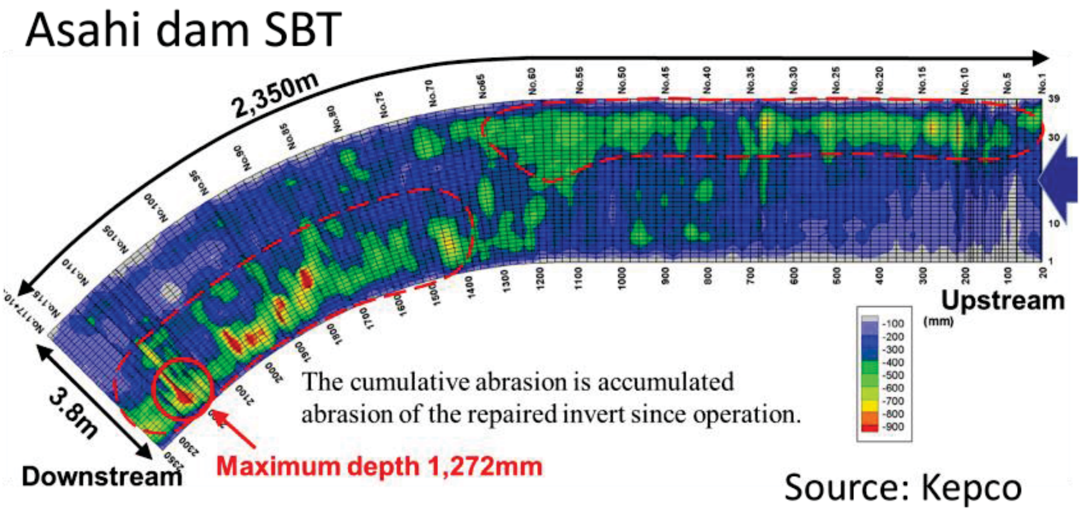

Figure 1. Accumulated abrasion depth (1998 to Nov.2011) at Asahi dam SBT（Nakajima 2015）

2. BEDLOAD MEASURING SYSTEMS

Measuring the bedload transport rate is important to support managing appropriate SBT maintenance works and evaluate the efficiency of the tunnel. Moreover, it is known that the volume of sediment yield in mountainous area does not only depend on flow discharge of the river but also on the scale of sediment supply origin and the seasonal variation. Therefore, it is essential to monitor the amount of sediment yield from mountains for comprehensive sediment management in the basin and mitigation of sediment or river related disasters.

2.1 Existing Measuring Methods

In a study at the Hodaka Sedimentation Observatory, DPRI, Kyoto University, bedload transport rates were measured by pipe hydrophones (Tsutsumi et al. 2014). As shown in Figure 2a, a hydrophone consists of a steel pipe and a microphone installed in it. The sediment transport rate is detected by the number of pulses and resulting sound pressure levels caused by gravel hits. Another technique developed in Switzerland is the geophone (Figure 2b) containing of a 36 by 50 cm steel plate and a vibration sensor below (Rickenmann et al. 2012). A geophone system was installed the first time in an SBT at the Solis dam which started to operate from 2012 on (Hagmann et al. 2015). Principles of both indirect monitoring techniques, the pipe hydrophone and the plate geophone, are similar but they have particular weak points. Their cons and pros are shown in Table 2. The most remarkable difference is that the hydrophone often underestimates bedload when the pulses are successive and overlap because the hydrophone pipe wide in the streamwise direction compared to 36 cm for the geophone plate. Furthermore, the hydrophone may easily deform when hit by large stones. In contrary, a geophone is shock-resistant but the minimum detectable grain size is 10mm to 40mm (Rickenmann et al. 2012). Figure 3 shows the temporal changes of hydrophone impulses (1 min averaged) observed at Erlenbach watershed during a rainfall event on July 29, 2013. In the figure, (A) is Hydrophone's result, and (B) is Geophone's one (Tsutsumi et al. 2014). It is evident that reactions of both systems are similar and worked well. A major difference is the number of pulses detected. The hydrophone detects about 600 times more than the geophone. This is due to two effects, the hydrophone can detect fine sediments, and the acoustic wave has a larger frequency compared to the vibration wave.

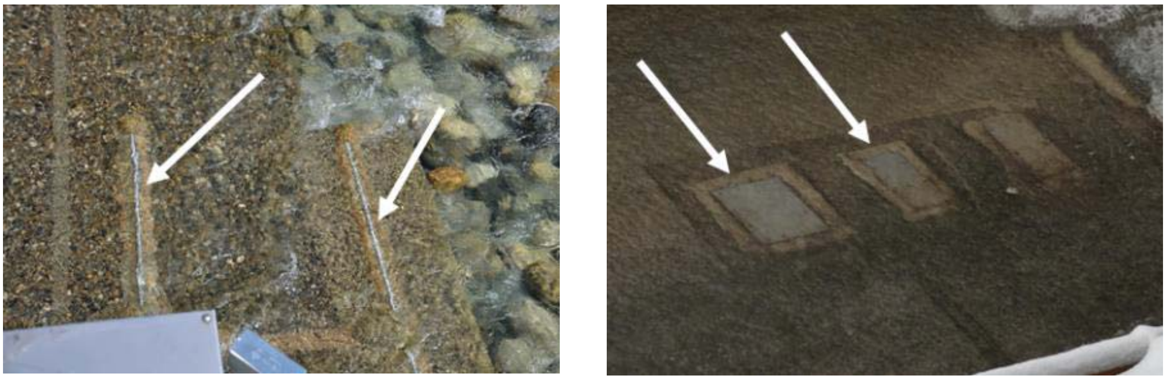

Figure 2. a) Hydrophones installed at Yodagiri River, b) Geophones installed at Ashiarai dani, Hodaka Observatory, DPRI, Kyoto University in Japan

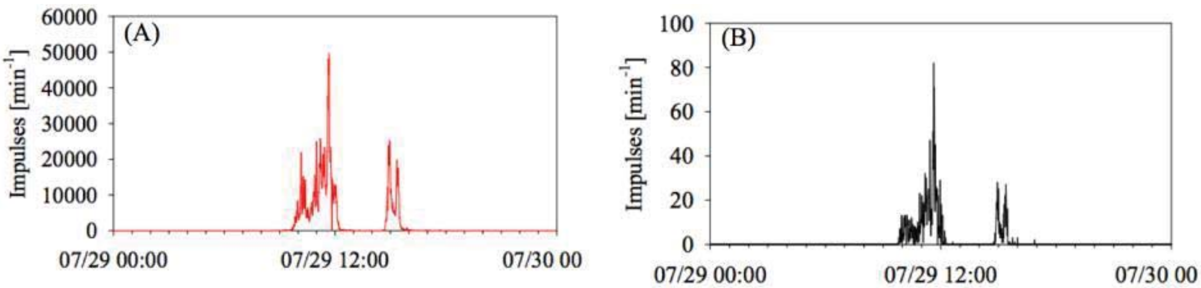

Figure 3. The difference of observed impulses between (A) Hydrophone and (B) Geophone (Tsutsumi et al. 2014)

Table 2. Pros and Cons of Hydrophone and Geophone

	Hydrophone	**Geophone**
Made in	Japan	Switzerland
Shape	Steel Pipe	Steel Plate
Principle	Counting number of pulses based on sound pressure	Measuring voltage of vibration caused by impacting sediment
Merit	● Inexpensive system setup ● the minimum detectable grain size is 10mm to 40mm	● Strong for large stones ● Thicker plate can deal with larger stones up to decimetres
Demerit	● Deforms easily when large stones hit ● Overestimate bedload rate during high sound or large amount of sediment	● Initial installation cost is high ● Minimum detectable grain size is 10mm to 40mm

2.2 Plate microphone and vibration sensor

A plate-microphone was developed in Japan as a method to measure the bedload transport rate to overcome disadvantages of the pipe-hydrophone as shown in Table 2. The plate-microphone system consists of a steel plate like the geophone and measures bedload transport rates based on sound pressure like the pipe-hydrophone. With these characteristics, the plate microphone is expected to record hitting sounds of fine sediment and also to be robust against hitting by coarse sediment. Additionally, a plate microphone contains a vibration sensor which has a different resonance frequency from a geophone in order to conduct more accurate observation using vibration data. Figure 4 and 5 show an inside view of the geophone and plate microphone, and a schematic view of a plate microphone, respectively.

The calibration experiments of these two devices were carried out in a laboratory flume at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland (Figure 6) (Koshiba et al. 2016). The flume was 7.56 m long, 0.5 m wide, and the intake was equipped with a jet-box to allow for precise flow depth adjustment. The devices were installed at the end of the flume. The flow depth of 80 mm and five grain size fractions were used: Mean diameter D = 2 mm, 5 mm, 10 mm, 50 mm, and 100 mm. Two flow velocities were tested: U = 2.7 m/s and 4.5 m/s. Although these values are below the ones of about 10 m/s in a prototype SBT (Auel & Boes 2011), they are higher than typical values in rivers and considered to be high enough to gain insight into the high-speed flow behaviour in a SBT. The impacts of hitting grains were recorded in a logger based on sound measurements at the plate microphone and vibration measurements at the plate sensor.

Figure 4. The inside of geophone (left) and plate microphone and vibration sensor (right)

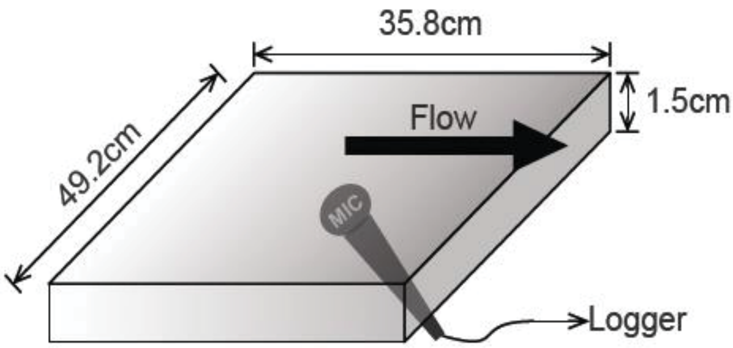

Figure 5. Schematic view of plate microphone and vibration sensor

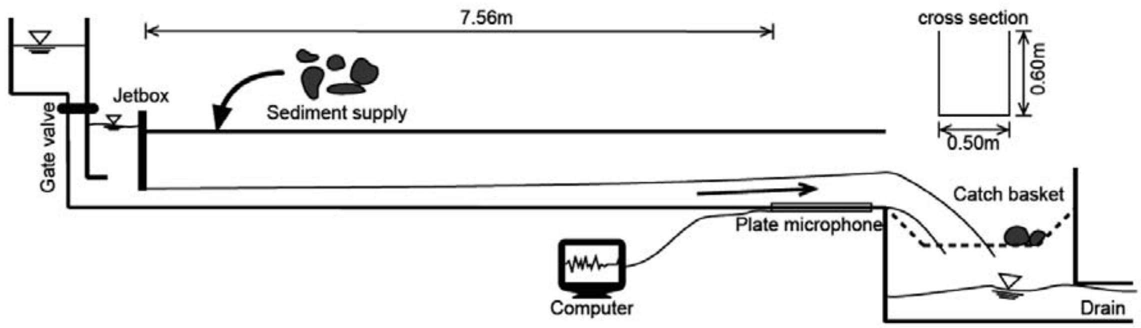

Figure 6. Sketch of a model flume at ETH Zurich

It was found that both devices can detect fine sediments of 2 mm and 5 mm grain size. Especially, it is found that the plate vibration sensor can detect the fine grain sizes. Figure 7 shows the wave form of grain hitting which explains the energy where x-axis and y-axis are time and voltage, respectively. The upper graph is plate microphone and bottom one is the plate vibration sensor. Left (a) and right (b) are cases of grain size of 100mm and 2mm, respectively. Both water velocity was fixed to 4.5m/s. Figure 7(b) shows that only vibration sensor detects hitting of 2mm grain clearly, and the time width of a vibration sensor wave which caused by one grain's hitting is shorter. It insists that waves by vibration sensor is hardly to interference with other waves. The experiments also clarify that almost all of these results are, however, underestimated or overestimated from the actual particle numbers. It leads the underestimation or overestimation of bedload transport rate, therefore it is essential to quantify an equation which convert the measured bedload transport rate into correct one by using flow and sediment conditions like jump length, sediment density, flow velocity and so on. Some relationships were already found by the experiment, but it is require to carry out more flume experiments to clarify the relationship. Moreover, it is also required to conduct in-situ measurement using real scale sediment volume and grain sizes, because the flume experiments are conducted with a little amount of bedload sediment load comparing with the actual condition in SBT. Regarding the problem, a calibration experiment with using real SBT will be started in concurrence with the commencement of the Koshibu dam SBT operation in 2016. Likewise, the geophone has been already installed in the Solis dam SBT in Switzerland and started operation. In the next section, details of these observations and results in the Solis SBT and expected results in the Koshibu SBT are introduced.

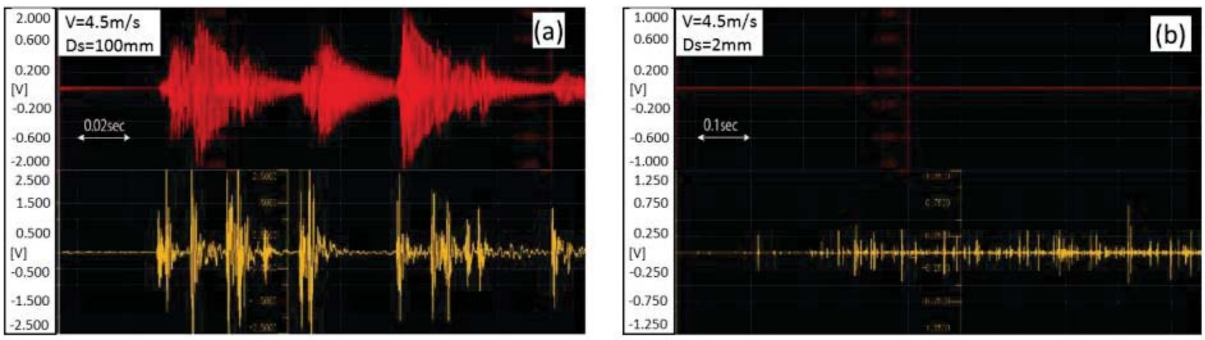

Figure 7. Wave forms (a) 100mm, (b) 2mm, top red is acoustic wave, and bottom yellow is vibration one

3. ON SITE APPLICATION OF BEDLOAD MEASURING SYSTEMS

3.1 Solis SBT

The Solis dam is located in Switzerland and impounds the Albula river in the canton of Grisons in the eastern part of the Swiss Alps. It is operated by the electric power company of Zurich (EWZ). The dam was built in 1986 and is 68 m high with a width of 75 m. The initial capacity of the reservoir was about 4.1 million m^3, and the annual inflow is about 800 million m^3 (Auel et al. 2011). This value is a large compared to the reservoir volume because the catchment area of the reservoir is approximately 900 km^2. Due to the large inflow, the reservoir suffered from 80,000 m^3 of sedimentation annually on average. Sedimentation in the reservoir reached to the minimum operation level and active storage capacity has started to decrease. The operator decided to build a SBT which started operation in 2012 (Figure 8). The length is 968 m, the cross section shape is archway with 4.40 m width and 4.68 m height. In order to measure the sediment flow, eight geophones have been installed at the tunnel outlet in a cross-sectional way (Figure 9). The geophones help to know temporal and transversal distribution of sediment transport, and to improve the tunnel operation and quantify the abrasion in the tunnel. Furthermore, the geophones are part of an in-situ monitoring system including turbidity meters and geophones upstream of the reservoir in order to quantify the total sediment budget. As the result of observation by geophones, uneven bedload transport rate in the cross sectional direction was found. This result is considerable to explain a secondary flow currents due to a curving portion of the tunnel located 100m upstream of the outlet (Hagmann et al. 2015).

Figure 8. Outlet of the Solis SBT (courtesy of C Auel).

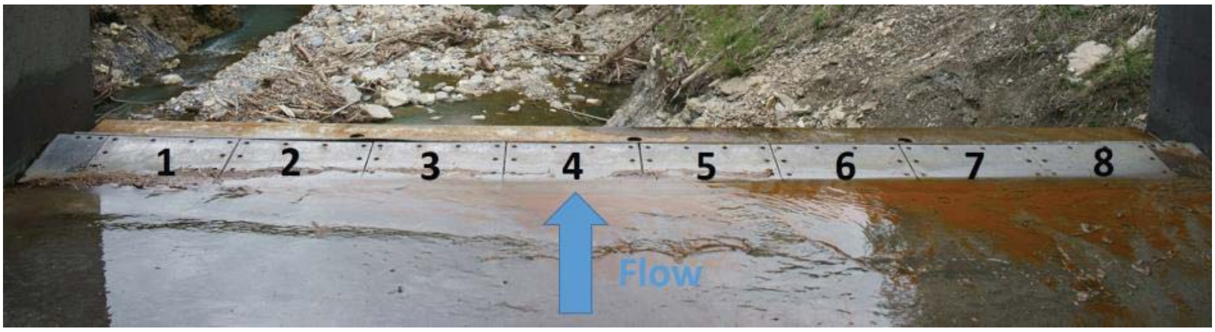

Figure 9. Installation of geophones at the tunnel outlet

3.2 Koshibu SBT

The Koshibu dam is located in the Koshibu river basin in Nagano prefecture, Japan, and is operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (Figure 10). The dam was built in 1969, and is 105 m high with a width of 293.3 m. This reservoir suffered several severe floods with high sediment inflows causing rapid sedimentation progress. In 2015, the sedimentation volume exceeds 15.6 10^6 m^3 almost reaching to 20.0 10^6 m^3 of original designed sedimentation capacity. Tunnel construction works have been almost completed and operation will start from spring 2016. The length of SBT is 3,982 with a cross section of circular shape and a plain invert. The width and height are 5.5 m and 7.9 m, respectively.

Similar to the Solis SBT, bedload transport rate measurements are planned in the Koshibu SBT. Figure 11 shows the SBT outlet where the measurement devices will be installed. Figure 12 shows the arrangement of measurement devices at the outlet where the line AB is corresponded to the line AB in Figure 11. Seven plate devices where both microphones and vibration sensors are mounted below, as well as two pipe hydrophones will be installed. The plate thickness is 15 mm (t15) for all plates despite one, where it is reduced to 12 mm (t12) in order to validate the detection sensitivity. The pipe hydrophones are attached in order to directly compare the difference of detection sensitivity and physical resistance to the plate hydrophones. Five t15 plates will be installed parallel in the spanwise direction. Additionally, the last t15 plate in the tunnel centre line will be inclined with 10 degree. Two pipe hydrophones will be installed symmetrically perpendicular to the flow. The inclination is introduced in order to verify an increase of detection rate due to the plate inclination toward the flow direction (Auel and Boes 2011).

In order to calibrate the devices, the amount of transported sediment has to be correlated to the number of impacts recorded. Laboratory experiments, however, are limited to confirm high velocity and large volume of sediment with mixed grain sizes. Hence, in-situ calibration experiments are planned in the tunnel before the start of normal operation in 2016. Measured amount of sediment will be put in the inlet of the SBT by trucks and then flushed through the tunnel by short gate opening. The measurement devices will record the impacts by the transported sediment with using both the plate microphone and the plate vibration sensor. With this test setup, precise calibration of the sensors will be possible since the amount of transported sediment is exactly known.

Through these measurements, it is expected that; 1) the cross sectional bedload transport will be asymmetric on the inner side of the curve due to a right curve upstream of the outlet; 2) plate t12 may detect finer sediment than t15; 3) plates with inclination should detect more amount of sediment compared to no inclination (Auel & Boes 2011b).

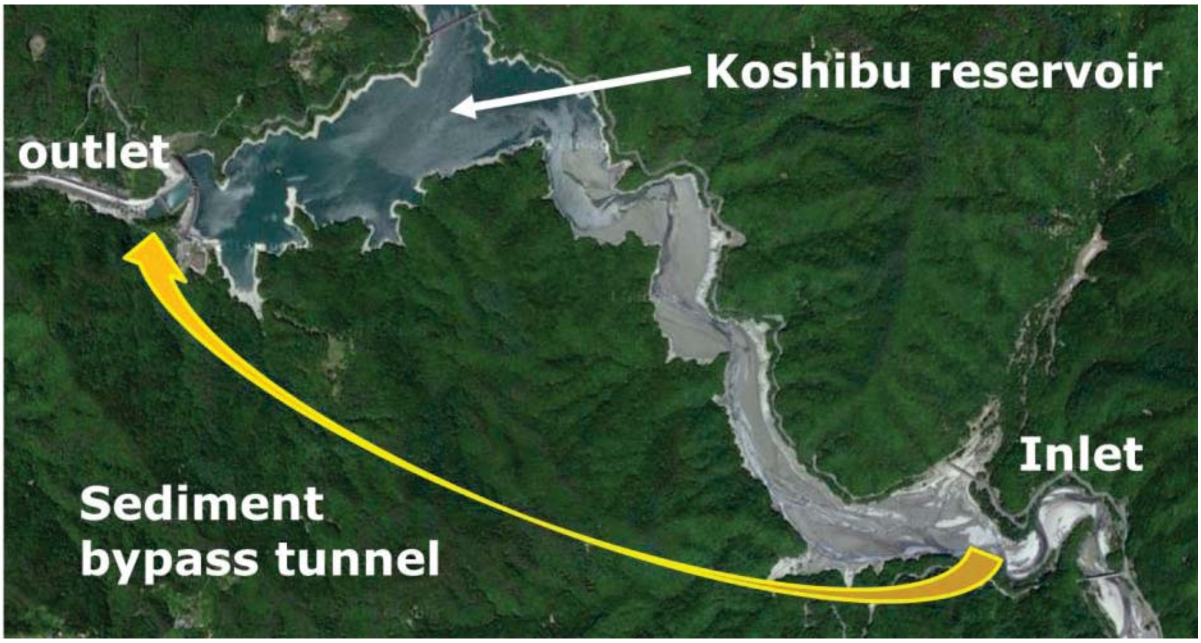

Figure 10. Map of Koshibu reservoir and SBT location

Figure 11. Outlet of the Koshibu dam SBT

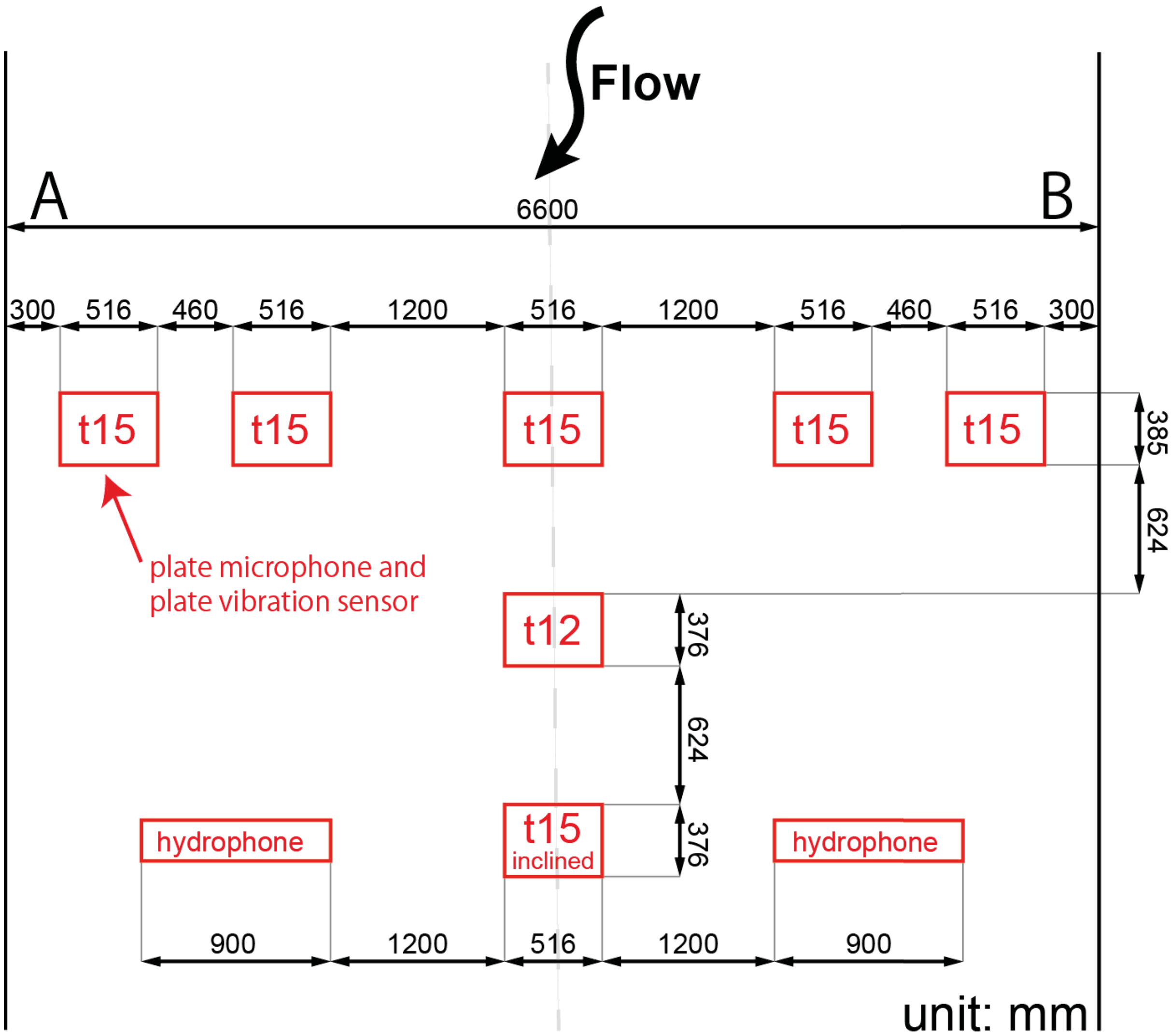

Figure 12. Plan view of hydrophone, plate microphone and vibration sensors installed on the Koshibu dam SBT cross sections

4. CONCLUSION

Around the world, there are a lot of existing dams with reservoir sedimentation problems. The current and the next generation of engineers has to ensure to maintain their important functions. Due to climate change, it is expected that the sedimentation problem will be more severe in the future with higher rates of estimated incoming sediments. Many of aged dams in Japan are suffering from such a problem. In order to maintain their functions and realize a sustainable use of dams, sediment bypass tunnels are an effective method of a sediment routing in Japan, Switzerland and more and more worldwide. Although a SBT is highly effective and ecologically favourable, one of serious problems is the invert abrasion existing at many SBTs.

To estimate and establish countermeasures against the problem, it is essential to clarify the bedload transport rate. Moreover, establishing a suitable method to measure bedload transport is also meaningful from the aspect of comprehensive river basin management. As existing methods, Japanese hydrophones and Swiss geophones are presented herein. Considering that both systems have particular weak points about durability and minimum detectable grain size, the newly developed plate microphone and plate vibration sensor are also introduced here. Even though their measuring accuracy is not exclusively analysed yet, it is shown that the experimental results are promising. Furthermore, both the ongoing bedload transport observation using geophones at the Solis SBT, Switzerland and the newly planned observation at the Koshibu SBT in Japan are introduced. Additional in-situ calibration experiments at Koshibu are to be conducted.

5. ACKNOWLEDGEMENTS

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