May 9-12
Kyoto-Japan
2017

2nd International Workshop on
Sediment Bypass Tunnels

Bedload monitoring in a mountain stream: Method for improving the accuracy of the calibration relationship between acoustic pulses and bedload discharge

Daizo Tsutsumi, Yutaka Higashi, Michinobu Nonaka and Masaharu Fujita

Abstract

Surrogate measurements using Swiss geophone plates and Japanese acoustic pipes/plates are effective for monitoring bedload transport in mountainous streams. They are also becoming important tools for obtaining sediment discharge measurements at the outlets of sediment bypass tunnels, to monitor bedload discharge through such tunnels. They have been installed at the bypass tunnel of the Solis dam in Switzerland and the Koshibu dam in Japan. To obtain the practical amount of bedload discharge from surrogate measurements, determining a calibration relationship between geophone impulses/ acoustic pulses and bedload is necessary. We have installed acoustic pipes and a slot sampler in the Ashiarai-dani supercritical flume, located in the Hodaka mountain range, Japan, and have been conducting bedload monitoring for more than a decade. Recently, we developed a new method of analyzing data obtained with a set of horizontal and vertical acoustic pipes, to overcome the disadvantages of bedload measurements obtained using acoustic pipes only: (1) bedload particles saltating over the pipe remain undetected, and (2) saturation problems of acoustic pulses under high-discharge conditions. A vertical pipe was installed on the wall of the flume and the horizontal pipe was installed on the flume bed. We propose a ratio (R_{hv}) between pulses detected by these sensors, and applied this ratio to calibrate the contemporaneous pulses detected with a pipe located immediately upstream of a bedload slot sampler. Indeed the R_{hv}-corrected pulses correlated well with the bedload discharge obtained with the slot sampler. We conclude that bedload monitoring using concomitant vertical and horizontal pipes can be used to calibrate a centrally located pipe, thereby representing bedload discharges more accurately than those based on a single acoustic pipe: this monitoring method may be useful at sediment bypass tunnels.

Key words: bedload measurement, sediment bypass tunnel, acoustic pipes, vertical pipe, calibration

1 Introduction

The plate geophone sensor was developed in Switzerland as a surrogate measurement technique and is used widely for bedload monitoring in some European countries and the United States (Rickenmann *et al*. 2014). The acoustic sensor, also called the Japanese pipe hydrophone, was developed for bedload measurement in Japan (Baezinger and Burch 1990, Mizuyama *et al*. 1996). It is used widely for bedload monitoring in many rivers in Japan (e.g., Hoshino *et al*. 2004, Nakaya *et al*. 2007). The Japanese pipe hydrophone consists of a steel pipe (generally with a diameter of 50 mm, wall thickness of 2 mm, and length of 0.5–2.0 m) with an acoustic sensor inside the pipe.

Pipe hydrophones are generally installed on a rigid river bed, such as a concrete flume or the spillway of a dam reservoir. Acoustic pulses, generated by collisions of bedload with the pipe, are recorded by a data logger. This surrogate technique does not measure the bedload discharge quantitatively; thus, it is also necessary to monitor the bedload discharge by a direct method, along with the pipe hydrophone, so that a calibration relationship between the acoustic pulses and the bedload discharge can be determined.

We have installed a pipe hydrophone and a Reid-type bedload sampler in the Ashiarai-dani supercritical flume, located in the Hodaka mountain range, Japan. The weight of trapped bedload is measured by load cells installed at the bottom of the bedload sampler, and the bedload discharge obtained from the differential of the weight change is correlated with the outputs from the pipe hydrophone (Tsutsumi *et al*. 2013).

Although pipe hydrophones have been used practically for bedload monitoring in mountain rivers in Japan throughout the past 10 years, some problems remain to be solved. One disadvantage of the pipe hydrophone is pulse saturation, caused by simultaneous collisions of bedload particles; the number of pulses may be underestimated due to the overlapping of acoustic pulses under the high bedload discharge condition. Using a mean acoustic wave level (acoustic energy) instead of a number of pulses has been proposed to solve this problem of pulse saturation (Mizuyama *et al*. 2008). Another disadvantage of bedload monitoring by pipe hydrophone is missing bedload collisions due to the saltation of particles. When monitoring by both pipe hydrophone and a direct bedload sampling method, the correlation between hydrophone pulses and bedload discharge accounts for this reduction in bedload detection due to particle saltation. However, because the correlation, including particle saltation effects, is not universal, instead depending on hydraulic conditions (e.g., water depth and flow velocity) and bedload size distribution, it may be a cause of inconsistent correlation curves between the hydrophone pulses and the bedload discharge obtained for multiple flood events (Tsutsumi *et al*. 2013).

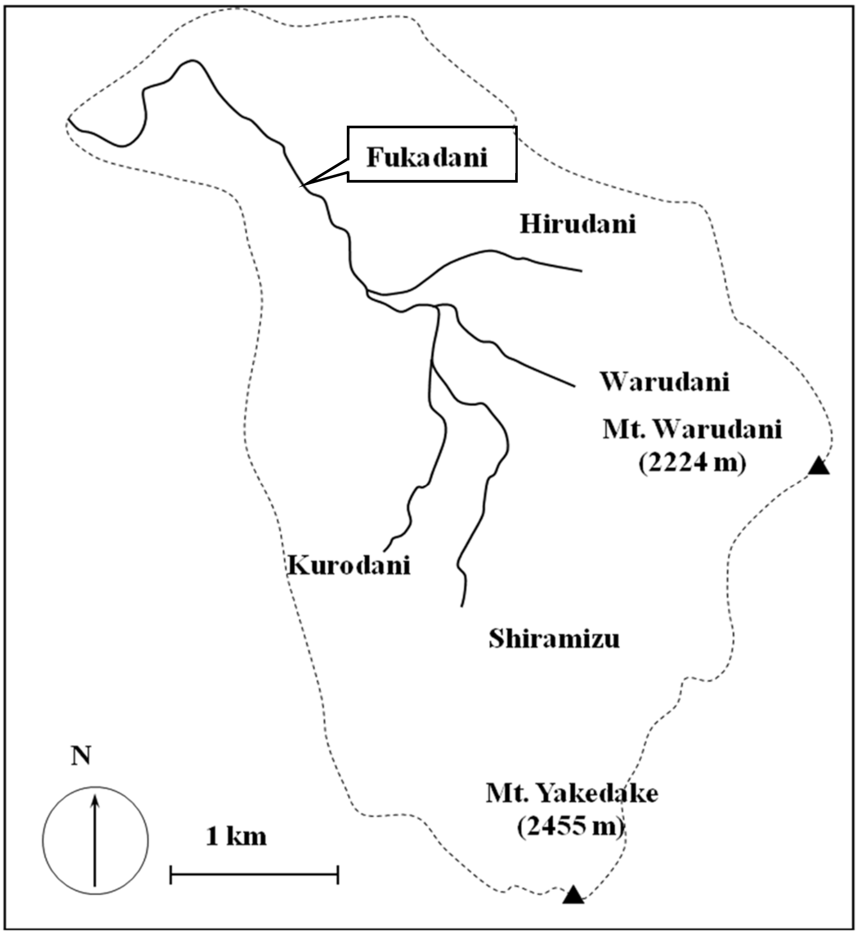


Figure 1: Bedload monitoring site of the Ashi-arai-dani catchment on the northern side of Mt. Yakedake in the Hida Mountain Range, Japan.

In the present research, to address the problems of the bedload monitoring method with a pipe hydrophone, described above, we propose a novel measurement method using a set consisting of a vertical and a horizontal pipe hydrophone. In the new method, we assume that the vertical pipe hydrophone can detect the bedload particles that saltate over the horizontal pipe on the bed, such that all of the bedload particles that pass through the cross section formed by the horizontal and vertical pipes can be detected. This method may enable more accurate measurement of bedload discharge and produce a universal correlation between hydrophone pulses and the bedload discharge obtained with a direct sampler.

2 Observation site and equipment

Bedload monitoring was conducted in the Ashi-arai-dani catchment on the northern side of Mt. Yakedake in the Hida Mountain Range, Japan (Fig. 1). An ordinal Japanese pipe hydrophone (diameter 5 cm, length 35 cm) and a Reid-type slot sampler (slot width of 20 cm) were installed in the center of the supercritical flume (length 11 m, width 5 m) at the Fukadani station in the downstream portion of the Ashi-arai-dani catchment (Fig. 2). The set, consisting of a vertical and a horizontal pipe hydrophone, was installed on the

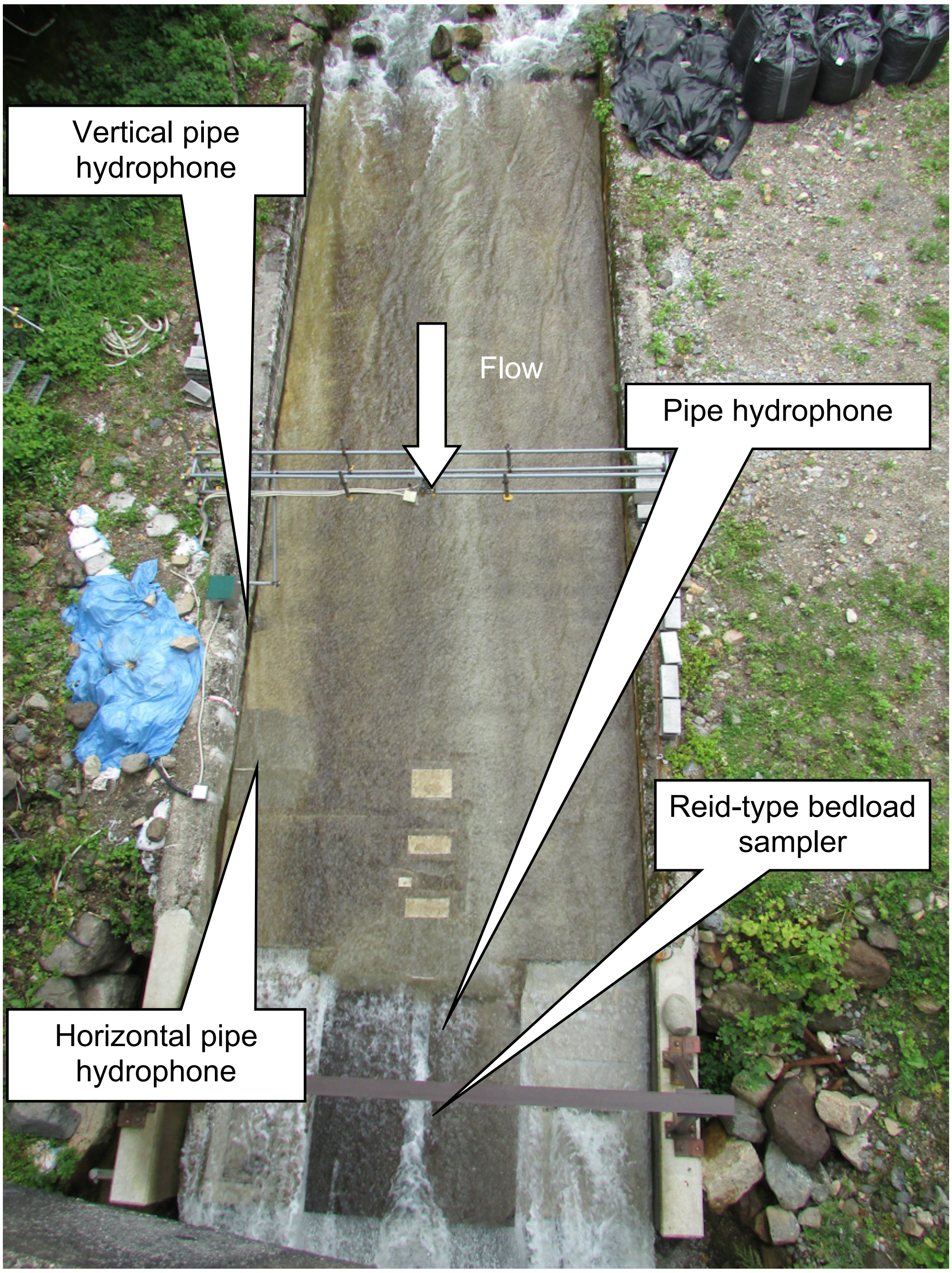


Figure 2: Pipe hydrophone and Reid-type bedload sampler installed at the supercritical flume in the Ashi-arai-dani catchment.

right side of the flume. The vertical pipe (length 60 cm) was installed on the bank wall of the flume, and the horizontal pipe (length 35 cm) was installed on the flume bed 2 m downstream from the vertical pipe (Fig. 2). The pipes are fixed on the wall and the bed, respectively, with concrete, leaving one-third of the pipe circumference exposed to the water flow (Fig. 3).

Figure 3: A set consisting of a vertical and a horizontal pipe hydrophone installed at the right side of the Ashi-arai-dani flume.

3 Method of analysis

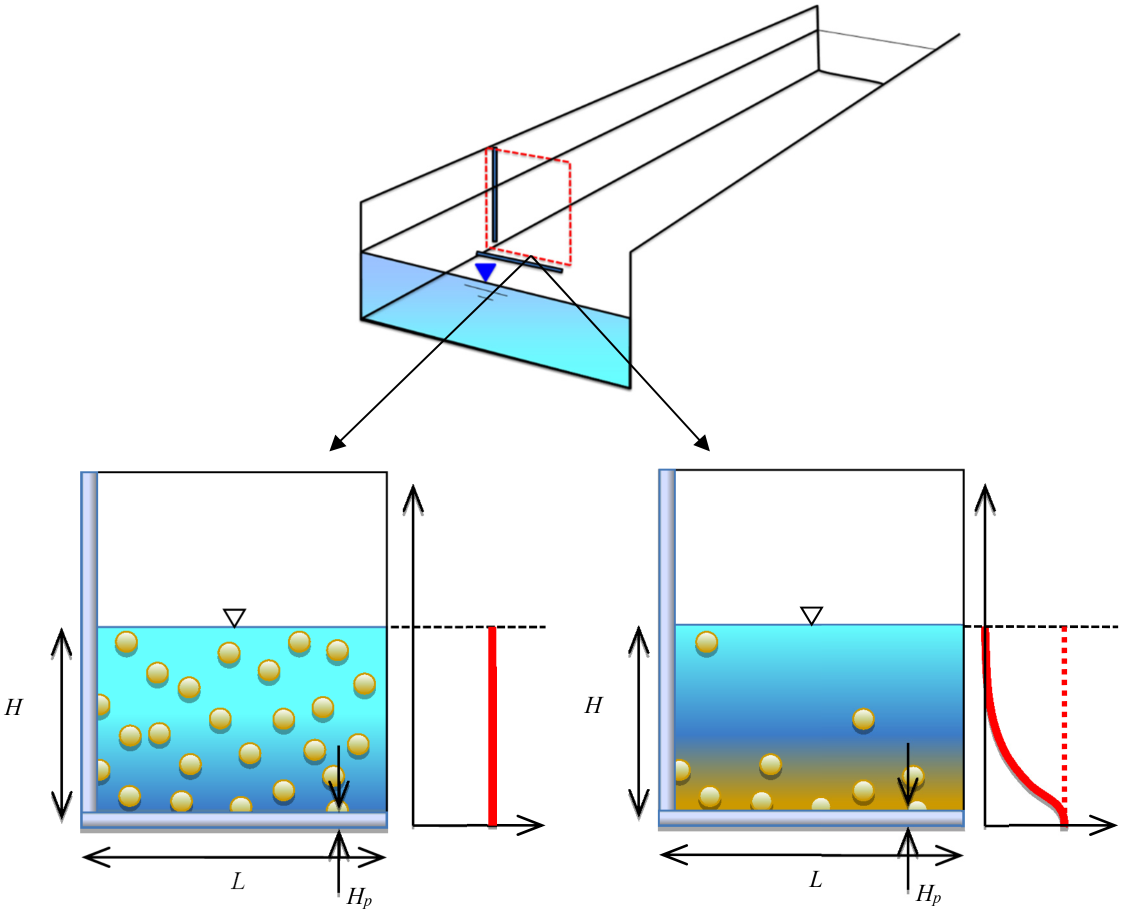
In this section, we propose a new method for bedload analysis that can take into account particles saltated over the horizontal pipe hydrophone. Assuming a homogeneous distribution of bedload particles within a cross section (Fig. 4a), the pulses detected by the horizontal and the vertical pipe hydrophone per unit length are equal:

$$\frac{P_h}{L} = \frac{P_v}{H} \qquad [1]$$

where P_h and P_v are the pulses detected by the horizontal and the vertical hydrophone, respectively, L is the length of the horizontal hydrophone, and H is the water level. However, in reality, the bedload distribution is not homogeneous in vertical profile, and bedload particles are generally concentrated close to the bed (Fig. 4b). Thus, the pulses detected per unit length by the horizontal and the vertical hydrophone show the following relationship:

$$\frac{P_h}{L} > \frac{P_v}{H} \qquad [2]$$

Because it is impossible to detect the locations of particle collisions on the vertical pipe, we cannot determine the vertical profile of the bedload distribution shown in Figure 4b with measurements from the vertical pipe hydrophone. However, we can estimate the reduction of bedload particles within the cross section from the hypothetical homogeneous distribution of bedload using the ratio of pulses per unit length detected by the vertical pipe to that detected by the horizontal pipe:



a) Homogeneus distribution

b) Practical distribution

Figure 4: Observation hypothesis for the set of horizontal and vertical hydrophones.

$$R_{hv} = \frac{P_v}{H} \Big/ \frac{P_h}{L} \qquad [3]$$

where R_{hv} is the ratio of the pulses per unit length detected by the vertical and horizontal pipe hydrophones. Under ideal conditions (no saturation of pulses), the ratio R_{hv} may have a value of $0.0 < R_{hv} < 1.0$, according to Eq. 2. The hypothetical total pulses that may be caused by all bedload particles passing though the cross section L × H under the condition of hypothetical homogeneous distribution (Fig. 4a) is

$$P_t = \frac{H}{H_p} P_h \qquad [4]$$

where Pt is the hypothetical total pulses and Hp is the height of the exposed part of the horizontal pipe, which detects the particle collisions. Thus, the total pulses that may be caused by all bedload particles under the real bedload distribution condition (Fig. 4b) is

$$P_t = R_{hv} \frac{H}{H_p} P_h \qquad [5]$$

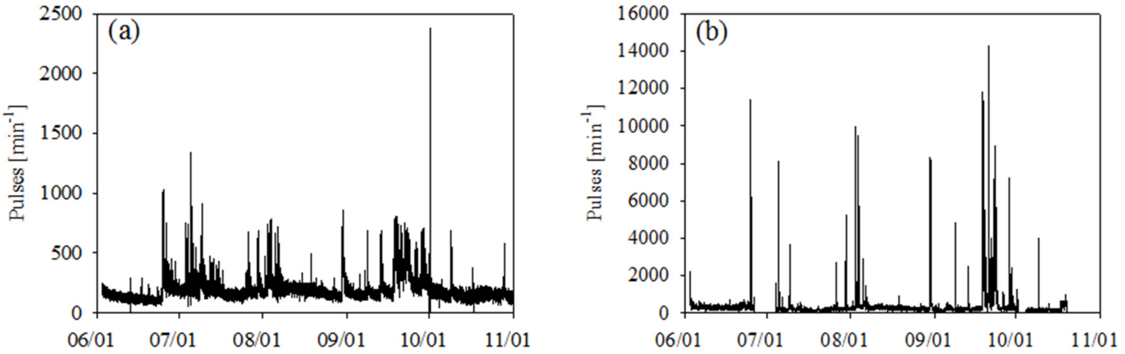


Figure 5: (a) the pulses measured by the acoustic pipe installed at the center of the flume, and (b) the pulses corrected by the Eq. [5] with the ratio R_{hv} obtained from the observation by the horizontal and vertical pipes installed on the right bank of the flume, during the period of June–October, 2016

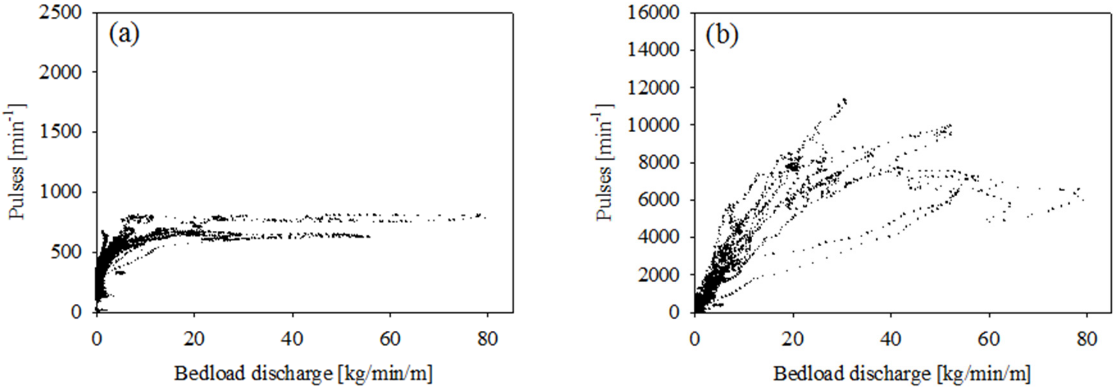


Figure 6: Correlations between bedload discharge measured by the slot sampler and the observed acoustic pulses (a) with and (b) without the correction by the horizontal and vertical pipe observation

In this study, we conducted field monitoring using a set consisting of a vertical and a horizontal hydrophone, calculated the ratio R_{hv} by Eq. 3 or 6, and substituted the ratio into Eq. 5 or 7 to obtain the hypothetical total values (pulses or acoustic energy) that represent the total bedload particles passing through an objective cross section. The value of Ph or Ah, in Eq. 5 or 7, respectively, can be monitored by the ordinal hydrophone installed at the center of the flume (Fig. 2). In such a case, we assume that the bedload particle distribution at the center of the flume is approximately equal to that on the right side of the flume.

4 Results and Discussion

The pulses measured by the acoustic pipe installed at the center of the flume (a), and the pulses corrected by Eq. 5 with the ratio R_{hv} obtained from the observation by the horizontal and vertical pipes installed on the right bank of the flume (b), during the period of May–November, 2016, are shown in Figures 5a and b (the amplification of the acoustic level is 1,024). The temporal change in pulses shows almost the same trend in both figures (Fig. 5a, 5b); however, the number of corrected pulses (Fig. 5b) is much higher (Fig. 5a).

Correlations between the bedload discharge measured by the slot sampler and the observed acoustic pulses, with and without correction by the horizontal and vertical pipe observations, are shown in Figs. 6a and 6b, respectively. In Fig. 6a, an obvious effect of pulse saturation can be seen in the data where bedload discharge is larger than 10 kg/min/m. However, although some data deviated from the majority, a good correlation between bedload discharge and corrected acoustic pulses can be seen in Fig. 6b. When the bedload discharge is lower than 10 kg/min/m (without pulse saturation), the corrected acoustic pulses (Fig. 6b) are about 6–7 times larger than the original pulses (Fig. 6a). This means that 6–7 times as many sediment particles pass over the pipe and are not detected by the pipe hydrophone, and that this underestimate can be corrected with the horizontal and vertical acoustic pipe measurements.

The bedload discharge was calculated with the correlation curve obtained from Fig. 6b, and is shown in Fig. 7 for the period during May–November, 2016. From the figure, the accumulated bedload discharge is ~140,000 kg/m (114 kg/km^2, using a flume width of 5 m and a catchment area of 7 km^2), which is a reasonable value from the view point of annual sediment production or the amount of sedimentation in dam reservoirs in this region.

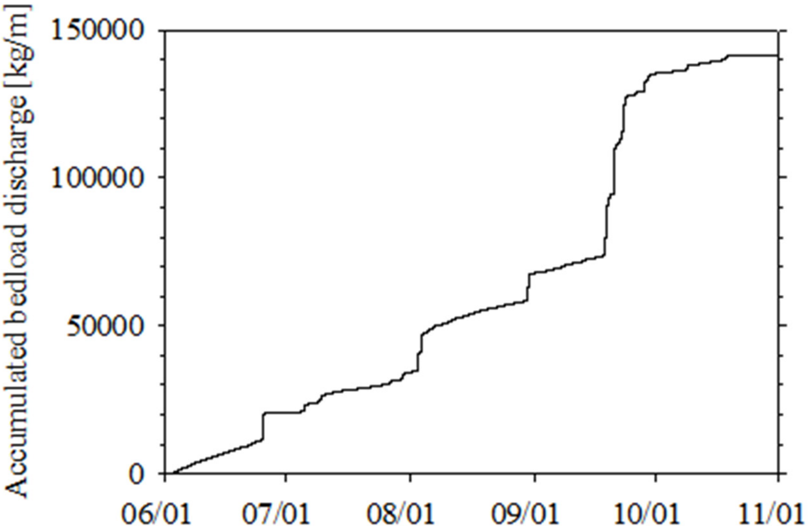


Figure 7: Cumulative bedload discharge calculated by the correlation curve for the period during June - October, 2016.

5 Conclusions

In this study, we describe a novel measurement method using a set consisting of a vertical and a horizontal pipe hydrophone, and applied the method to monitoring bedload during May–November, 2016, in the Ashiarai-dani station. From the results, we conclude that the new method can resolve underestimates of the pulses due to pulse saturation and bedload saltation problems, and it can be used effectively for bedload monitoring in mountain streams and sediment bypass tunnels.

Acknowledgments

We thank the reviewer for valuable suggestions and comments. We also thank the organizers for their efforts in hosting the outstanding workshop.

References

Baezinger, R., Burch, H. (1990). Acoustic sensors (hydrophones) as indicators for bedload transport in a mountain torrent, Hydrology in Mountain Regions, 1-Hydrological Measurements. *the Water Cycle, Proceedings of two Lausanne Symposia*, August 1990, IAHS Publ. No. 193.

Hoshino, K., Sakai, T., Mizuyama, T., Satofuka. Y, Kosugi, K., Yamashita, S., Sako, Y., Nonaka, M. (2004). Sediment monitoring system and some results in the Rokko–Sumiyoshi River. *Journal of Japan Society of Erosion Control Engineering*, 56 (6), 27–32. (in Japanese with English abstract)

Mizuyama, T., Matsuokoa, M., Nonaka, M. (2008). Bedload measurement by acoustic energy with Hydrophone for high sediment transport rate. *Journal of Japan Society of Erosion Control Engineering*, 61 (1), 35–38. (in Japanese with English abstract)

Mizuyama, T., Nonaka, M., Nonaka, N. (1996). Observation of sediment discharge rate using a hydrophone. *Journal of Japan Society of Erosion Control Engineering*, 49 (4), 34–37. (in Japanese with English abstract)

Nakaya, H., Tsuruta, K., Yoshimura, N. (2007). Sediment discharge observation and its analysis by means of a hydrophone in the upper Tedorigawa river basin. *Journal of Japan Society of Erosion Control Engineering*, 60 (3), 20–25. (in Japanese with English abstract)

Rickenmann, D., Turowski, J.M., Fritschi, B., Wyss, C., Laronne, J.B., Barzilai, R., Reid, I., Kreisler, A., Aigner, J., Seitz, H. and Habersack, H. (2014). Bedload transport measurements with impact plate geophones: comparison of sensor calibration in different gravel-bed streams. *Earth Surface Processes and Landforms*, 39, 928–942.

Tsutsumi, D., Nonaka, M., Mizuyama, T., Shida, M., Ichida, K., Miyata, S., Fujita, M. (2013). Quantitative observation of bed-load in mountainous streams by hydrophones, *Annuals of Disas. Prev. Res. Inst., Kyoto Univ.*, 56B, 465–471. (in Japanese with English abstract)

Authors

Daizo Tsutsumi (corresponding Author)
Masaharu Fujita
Research Center for Fluvial and Costal Disaster, Disaster Prevention Research Institute, Kyoto University, Japan
Email: tsutsumi.daizo.8m@kyoto-u.ac.jp

Yutaka Higashi
Graduate School of Engineering, Kyoto University, Japan

Michinobu Nonaka
Hydrotech Co. Ltd., Japan