Experimental study on measurement method of gravel discharge rate in high-speed flow using plate-type sensor

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Abstract

A sediment bypass tunnel is used as one of the methods of sediment management for reducing the sedimentation of the dam reservoir and conserving and improving the sediment transport downstream of the dam. Measurement of the amount of sediment passing through the sediment bypass tunnel is important for operation and maintenance of the facility concerning abrasion damage, examination and evaluation of riverbed environmental change of the downstream river. Therefore, considering the application to the Koshibu Dam sediment bypass tunnel, the authors are investigating measurement method of gravel flow amount in high-speed flow. The sediment bypass tunnel began test operation in the autumn of 2016 at the Koshibu Dam built in the Koshibu River, the tributary of the Tenryu River in Japan. In this paper, the authors report the results of examining the response characteristics and measurement method of the plate-type sensor against gravel flow by the flume experiment reproducing high speed flow of about 10 m/s.

Keywords: plate-type sensor, high-speed flow, gravel discharge rate, flume experiment, grain size

1 Introduction

Measuring the amount of sediment passing through the sediment bypass tunnel is important for operation of the facilities, maintenance and countermeasures for wear and damage of the facilities, grasp of the amount of sediment supply to the downstream, etc. However, the measuring method for that is not well established.

Therefore, the authors are investigating the measurement method with the aim of grasping the amount of gravel about 2 mm or more in the bed load passing through the facility. Target of this study is to establish the measurement method to be able to be applied to the Koshibu Dam's sediment bypass tunnel (Kashiwai *et al.* 2015) which began test operation in the autumn of 2016. As a past study, two bed load measuring systems exist: hydrophone (Tsutsumi *et al.* 2013, Suzuki *et al.* 2013, Koshiba *et al.* 2015) which is under consideration many in sabo field such as observation at Hodaka Sabo Observatory of Kyoto University and Swiss geophone (Hagmann *et al.* 2015).

In this study, considering the high speed flow (about 15 m/s maximum) assumed for the Koshibu Dam's sediment bypass tunnel, the authors are investigating the measurement using a plate-type sensor with high durability. In this paper, we report findings obtained on measurement characteristics and measurement method when gravel flows down in high speed flow by flume experiments.

2 Experimental method

An outline of the experimental equipment and plate-type sensor is shown in Figure 1. A steel channel (bottom made of stainless steel) with a height of 0.5 m, a width of 0.5 m, a length of 10 m, and a slope of 1/50 was manufactured. A flow rate of 1.0 m^3/s was rectified by a nozzle having a rectangular outlet (a height of 0.2 m and width of 0.5 m) through a water supply pipe from the pump to the channel.

The plate-type sensor shown in Figure 1 was installed on the downstream end of the channel as the same plane as the bottom of the channel. The plate-type sensor consists of a steel plate with 0.5 m long side, 0.36 m short side, 15 mm thickness and three sensors installed on the back side. Three sensors are an acoustic sensor (hydrophone), a vibration sensor and a geophone. In this study, we used two sensors, an acoustic sensor and a vibration sensor.

In the experiments, the voltage output from the sensor was recorded for 10 sec at 20 μsec intervals (50 kHz). During the recording period, gravel material whose mass was measured according to the experimental conditions was dropped into the upstream end of the channel from the vicinity of the water surface.

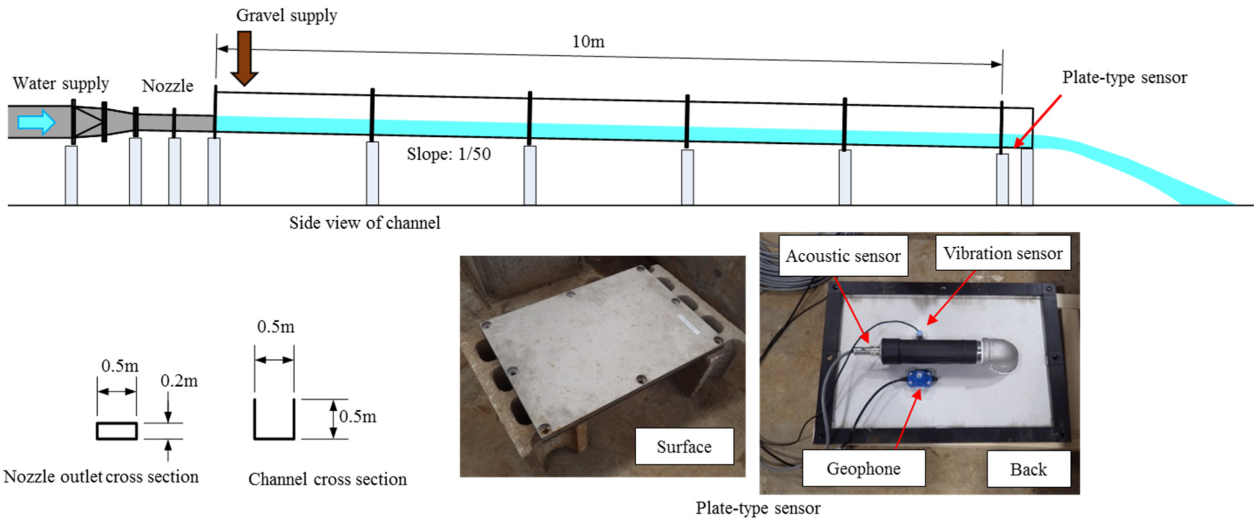

Figure 1: Outline of experiment equipment and plate-type sensor

The gravel material used for the experiments was collected from the river bed in the immediately upstream of the inflow portion of the Koshibu Dam's sediment bypass tunnel. The gravel which was sieved to six uniform particle sizes shown in Table 1 was used.

The experimental conditions were 7 cases where grain size and amount of gravel were changed. Experimental cases are shown in Table 2. In Case 7, six particle sizes were flowed simultaneously.

Table 1: Specifications of gravel material used in the experiments

Grain size [mm]	Sieve opening [mm]	Average mass [g]	Average volume [cm^3]	Average density [g/cm^3]
2	2.00 - 2.80	0.019	0.0070	2.715
5	4.75 - 5.60	0.261	0.0976	2.669
10	9.52 - 13.20	2.765	1.0308	2.683
20	19.1 - 22.4	15.591	5.8690	2.656
50	45 - 63	251.453	94.6839	2.656
100	90 - 100	1670.423	625.2399	2.672

Table 2: Experimental conditions

Case No.	Trials [times]	Grain size [mm]	Gravel amount (per trial) [Number of particle]	Total gravel mass [g]	Total gravel volume (without void) [cm^3]
1	10	2	About 26,000 (500 g)	5,000	1,842
2	10	5	About 1,900 (500 g)	5,000	1,874
3	10	10	About 360 (1000 g)	10,003	3,728
4	10	20	50	6,955	2,618
5	20	50	25	133,404	50,233
6	40	100	10	670,391	250,928
7	10	2	About 26,000 (500 g)	5,000	1,842
		5	About 1,900 (500 g)	5,000	1,874
		10	About 360 (1000 g)	10,002	3,728
		20	50	6,894	2,595
		50	10	25,976	9,781
		100	5	82,123	30,739

3 Experiment results

As a result of measuring the water surface shape along the center line of the channel (time average water level by visual observation), the water surface shape was generally stable. The average flow velocity of the water flow was 8.62 m/s. This velocity was calculated by averaging the water depth measurements at distances of 2 m to 8 m from the upstream end of the channel.

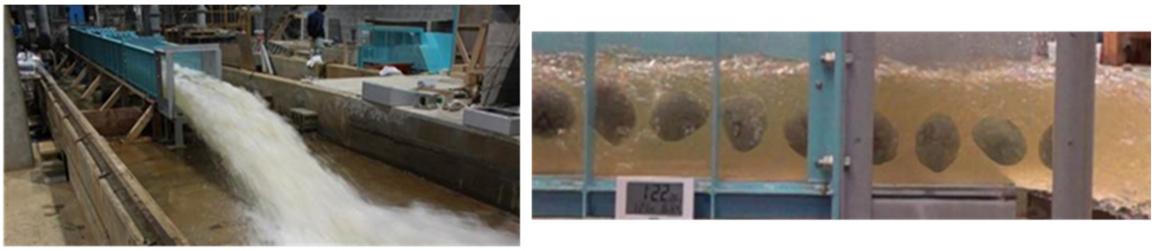

Figure 2: Flow situation at the upstream end flow velocity of 10 m/s (left) and gravel flowing situation shot at high speed (right)

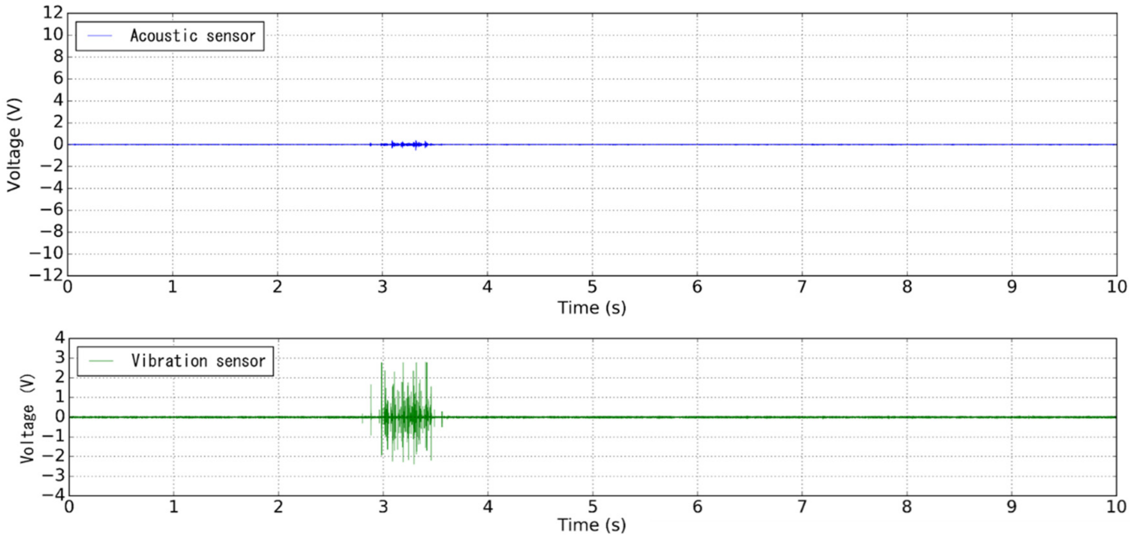

Figure 3: Example of measurement results of Case 3 (grain size: 10 mm)

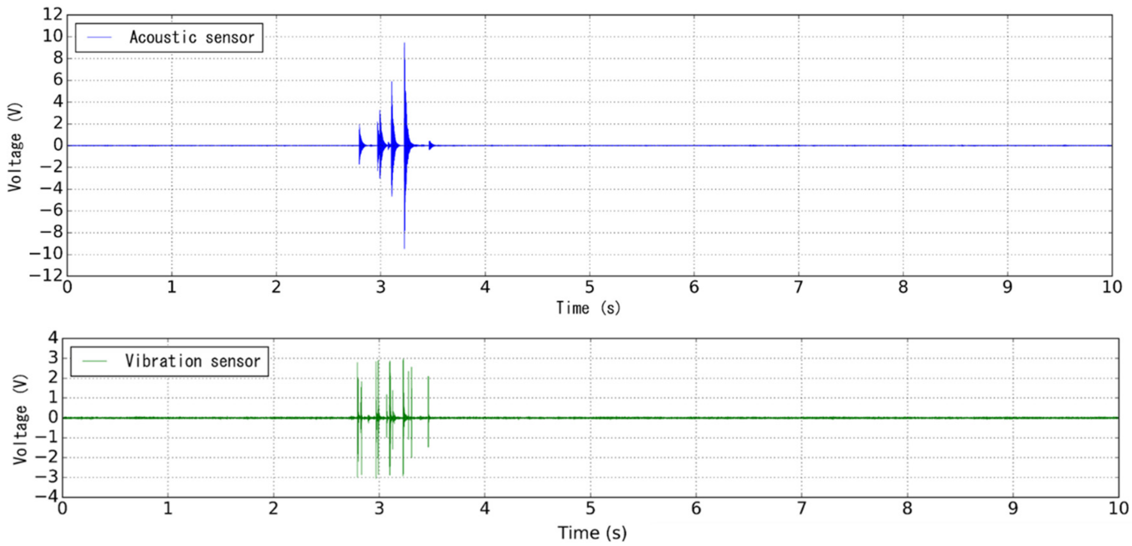

Figure 4: Example of measurement result of Case 5 (grain size: 50 mm)

An example of the flow situation of experiment results is shown in Figure 2. As examples of measurement results of output voltage when gravel flows down, the results of one trial of Case 3 and Case 5 are shown in Figure 3 and Figure 4. As a result of confirming measurement waves other than those shown here, the amplitude of the wave was found to be correlated with the particle size. This tendency was remarkable in the result of the acoustic sensor. The vibration sensor reacted even to small particle size and was sensitive. On the other hand, the amplitude reached the measurement upper limit value even with small impact.

4 Measurement method of gravel flow amount

4.1 Concept of gravel flow amount measurement method

The wave of the voltage outputted by the collision of the gravel is converted into the envelope line, and the wave appearing in the envelope line is defined as the "envelope wave". As a method of measuring the gravel flow amount from the output voltage recorded by the plate type sensor, we considered to estimate the gravel flow amount from the number of envelope waves and its peak voltage. When such a measurement method is adopted, the following items are considered to be error factors.

(1) Jump over: underestimation of the gravel flow amount caused by saltating gravel jumping over the plate.

(2) Overlap of waves: underestimation of the gravel flow amount due to the overlapping of small amplitude waves with large amplitude waves.

(3) Changes in collision situation: underestimation of gravel size due to changes in angle of collision and impact force due to gravel shape.

(4) Multiple collisions of particles: overestimation of the gravel flow amount due to one gravel particle collides with the plate many times.

(5) Echo: overestimation of the gravel flow amount by detecting the echo signal when gravel collides around the plate.

The following describes the results of investigation on the measurement method considering these factors.

4.2 Envelope process of output voltage waves and frequency distribution of envelope waves

For the measured output voltage wave, the number of envelope waves generated by the collisions of the gravels and its peak voltage were calculated by the following operation. From the results, frequency distribution data of the number of envelope waves for each magnitude of peak voltage during the measurement period was created.

(1) Convert output voltage value to absolute value.

(2) Create envelope data from the data in (1). At this time, it is judged whether or not it becomes the peak of the envelope wave depending on whether or not it becomes the maximum value in the time range of 5,000 μsec before and after regarding the absolute value data at a certain time.

(3) For waves whose envelope data peak voltage is 0.2 V or more, count wave numbers at 0.2 V intervals for acoustic sensors and 0.1 V intervals for vibration sensors, and create frequency distribution data.

The frequency distributions of the envelope wave numbers of trial total at each experimental case are shown in Figure 5 and the left side of Figure 6. From Figure 5, in the case of only small particle sizes of Case 1 and Case 2, the number of the envelope waves detected by the acoustic sensor is small. In the case of particle sizes of Case 3 to Case 6 of 10 mm or more, the distribution shapes of frequency are different depending on the particle size, and the larger particle diameter, the larger the number of envelope waves of the larger peak voltage increases.

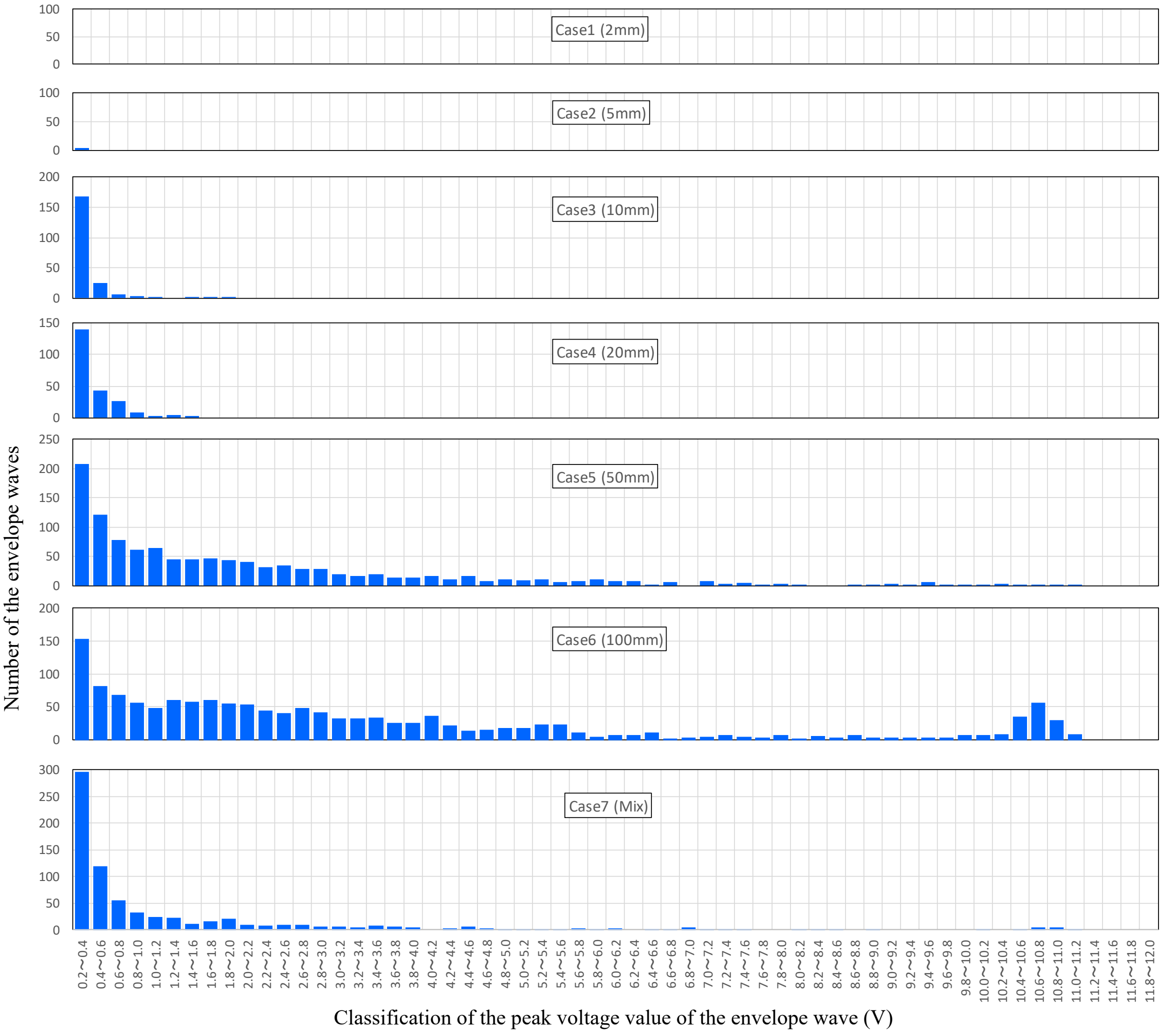

Figure 5: Frequency distribution of the numbers of the envelope waves detected by acoustic sensor

From the figure on the left side of Figure 6, in the case of particle sizes of 10 mm or more in Case 3 to Case 6, the envelope wave of the peak voltage at the measurement upper limit of about 3 V is counted. Therefore, it is considered difficult to classify particle sizes from the distribution of the number of envelope waves detected by the vibration sensor.

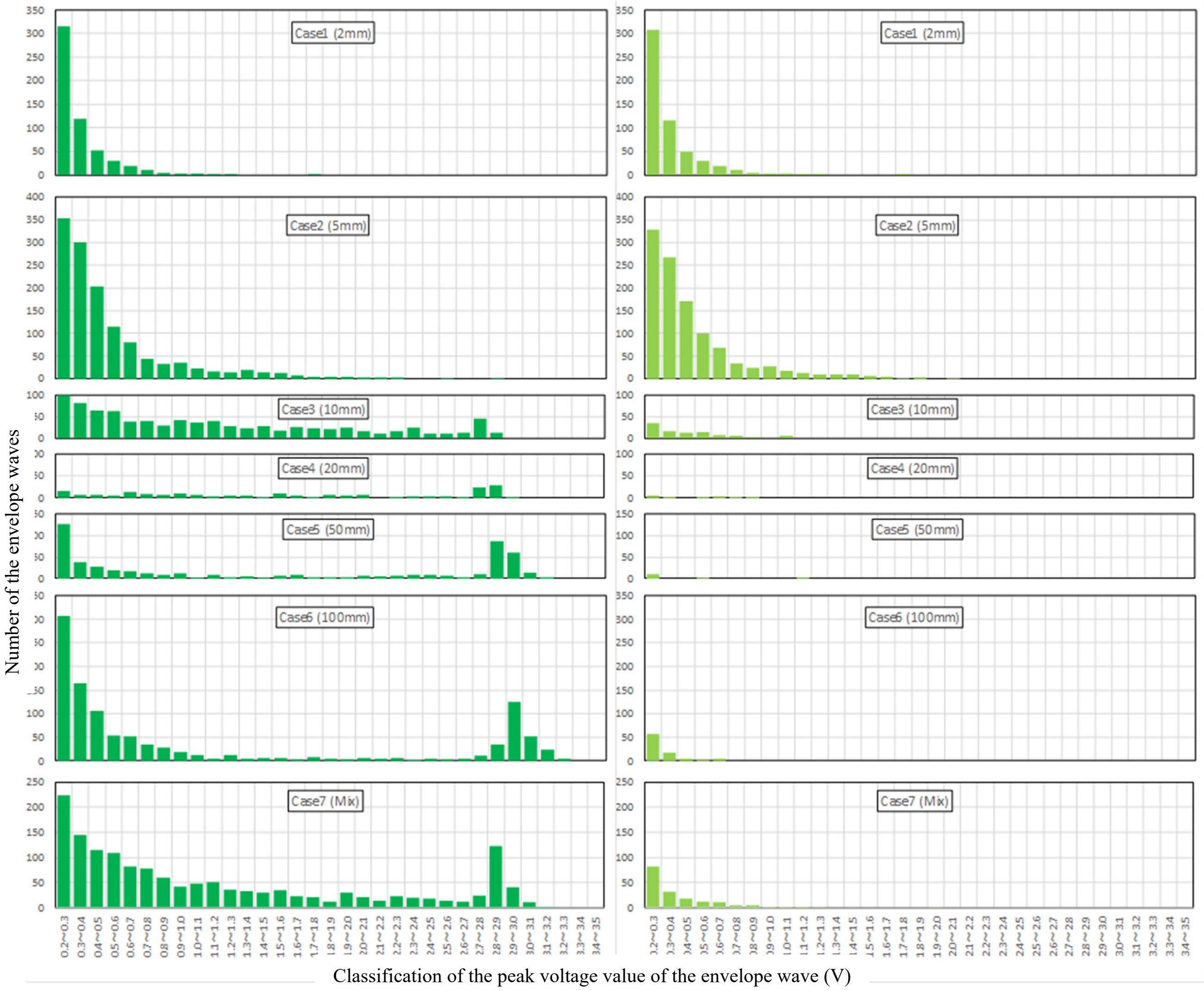

Figure 6: Frequency distribution of the numbers of the envelope waves detected by vibration sensor (The figure on the left shows the original distribution. The figure on the right shows the distribution when the wave with acoustic sensor value of 0.2 V or more is excluded)

4.3 Proposal of measurement method

From the frequency distributions in Figure 5 and Figure 6, it was decided to estimate the gravel flow amount from the results of the acoustic sensor for the gravel with a grain size of 10 mm or more, from the result of the vibration sensor for the grain sizes 2 mm and 5 mm. However, for the frequency distribution of the vibration sensor, it is considered that the envelope wave due to the collision of the gravel having a particle size of 10 mm or more is counted. To improve this, we decided to count only when the value of the envelope data of the acoustic sensor at the same time at the peak of the envelope wave of the vibration sensor was 0.2 V or less. The result of this operation is shown in the graph on the right side of Figure 6. From Figure 6, it can be confirmed that the envelope wave of the vibration sensor decreases when a large particle size is supplied by this operation. From these frequency distributions, the range of the peak voltage representing the gravel flow amount of each grain size was selected as shown in Table 3. Table 4 summarizes the number of envelope waves for each experiment case for each range of selected peak voltages.

When large size gravel flows down, envelope wave of peak voltage smaller than the range shown in Table 3 are counted due to the factors (3) and (5) shown in 4.1. In order to improve the overestimation due to this, we decided to estimate the gravel flow amount in order from the larger particle diameter, and to subtract the number of envelope waves in the range smaller than the range of the representing peak voltage by the ratio of the number of envelope waves obtained from the experimental results of uniform particle size (Case 1 to Case 6). Table 5 shows the ratios of subtracting each particle size. We decided to calculate the gravel flow amount by multiplying the number of envelope waves in the representing peak voltage range by a coefficient. The coefficients are shown in Table 6. These coefficients were obtained with reference to experimental results of uniform particle size.

Table 3: Range of peak voltage representing gravel flow amount of each grain size

Grain size [mm]	2	5	10	20	50	100
Range of the peak voltage representing gravel flow amount	Vibration 0.2-0.8V	Vibration 0.8V or more	Acoustic 0.2-0.6V	Acoustic 0.6-2V	Acoustic 2-10V	Acoustic 10V or more

Table 4: Number of envelope waves summed for each range of representing peak voltage

Sensor	Range of peak voltage [V]	Case1 (2mm)	Case2 (5mm)	Case3 (10mm)	Case4 (20mm)	Case5 (50mm)	Case6 (100mm)	Case7 (Mixed size)
Acoustic	0.2-0.6	0	3	192	183	329	236	415
	0.6-2	0	0	15	45	384	408	185
	2-10	0	0	0	0	407	664	120
	10 or more	0	0	0	0	9	148	14
Vibration	0.2-0.8	536	970	93	12	11	84	162
	0.8 or more	15	123	22	1	1	0	13

Table 5: Ratios used when subtracting the number of envelope waves in estimating the gravel flow amount of each grain size

Sensor	Range of peak voltage [V]	Grain size [mm] 2	5	10	20	50	100
Acoustic	0.2-0.6	-	-	1.00	4.07	0.81	1.59
	0.6-2	-	-	-	1.00	0.94	2.76
	2-10	-	-	-	-	1.00	4.49
	10 or more	-	-	-	-	-	1.00
Vibration	0.2-0.8	1.00	7.89	-	-	-	-
	0.8 or more	-	1.00	-	-	-	-

Table 6: Coefficients for multiplying the number of envelope waves in the range of representing peak voltage to estimate the gravel flow amount of each grain size

Sensor	Range of peak voltage [V]	Grain size [mm] 2	5	10	20	50	100
Acoustic	0.2-0.6	-	-	21.8	-	-	-
	0.6-2	-	-	-	58.2	-	-
	2-10	-	-	-	-	95.4	-
	10 or more	-	-	-	-	-	1695.5
Vibration	0.2-0.8	3.9	-	-	-	-	-
	0.8 or more	-	14.7	-	-	-	-

4.4 Comparison of the gravel volumes of experiment and measured values

Table 7 shows the gravel volumes supplied in the experiments. Table 8 shows measured volumes calculated by the measurement method shown in 4.3. Table 9 shows the error ratios between experimental volumes and measured volumes based on the total gravel volumes supplied in the experiments. From Table 9, it was possible to measure with an error of about 30% on the total of the gravel volume and its grain size classification. In the cases of Case 1 to Case 6 (uniform grain size), the errors of the total gravel volumes are 10% or less, those are all overestimated. For Case 1 to Case 6, errors of 5 mm, 20 mm, and 100 mm are small at 3.5% or less, and somewhat larger at 2 mm, 10 mm, and 50 mm at about 10% to 30%. In Case 7 of the mixed grain size, the error of the total volume of the gravel is 30.8%, which is larger than in the cases of uniform grain size, and which is underestimated. In Case 7, it is greatly underestimated at a small grain size (2 mm to 10 mm) when comparing among the same grain sizes. It is considered that this is due to the overlap of waves shown in (2) of 4.1.

Table 7: Gravel volumes supplied in the experiments (without void, unit: cm^3)

Grain size [mm]	Case1 (2mm)	Case2 (5mm)	Case3 (10mm)	Case4 (20mm)	Case5 (50mm)	Case6 (100mm)	Case7 (Mixed size)
2	1,842						1,842
5		1,874					1,874
10			3,728				3,728
20				2,618			2,595
50					50,233		9,781
100						250,928	30,739
Total	1,842	1,874	3,728	2,618	50,233	250,928	50,558

Table 8: Gravel volumes measured using plate-type sensor (without void, unit: cm^3)

Grain size [mm]	Case1 (2mm)	Case2 (5mm)	Case3 (10mm)	Case4 (20mm)	Case5 (50mm)	Case6 (100mm)	Case7 (Mixed size)
2	1,621	0	0	16	12	326	231
5	221	1,809	323	15	15	0	191
10	0	65	2,855	0	0	0	0
20	0	0	873	2,618	773	0	5,378
50	0	0	0	0	34,976	0	5,456
100	0	0	0	0	15,259	250,928	23,736
Total	1,842	1,874	4,051	2,649	51,035	251,254	34,993

Table 9: Error ratios between experimental volumes and measured volumes based on the total gravel volumes supplied in the experiments

Grain size [mm]	Case1 (2mm)	Case2 (5mm)	Case3 (10mm)	Case4 (20mm)	Case5 (50mm)	Case6 (100mm)	Case7 (Mixed size)
2	-12.0%	0.0%	0.0%	0.6%	0.0%	0.1%	-3.2%
5	12.0%	-3.5%	8.7%	0.6%	0.0%	0.0%	-3.3%
10	0.0%	3.5%	-23.4%	0.0%	0.0%	0.0%	-7.4%
20	0.0%	0.0%	23.4%	0.0%	1.5%	0.0%	5.5%
50	0.0%	0.0%	0.0%	0.0%	-30.4%	0.0%	-8.6%
100	0.0%	0.0%	0.0%	0.0%	30.4%	0.0%	-13.8%
Total	0.0%	0.0%	8.7%	1.2%	1.6%	0.1%	-30.8%

5 Conclusions

Authors have devised a method to measure the gravel flow amount and its grain size distribution in high-speed flow using acoustic sensor data and vibration sensor data measured by the plate-type sensor at flume experiments reproducing a high-speed flow of about 10 m/s. It was confirmed that the gravel flow volume can be measured by this measurement method with an error of about 30% or less within the range of experimental conditions. For the future, we will study about the influence of flow velocity, grain size distribution, concentration of gravel flow, etc., and promote application to actual facilities.

Acknowledgement

The authors thank Tenryu River Dam Integrated Management Office, Chubu Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism for supporting to collect experimental materials for this research.

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