Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). IAHS Publ. no. 210, 1992.

A new acoustic sensor for sediment discharge measurement

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ABSTRACT A new type of acustic sensor is proposed to measure the amount of sediment discharge in real-time in this paper . When a stone or small particle of sand transported by flowing water collides with a pipe set on a river-bed, the sound can be picked up by a microphone held in the pipe. The laboratory basic experiments have made clear that the circumference mode of the air oscillation in the pipe is useful in counting the number of particles striking the pipe and the amount of sediment discharge is related to the number of output electrical pulse. The estimation error was within 30%. This sensor has the advantage of providing an indirect method for measuring the amount of sediment discharge; on the other hand, the direct method is used to measure the weight of the sediment discharge gathered in the bucket. The practical instruments of the sensor have been set at a branch of the Jyoganji River in Tateyama, Toyama Prefecture for a feasibility test, comparing with the direct method.

INTRODUCTION

In developing master plans for land erosion and river control, it is very important to measure the amount of sediment discharge. The amount of sediment discharge has been measured using several methods, for example, estimation from data of past disasters and measurement of the weight of sediment accumulating in a collector. This is the direct method. There are many techniques involving collectors and samplers. In Japan, several methods measuring sediment discharge have been developed (Study Group & Sediment Measurement Techniques, 1971). However, the following problems are associated with the direct method of sediment discharge measurement.

(a) The equipment used in the direct method disturb the flow of water and the sediment.
(b) The equipment is large and expensive.
(c) Automatic and real-time operation of the direct method is not possible.

We propose that the amount of sediment discharge can be measured indirectly using a transducer. There are several media wich can be used to measure the amount of sediment discharge indirectly. These are sound (acoustic, pulse wave, supersonic), magnetic waves (light, laser, microwave, X-ray, γ-ray), pressure (hydraulic pressure, density), and electricity (resistance, inductance). The sound media is better than the others, because the other media are influenced by absorption or scattering by the water and particles. Therefore, we propose to pick up the sound generated by particles striking a pipe. In this paper, we propose a new acoustic sensor with signal processing for sediment discharge measurement and describe the results of the feasibility tests and the procedures for estimating the amount of sediment discharge.

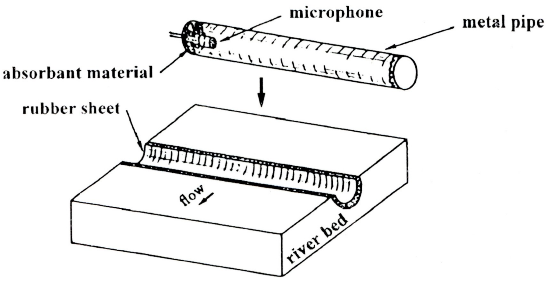

FIG. 1 Configuration of the acoustic sensor.

PRINCIPLE OF THE SENSOR

The configuration of the acoustic sensor is shown in Fig.1. The acoustic sensor based on a steel pipe is a very simple device. A microphone is attached to the other end of the pipe. Both ends of the pipe are closed so that water does not enter. When a floating particle collides with the acoustic sensor, oscillation of air is generated and propagates to circumference, radial and axis direction in the closed pipe. Each frequency of the first mode in the circumference(f_{10}), radial(f_{01}) and axis(fz) direction are represented by:

$$f_{10} = 0.298c/a \quad (1)$$
$$f_{01} = 0.61c/a \quad (2)$$

and

$$f_z = c/(2l) \quad (3)$$

respectively. Where c is the sound velocity in the air, a is the radius and l is the length of the confined space of the pipe. The energy density of the echo, ε, in a room with volume, V, and surface area, S, is represented by:

$$\varepsilon = \varepsilon_0 \, exp(-13.6t/T) \quad (4)$$

and the characteristic time of the echo, T, is represented by:

$$T = 0.16V / (kS) \quad (5)$$

where ε_0 is the initial energy density of the sound, *k* is the average absorption rate and *t* is elapsed time (Kido, 1982).

The value of ε_0 depends on many factors such as the velocity, mass, position and angle of collision. Some basic experiments were undertaken to obtain the relationship between the energy density of the echo (ε_0) and these factors by using various steel balls instead of the particles. The result is shown in Fig. 2. *x*-axis is the momentum in *log* scale, *y*-axsis is the amplitude (*e*) of the output signal corresponding to the circuference mode, which is also in log scale. The amplitude (*e*) is proportional to the initial energy density (ε_0) due to the characteristic of the microphone.

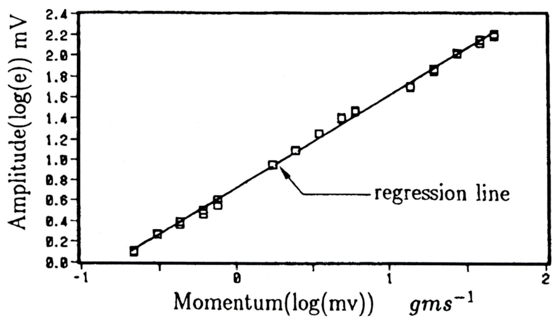

FIG. 2 The relationship between momentum and amplitude.

The line in Fig. 2 represents the simple regression line. Moreover, the value of ε_0 of the circumference mode was independent of the collision position of the pipe. On the other hand, radial and axis mode were not sensitive to small particles and depended on the collision position.

According to these results of the basic experiments, it was understood that the circumference mode is useful to detect the value of ε_0, rather than radial and axis mode. Furthermore, the sound of the axis mode should be restrained by absorbant material in both ends of pipe so as not to disturb the circumference mode.

Therefore, if the particle collides coaxially to the pipe and the velocity is known, it is possible to estimate the particle mass from the value of ε_0. If the collision angle and velocity are not constant, the relation between ε_0 and the mass varies widely. But even in that case, it is possible to estimate the distribution of the particle mass from the distribution of ε_0 statistically.

We made two models of the acoustic sensor to be set on a flat-base, e.g. on a dam crest, or on the river-bed, for a particle to be able to collide constantly and for the sensor not to be buried in the sand. One is 3cm in diameter, 30cm in length and 3mm in thickness and was used for a feasibility test, and the other is 6cm in diameter, 2m in length and 4mm in thickness and was used for a field test.

The upper plot in Fig. 3 shows the spectrum of the characteristic frequencies of the sensor for a feasibility test, and the lower plot shows the original wave form. The dominant frequency is about 8.5kHz which corresponded to the first mode represented by equation (1). The second peak appears around 0.7kHz which corresponded to the first mode represented by equation (3).

To obtain the clear characteristic frequencies, it will be better to support both ends of the pipe for free vibration. Moreover, to limit the propagation of noise through the base, it is better to spread a rubber sheet between the sensor and the base. The experiment to examine the effect of the rubber sheet was undertaken using sensor for the field test.

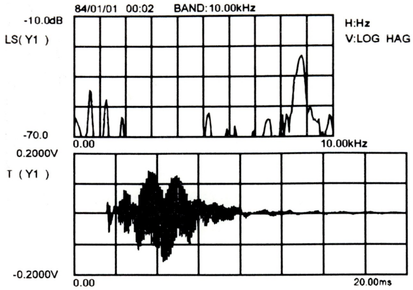

FIG. 3 Spectrum of the characteristic frequencies.

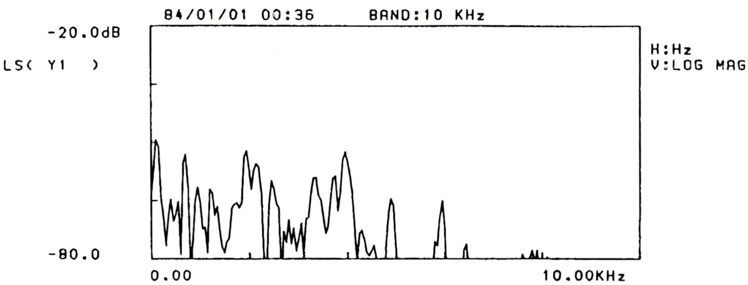

FIG. 4 Power spectrum of noise without rubber sheet.

Figure 4 shows the spectrum of the noise propagated through the base without the rubber sheet. Fig. 5 shows the spectrum with the rubber sheet. It was clear that the propagated noise was substantially reduced by the rubber sheet, and that the frequency of the circumference mode could not be disturbed by the propagated nosie unlike the axis mode, because the frequency of the axis mode could not be contolled perfectly.

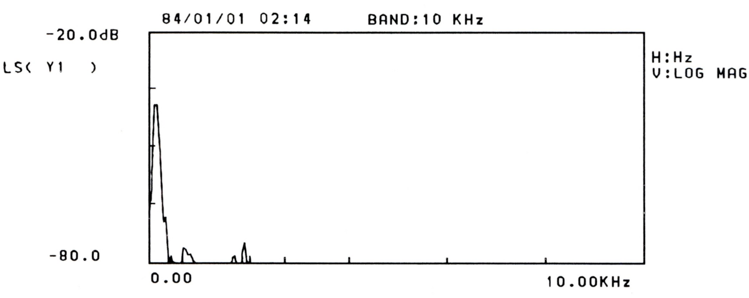

FIG. 5 Power spectrum of noise with rubber sheet.

SIGNAL PROCESSOR

A block diagram of the signal processor is shown in Fig. 6. As the circumference mode is useful, only the frequency of the circumference mode is taken out by a band pass filter, and the original wave form is transformed to a pulse form by the wave detector circuit.

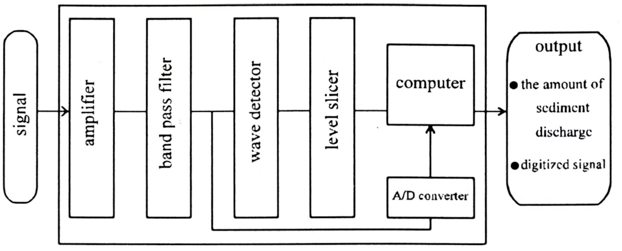

FIG. 6 Block diagram of the signal processor.

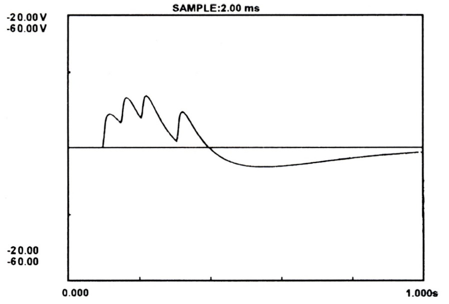

FIG. 7 Pulse form of the final output signal.

Fig. 7 shows the pulse form of the final output signal, when four particles have just collided. The output wave form is classified into five ranks according to the amplitude, and the number of pulses are counted by a computer to estimate the sediment discharge in unit time. The original output analog signal can be digitized by A/D converter and saved in the magnetic disk device of the computer simultaneously.

FEASIBILITY TEST

The feasibility tests were undertaken in a flume under conditions of known water flow velocity, water volume and inclination of the bed at the Disaster Prevention Research Institute of Kyoto University. The flume was 20cm in width, 30cm in depth and 10m in length. The sensor for the feasibility test was installed at the end of the flume. Half of the sensor was exposed to the water and the other half was buried in the base of the flume. The rubber sheet was spread between the sensor and the base to restrain the propagation of noise through the base.

The following hypothesis were examined:

1. Under a constant flow velocity the rank of output signal amplitude is related to the weight of a particle, including errors due to the distribution of collision angle and particle velocity.
2. It is possible to estimate the sediment discharge using the following equation:

$$y = \sum_{i=1}^{n} a_i x_i \tag{6}$$

where n is a number of ranks, a_i is the mean weight of the particles of rank-i estimated from the relation between the amplitude and the weight for the same velocity, x_i is the number of pulse of rank-i. If the number of ranks is increased, the calculation error is decreased.

3. The sum total of pulses of a certain rank is related to the sediment discharge.

The experiments were undertaken with the following two conditions:

case-1. A velocity of flow (v) of $1.5ms^{-1}$ and a rate of flow(Q) was $12ls^{-1}$.

case-2. A velocity of flow (v) of $2.0ms^{-1}$ and a rate of flow(Q) was $24ls^{-1}$.

First of all, to examine hypothesis(1), particles of known weight were thrown into the flume separately. Fig. 8 shows the relation between the momentum of a particle and the rank of the amplitude of the output signal under the condition of case-1. A relation between amplitude and weight of particle has been obviously confirmed. It was also confirmed under the condition of case-2.

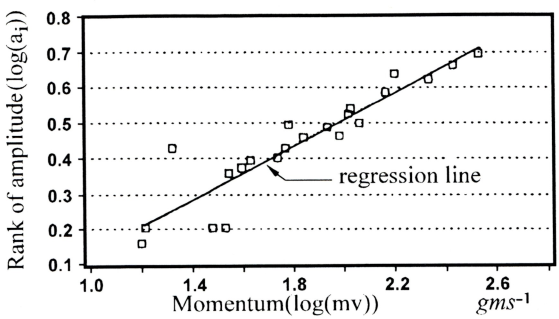

FIG. 8 Relation between momentum and amplitude.

Second, to examine hypothesis (2) and (3), a mixture of particles characterized by the size distribution shown in Fig. 9 were thrown into the flow at the rate of 2kg, 4kg,

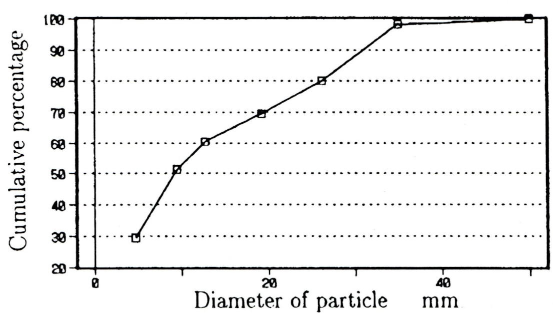

FIG. 9 Distribution of the diameter of the thrown particles.

6kg, 8kg, 10kg per minute.

Table 1 shows the number of pulses and the estimated sediment discharge calculated using equation (6) under the condition of case-1. According to the results of this experiment, if the amount of sediment discharge is small, it is possible to estimate the amount of sediment discharge using equation(6) within an error of 30%. However the error increased with large sediment discharges, because the amplitude of the signal was shifted to the upper rank by the incessant oscillation of the air in the pipe. The size of the

TABLE 1 Number of pulses and the estimated amount.

rank-5	rank-4	rank-3	rank-2	rank-1	supplied amount	estimated amount	error(%)
4	7	19	30	75	2 $kgmin^{-1}$	2.3 $kgmin^{-1}$	15
10	14	43	61	96	4 $kgmin^{-1}$	5.1 $kgmin^{-1}$	28
28	50	50	86	78	6 $kgmin^{-1}$	11.1 $kgmin^{-1}$	85
56	70	86	88	53	8 $kgmin^{-1}$	18.3 $kgmin^{-1}$	128
76	88	109	76	43	10 $kgmin^{-1}$	23.4 $kgmin^{-1}$	134

pipe and the time constant of the wave detector circuit will be investigated to improve the sensor.

Figure 10 shows the relation between the summation of pulses over rank-3 and the amount of sediment supplied. A propotional relation between both variables could be confirmed. If this rule can be applied to an actual river, it will be very useful.

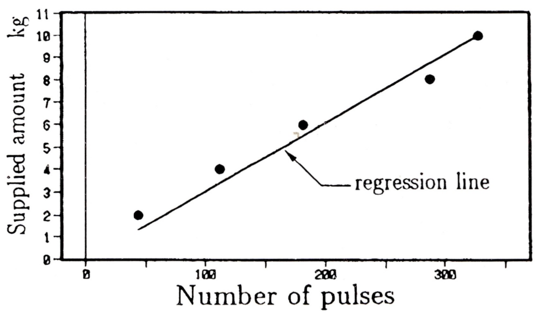

FIG. 10 Relation between the number of pulses and the amount of sediment supplied.

APPLICATION TO AN ACTUAL RIVER

In 1990, the sensor for the field test was set on the dam crest on a tributary of the Shomyo River, Toyama prefecture, and succeeded in the measuring a small amount of sediment discharge. Simultaneously, direct maesurments of sediment discharge were made at the edge of the dam crest to compare with the sensor data. The equipment used for the direct measurments is currently being adjusted. If both data can be obtained for an actual river the results can be compared and the acoustic sensor evaluated. We expect to report the results in another paper.

CONCLUSION

A new type of acoustic sensor proposed here has possibility for measuring the amount of sediment discharge in real-time. The basic laboratory experiments confirmed the efficacy of the acoustic sensor; that is, the amplitude of the output signal was related to the momentum of the particle. Therefore, if a particle collides with the pipe and the velocity is known, it is possible to estimate the particle mass from the amplitude of the output signal.

Two procedures for estimating the amount of sediment discharge were examined in the flume at the Disaster Research Prevention Institute of Kyoto University. The first one was to sum the quantities calculated using equation (6), and the other was to estimate the amount of sediment discharge from the summation of pulses above a certain rank. According to the results of the feasibility test, it was shown that small amounts of sediment discharge could be estimated using the former procedure, and that the summation of the pulses over rank-3 could be related to the amount of sediment discharge using the latter procedure. More accurate estimation of the amount of sediment discharge needs a probability model for signal processing. Some basic experiments have been undertaken for this purpose. For developing the practical estimation procedures, it is necessary to compare data collected using both the direct method and the indirect method in an actual river. We expect to obtain both data for a tributary of the Shomyo River.

ACKNOWLEDGEMENTS The authors wish to express their sincere appreciation to Prof. Dr. H. Ogura, Ass. Dr. K. Sawai of Kyoto university and Ass. Dr. J. Nakayama of Kyoto Institute of Technology for useful comments on this work.

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