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Laboratory Tests of a Japanese Pipe Geophone for Continuous Acoustic Monitoring of Coarse Bedload

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ABSTRACT

A series of flume experiments were undertaken to determine the extent to which characteristics of a pipe-type geophone affect its ability to monitor bedload flux and texture. Two types of geophone were used: L-shaped with one microphone and U-shaped with 2 microphones. The impacts caused by collision of particles on the geophone were simultaneously recorded at various channel sensitivities. The length of pipe and that of its sensitive segment as well as microphone sensitivity varied among runs, flume width and slope were in the range 0.3-1.0 m and 2-5% respectively, grain size (2, 4, 8 and 16 mm) in each run was uniform. Bedload flux was separately determined.

Results show that the characteristics of the geophone have a considerable affect on the extent to which surrogate bedload monitoring may be undertaken. The length of the segment of pipe where collisions are recorded affects the number of pulses more than the length of the pipe. Long segments cover a larger width of a channel but they cause dampening of acoustic signals, particularly when bedload flux is high. Location (tip, center or root) where collisions are recorded affects the number of recorded collisions, increasing towards the root, this limiting allowable pipe length. Lowering microphone sensitivity allows recording at higher bedload discharges. Monitoring of high bedload discharge may be undertaken with undampened, lower channel sensitivity. The thickness of the geophone pipe limits its sensitivity to a lower 8 mm grain-size. Because bedload transport involves considerable impact forces at high bedload discharges, the need for the geophone to protrude a height equal to one pipe radius from the bed implies that it may be practical only for bedload coarser than 8 mm, or at most 4 mm.

INTRODUCTION

Acoustic detection of bedload has been studied during half a century (e.g., Ivicsics, 1956; Bedeus and Ivicsics, 1964; Johnston and Muir, 1969; Tywonicvk and Warnock, 1973; Anderson, 1976; Jonys, 1976; Richards and Milne, 1979; Froehlich, 1982; Thorne, 1986; Bänziger and Burch, 1990; Sawai, K. 1990). Although some success has been gained in the deployment of hydrophones and geophones (the former suspended above the bed and the latter on the channel bed) to monitor bedload discharge (Jagger and Hardisty, 1991; Rouse, 1994; Rickenmann, 1997; Mizuyama et al., 1998, Taniguchi and Itakura, 1992; Mizuyama, 2002; Rickenmann, 1998; Hoshino et al., 2004; Oda et al., 2004, 2005), several technical problems have remained unsolved. Among the most crucial aspects requiring further investigation are (1) the characteristics of an acoustic device that determines the detection limit of small bedload particles and, relevantly, (2) the detection of small bedload discharges, (3) the extent to which the acoustic signals determined by particle mass (essentially size, but may also include density) and shape can be separated from the effects of bedload discharge, and (4) acoustic monitoring of very high bedload discharges.

Flume runs undertaken in 2003 directed our attention to the problematic effect of very high bedload discharge on acoustic signals (Oda et al., 2004; 2005). Reverberation within and vibration of a pipe utilized to monitor the number of particle collisions causes damping of acoustic signals. When bedload discharge is elevated, the number of pulses temporarily decreases or drops to zero (Fig.1). This dampening results from two factors: the large bedload discharge (i.e., numerous particles) makes it impossible to sort individual particles based on number of pulses, and the high bedload discharge causes a reverberant sound. Therefore, our 2003 experiments with elevated bedload discharges applied the following conditions when measuring acoustic response by counting pulses: the (1) acoustic material was placed in metallic pipes to reduce reverberant sound, and (2) a low-sensitivity channel was used.

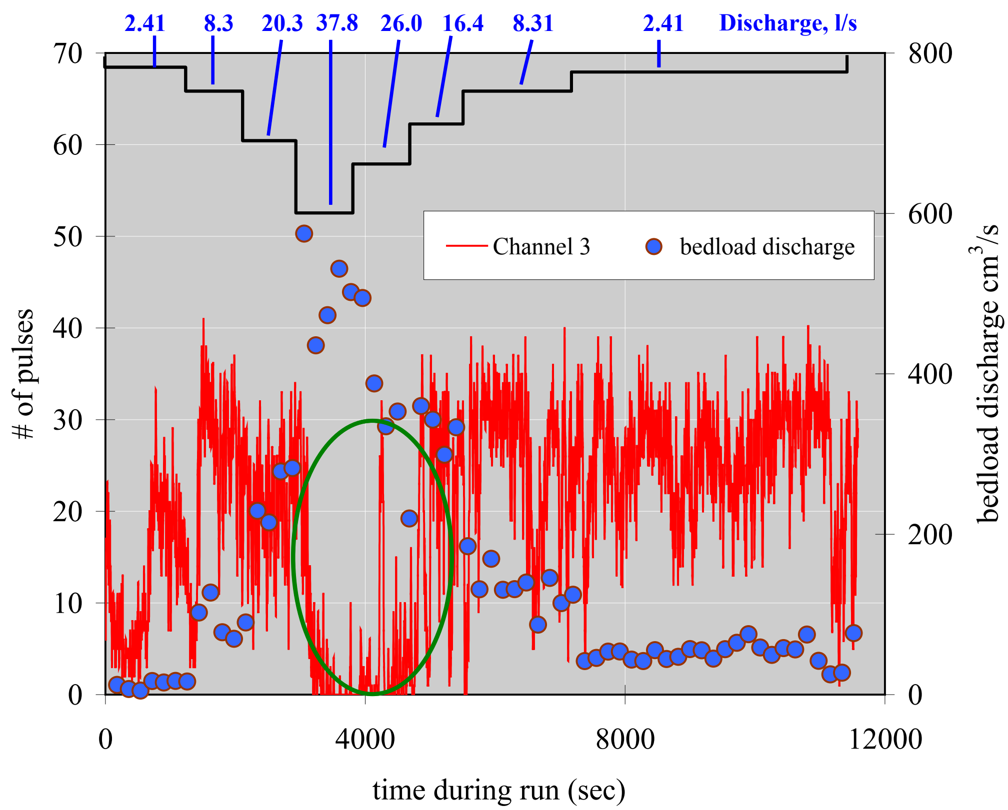

Figure 1. Example of experimental flume measurements, showing a decrease in number of pulses during contemporaneous *increase* (here at peak) in bedload discharge.

The first condition did alleviate temporarily reducing the pulse by decreasing reverberant sound, likely because the metallic pipe not only reverberated, but also vibrated. Resolving this problem was unachievable because of the difficulty in suppressing the vibration of the fixed metallic pipe during pulse measurement when particles collide. Despite this situation, the experiments confirmed that the temporary decrease in the number of pulses during high bedload discharge does not occur in the lower-sensitivity channel. Nonetheless, the number of pulses in the lower-sensitivity channel thereafter increased by a several-fold factor, thereby enlarging the error margin in the conversion number of pulses to bedload discharge.

In the present study we investigated the extent to which the number of pulses is affected by grain-size, bedload discharge, pipe length and geophone characteristics.

OUTLINE OF EXPERIMENTS

Flume runs were undertaken in a rectangular straight flume with variable inclination. The flume is 9 m long, 10 cm wide and 30 cm deep and can incline 1.1–7.5° (2–13.2%). An artificial riverbed was constructed in the flume bottom, using uni-modal very well-sorted substrate sand with an average size of 1.42 mm. Prior to each run a pre-determined volume of sediment was carefully deposited on the upstream bed of the flume in a thin trapezoid filling the entire width of the flume. Its volume refers to the sediment and voids. The bulk density of the sand was determined by weighing all the sand transported out of the flume; thus the mass of this sand wedge is known. This mass divided by the time during which the sand was entirely transported out of the flume is the bedload flux. The duration of each run lasted until all the sediment was transported out of the flume. Uniform sediment of four grain sizes (2, 4, 8, and 16 mm) was used in the experiments. Some runs were undertaken in a larger rectangular and straight flume: 20 m long, 1.0 m wide and sloping at 2%.

Two configurations of metallic pipes were used as geophones: L-type and U-type (Fig 2). The pipes have an outside diameter of 27.2 mm and 1 mm thickness. The metallic pipe was set up in the pedestal without affecting the flume’s downstream edge (Photo 1). One microphone was deployed within the end of the L-type pipe. Two microphones, one at each end, were installed in the U-type pipe, of which one microphone was covered with a sponge filter (Photo 2). Amplifier magnification was switched to two stages with a ratio of 3:5. Four channels were used, the sensitivity of which increased sequentially by a factor of approximately 2.35. Channel 1 had the lowest sensitivity index, shown as amplifier magnification (Table 1). The number of pulses was recorded every 5 s during an entire run. Five experiments were conducted, varying pipe length, location of sediment collision, microphone sensitivity, bedload discharge and bedload grain-size.

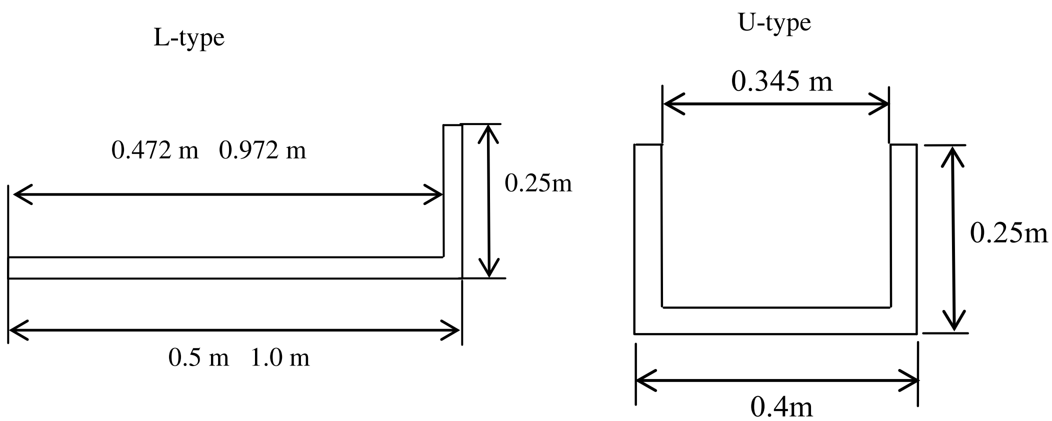

Figure 2. Experimental L-type and U-type steel geophone pipes.

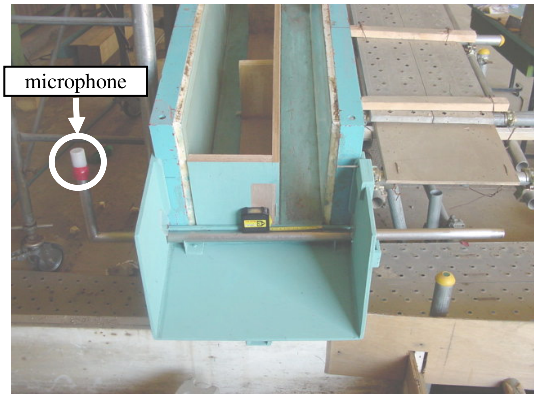

Photo 1. Installation of steel pipe (L-type geophone) at downstream end of flume.

Photo 2. U-type type steel pipe and two geophones, one with filter causing diminished sensitivity.

Table 1. Relationship between amplifier magnification and sensitivity index.

amplifier magnification	channel 1	2	3	4
3	3.0	7.1	16.6	38.9
5	5.0	11.8	27.6	64.9

VARIATION OF NUMBER OF PULSES WITH PIPE LENGTH

Experimental conditions

In this experiment, we observed changes in the number of pulses by varying the length of the pipe portion on which bedload particles collided. Condition 1: Collision occurred on a 30 cm portion in the center of an L-type pipe of length 0.5 and 1.0 m. Flume inclination was 1/16.6 (6.0%), the discharge was 4.0 ℓ/s, the total sediment volume was 18.0 ℓ, the amplifier magnification index was 3 and the grain size was 8 mm. Condition 2: Collision took place on the tip of an L-type 1.0 m long pipe deployed in the 1.0 m wide flume. Flume inclination was 1/50 (2.0%), the discharge was 30.0 ℓ/s, the total sand volume was 30.0 ℓ, the amplifier magnification index was 3, and the grain size was 4 mm. Table 2 summarizes the experimental conditions for this set of runs.

Table 2. Experimental conditions: pipe length.

zrun	pipe length m	collision segment length m	channel width m	unit bedload discharge g/s m
25	1.0	0.3	0.3	1310
26	1.0	0.3	0.3	1240
27	0.5	0.3	0.3	1030
28	0.5	0.3	0.3	1080
29	1.0	0.925	1.0	170
30	1.0	0.925	1.0	183
31	1.0	0.5	1.0	161
32	1.0	0.5	1.0	170
33	1.0	0.25	1.0	162
34	1.0	0.25	1.0	170
35	1.0	0.375	1.0	169
36	1.0	0.375	1.0	167

Experimental results

Varying pipe length affected the total number of pulses for a given a given length of a collision segment (Fig 3, runs 25–28). The total number of pulses increased only in channel 1, tending to increase more for the longer (1.0 m) pipe. Maximum total number of pulses for the 0.5 m length of pipe was similar to the minimum values for the 1.0 m length of pipe. The length of the steel pipe likely influences the distance of transmitted sound due to particle collision, but in this experiment the length of the pipe did not have a sizeable influence on the total number of pulses.

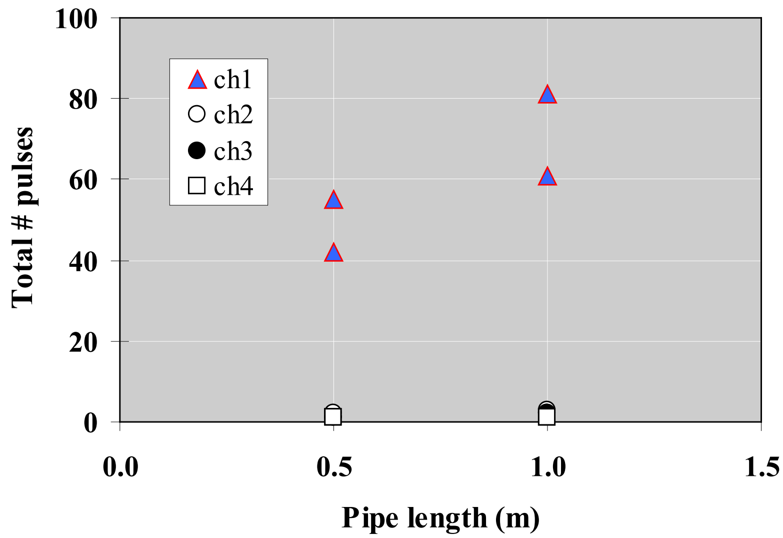

Figure 3. Variation of total number of pulses with pipe length.

Varying collision portion length affected the total number of pulses for a given a given pipe length (Fig 4, runs 29–36). Very few pulses were observed for channels 3 and 4; these were omitted. For the lowest-sensitivity channel 1, the number of pulses increased as collision portion length increased from 0.3 to 0.5 m due to the increase in the number of colliding particles. However, when collision portion length was increased to 1.0 m, the number of pulses decreased. This may be attributed to the fact that too many collisions were generated as bedload discharge increased (see henceforth effect of sediment discharge).

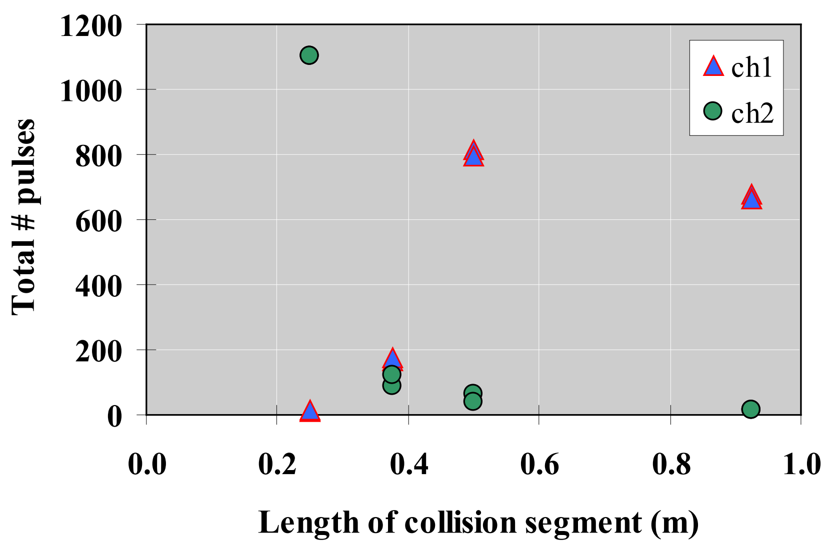

Figure 4. Variation of total number of pulses with length of collision pipe-element.

An opposite trend, where the number of pulses increases as the length of the collision segment decreases, was recorded by the higher-sensitivity channel 2. Hence when bedload discharge is high, the number of pulses can be counted when the length of the collision portion is sufficiently small, thereby reducing the number of collisions. This implies that it should be possible to monitor the number of pulses even under conditions of very high bedload discharge, among others by reducing the length of the collision segment.

VARIATION OF NUMBER OF PULSES WITH LOCATION OF BEDLOAD COLLISION

Experimental conditions

In this experiment we observed changes in the number of pulses by varying the location on the pipe where collision takes place. The experiment used an L-type pipe 1.0 m in length and flume width was 10 cm. The location of particle collision was on the tip, center or root segments of a steel pipe, the length of which was equal to flume width. Sediment grain-size was 2, 4, or 8 mm and water discharge was 3.0 ℓ/s: for 16 mm grain-size water discharge was 5.0 ℓ/s. The total volume of transported sediment was 3.0 ℓ and amplifier magnification was 5 (Table 3).

Table 3. Experimental conditions: location of collisions.

run	collision on	grain size mm	slope	unit bedload discharge g/s m
1	tip	2	1/50	191
2	tip	4	1/50	170
3	tip	4	1/50	147
4	tip	8	1/50	98.0
5	tip	8	1/50	79.8
6	center	2	1/50	208
7	center	4	1/50	154
8	center	4	1/50	152
9	center	8	1/50	80.3
10	center	8	1/50	86.1
11	root	2	1/50	217
12	root	4	1/50	155
13	root	4	1/50	154
14	root	8	1/50	74.0
15	root	8	1/50	75.7
37	tip	16	1/20	862
38	tip	16	1/20	809
39	center	16	1/20	702
40	center	16	1/20	745
41	root	16	1/20	723
42	root	16	1/20	900

Experimental results

The effect of the location of collision for varying bedload grain-size on number of pulses is shown in Figure 5. For the finest sediment (2.0 mm) all channels except 4 were insufficiently sensitive to record but few pulses, though channel 3 shows a tendency for number of pulses to increase toward the root, the part of the pipe where the microphone was placed. The number of pulses was lowest at the center and highest at the root for channel 4 (Fig. 5a). It is apparent that the small mass of these fine-grained particles was insufficient to generate pulses in the low-sensitivity channels except near the root. Using a grain-size of 4 mm, the number of detected pulses was negligible for the least sensitive channel 1. The maximum number of pulses occurred at the tip (channel 2) or for more sensitive channels 3, 4 at the center (Fig. 5b). The use of channels to obtain the number of pulses based on the location of collision is complex for this relatively fine sediment.

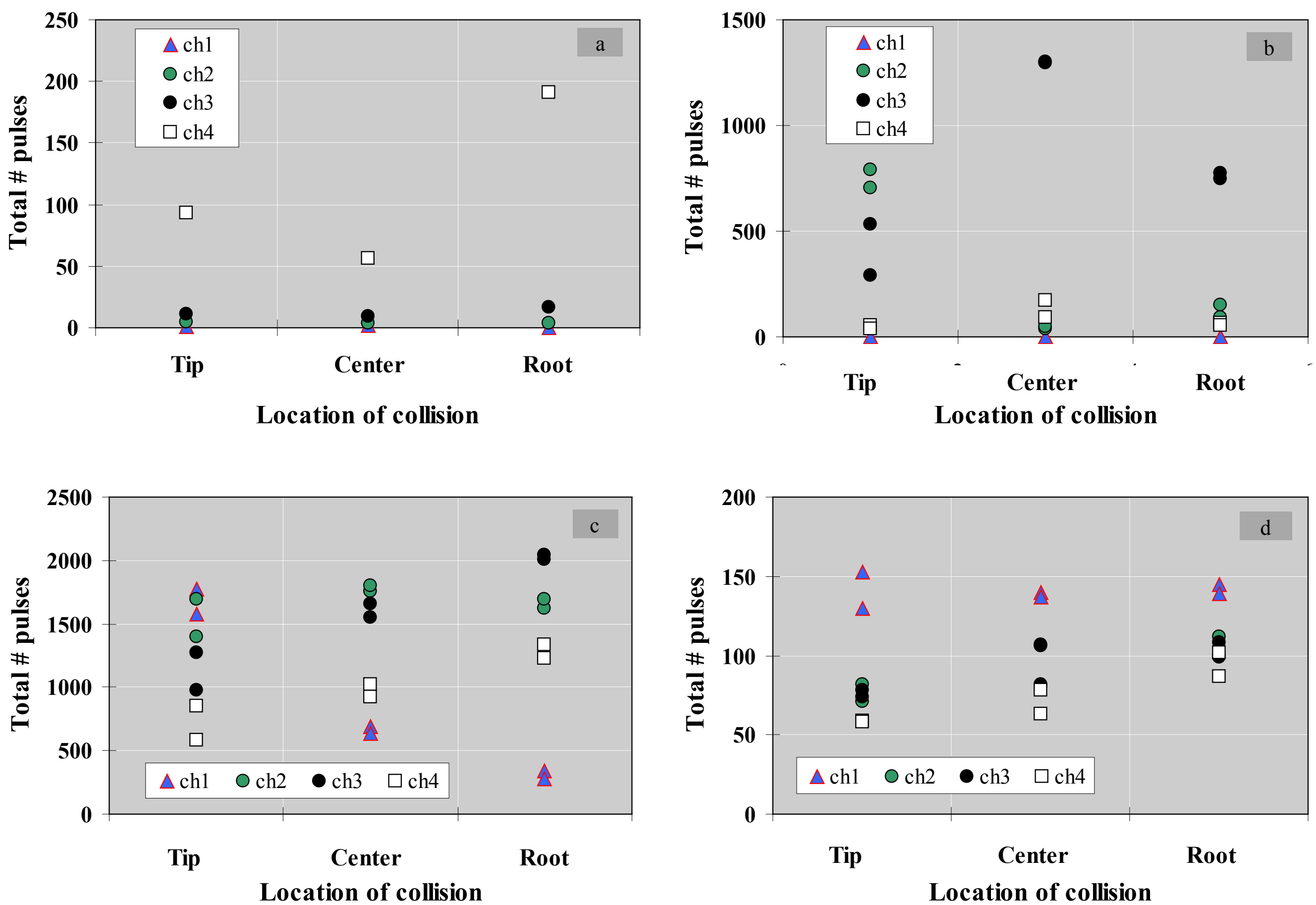

Figure 5. Variation of total number of pulses with location of collision for varying grain-size: 2 mm (a); 4 mm (b); 8 mm (c); and 16 mm (d).

Coarser-grained sedimentary particles have a larger mass and therefore detection of their collision on the pipe is easier. The number of pulses increased root wards (channels 3, 4) or tended to increase toward the root (channel 3), but for the least sensitive channel 1 it decreased towards the root for 8-mm sediment (Fig. 5c). Similarly, for 16 mm sediment the number of pulses tended to increase toward the root also when using 16 mm sediment (Fig 5d), varying only slightly for channel 1. This lack of variation may be related to microphone sensitivity and the characteristics of the pipe, such as its natural period.

In summary, it appears that for coarse-grained (> 8 mm) bedload the number of pulses may be about twice larger for the root in comparison with the tip. Thus, calibration of a pipe-geophone also requires specification of the location (on a pipe) of the collision segment, which in a river would often be located centrally.

VARIATION OF NUMBER OF PULSES WITH MICROPHONE SENSITIVITY

Experimental conditions

In this experiment, we observed changes in the number of pulses by varying the sensitivity of the microphone, using an uncovered microphone at one end of a U-type pipe and a microphone covered by a filter installed at the other end of the U-type pipe. The length of the centrally-located pipe segment on which particles collided was 10 cm (Photograph 2). The flume width was 10 cm and slope ranged between 1/50 to 1/13 (2.0–7.5%). Both 4 and 8-mm particles were used in these runs, the volume of sediment was 6.0 ℓ and amplifier magnification was 3 (Table 4).

Table 4. Experimental conditions: microphone sensitivity.
'High' – no cover over microphone; 'Low' – microphone with cover.

run	sensitivity	slope	grain size mm	unit bedload discharge g/s m
43	High	1/20	4	1030
44	High	1/20	4	867
45	Low	1/20	8	964
46	High	1/50	8	40.3
47	High	1/50	8	51.5
48	Low	1/33	8	70.2
49	Low	1/33	8	295
50	Low	1/33	8	235
51	High	1/33	4	376
52	High	1/33	4	380
53	High	1/13	4	2330
54	High	1/13	4	2330

Experimental results

The variation of number of pulses was almost identical for channels 3 and 4 (for a 4 mm grain-size): the maximum number of pulses was recorded on channel 2 without a filter and on channel 3 with filter (Fig 6a). The number of pulses in the high-sensitivity channel was higher in the microphone with filter due to decrease of its sensitivity. For high bedload discharge (runs 43, 44), the number of pulses could be identified only by deploying a filter. However, use of the filter to decrease microphone sensitivity was insufficient for detection of pulses when bedload discharge was highest (runs 53, 54).

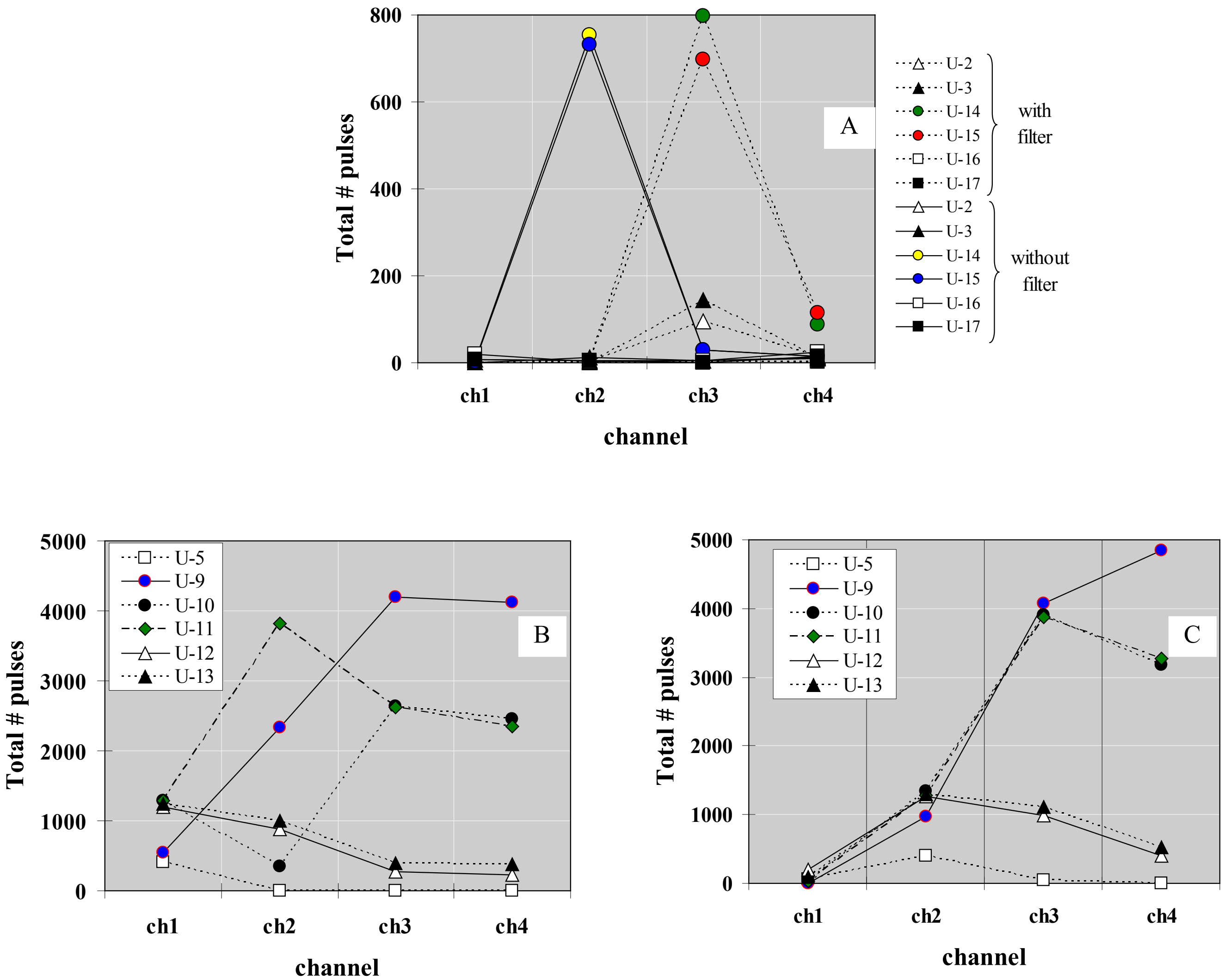

Figure 6. Variation of total number of pulses with microphone sensitivity for varying grain-size: 4 mm (A), 8 mm without filter (B) and 8 mm with filter (C).

For a grain-size of 8 mm, the filter increased the number of identified pulses in runs 45, 49 and 50 (Figs. 6b, 6c). The response for 8 mm grain-size with filter was more straightforward than for the uncovered microphone: number of pulses increased with channel sensitivity (except for channel 4, the most sensitive), but it was also governed by bedload discharge (Fig 6c). Installation of the filter increased the number of pulses in high sensitivity channels. In runs 46, 47, and 48, which had the lowest bedload discharges, the number of pulses at each channel did not depend on microphone sensitivity. These results indicate that reducing microphone sensitivity allows identification of pulses also when bedload discharge is high. However, because sensitivity must be reduced as discharge increases, other means in addition to the decrease of microphone sensitivity are required to monitor very high bedload discharges.

VARIATION OF NUMBER OF PULSES WITH BEDLOAD DISCHARGE

Experimental conditions

In this experiment we observed changes in the number of pulses by varying bedload discharge. The flume widths were either 10 cm or 30 cm with constant slope using both L-type as well as U-type pipes. The segment where particle collisions took place was centrally located and its length remained 0.1 m in all the runs. Flume inclination was 1/16.6 (6.0%), amplifier magnification index was 3 and grain size was 8 mm (Table 5).

Table 5. Experimental conditions: bedload discharge.

run	water discharge	channel width	unit bedload discharge
	ℓ/s	m	g/s m
16	2	0.1	909
17	2	0.1	795
18	2	0.1	830
19	2	0.1	994
20	2	0.1	1080
21	2	0.1	1070
22	2	0.1	1110
23	4	0.3	1140
24	4	0.3	1150
25	4	0.3	1310
26	4	0.3	1240

Experimental results

The total number of pulses *decreases* with increase in bedload discharge using an L-type pipe, as is shown for the least sensitive channel 1 (Fig 7a). The number of recorded pulses was very low in the more sensitive channels at this range of bedload discharge. It is likely that the level of sound collision was above the set threshold, resulting in an inability to count pulses in the more sensitive channels also at the lowest bedload discharge used in this run. The same effects were documented in the run using the U-type pipe without a filter (Fig 7b).

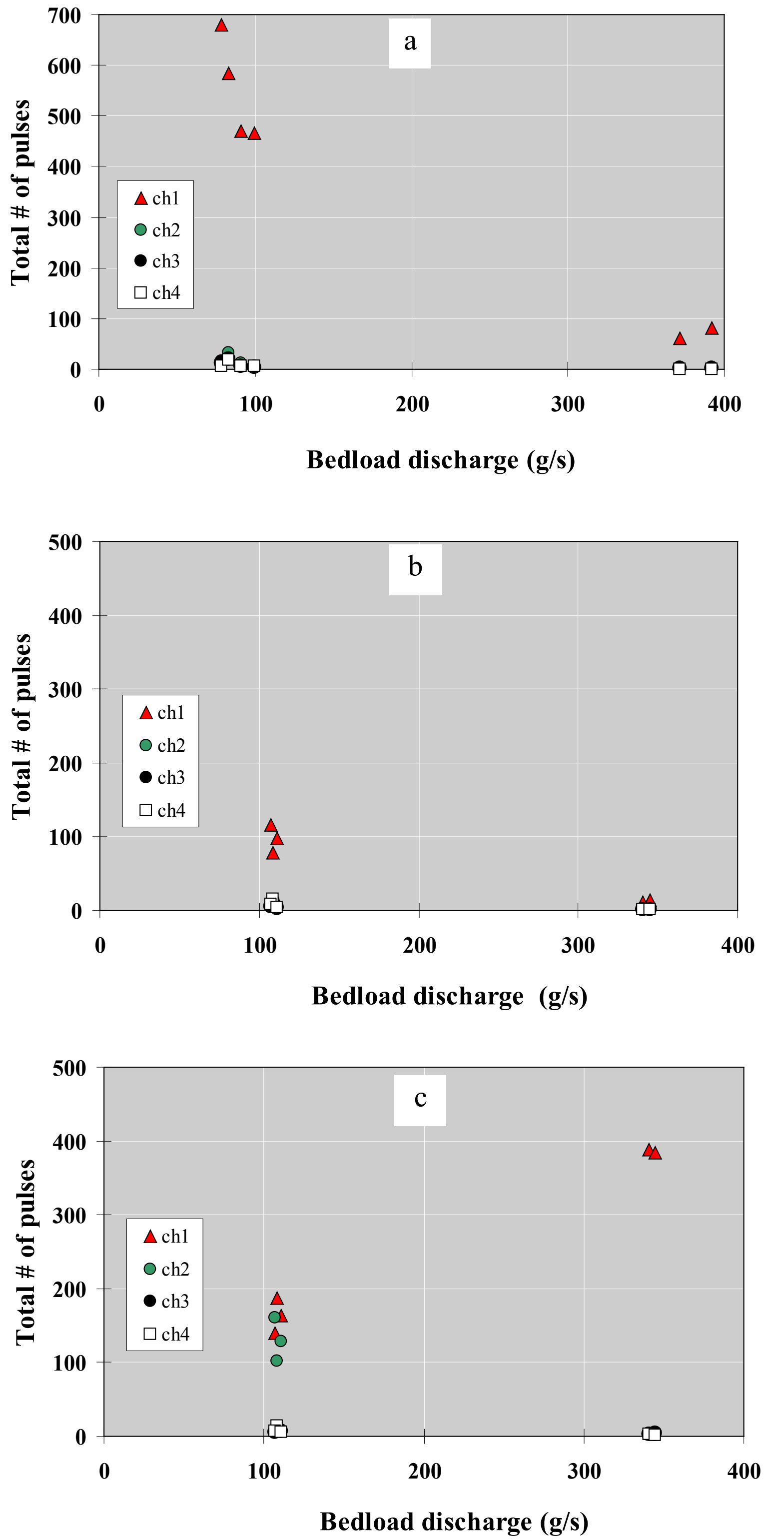

Figure 7. Variation of total number of pulses with bedload discharge using an L-type pipe (a); U-type pipe without filter (b) and U-type pipe with filter (c).

The total number of pulses increased with increase in bedload discharge using a U-type pipe with a filter (Fig 7c). The number of pulses increased by a factor of 2.35 (using magnification to arithmetical averages of the number of pulses in each case). The contemporaneous increase in bedload discharge was by a factor of 3.1. In channel 2 the total number of pulses decreased with an increase in bedload discharge; the total number of pulses did not vary in other channels (Fig. 7c). The tendency observed in channel 2 was likely the same as that when no filter was used (Fig 7a).

These results indicate that the number of pulses will decrease when bedload discharge is high unless microphone sensitivity is adjusted (e.g., by using a filter). Furthermore, when microphone sensitivity is indeed adjusted, a high correlation appears between total number of pulses and bedload discharge, suggesting that it is possible to quantitatively monitor bedload discharge by using a geophone.

VARIATION OF NUMBER OF PULSES WITH BEDLOAD GRAIN-SIZE

Experimental conditions

In this experiment we observed changes in the number of pulses by varying bedload grain-size. The flume width was 10 cm, and this flume experiment used an L-type pipe 1.0 m long. The length of the portion of pipe on which particles collided was constant throughout this experiment. Runs were separately undertaken for the tip, center and root sections of the pipe. Flume inclination was 1/50 (2.0%), discharge was 3.0 ℓ/s, total sediment volume was 3.0 ℓ, amplifier magnification index was 5, and the experiment used three bedload grain-sizes: 2, 4, and 8 mm (Table 6).

Table 6. Experimental conditions: bedload grain-size.

run	grain size	collision on	unit bedload discharge
	mm		g/s m
1	2	tip	190
2	4	tip	170
3	4	tip	147
4	8	tip	98.4
5	8	tip	79.8
6	2	center	208
7	4	center	154
8	4	center	152
9	8	center	80.3
10	8	center	86.1
11	2	root	217
12	4	root	155
13	4	root	154
14	8	root	74.0
15	8	root	75.7

Experimental results

For 2.0-mm grain-size the total number of pulses was altogether very low and did not vary substantially with location of microphone in the pipe - including the most sensitive channel 4 (Fig 8). This lack of response likely occurred because (1) channel sensitivities were low in comparison with the sound of collision, and (2) the sound of collisions was weak in comparison with that of the flow.

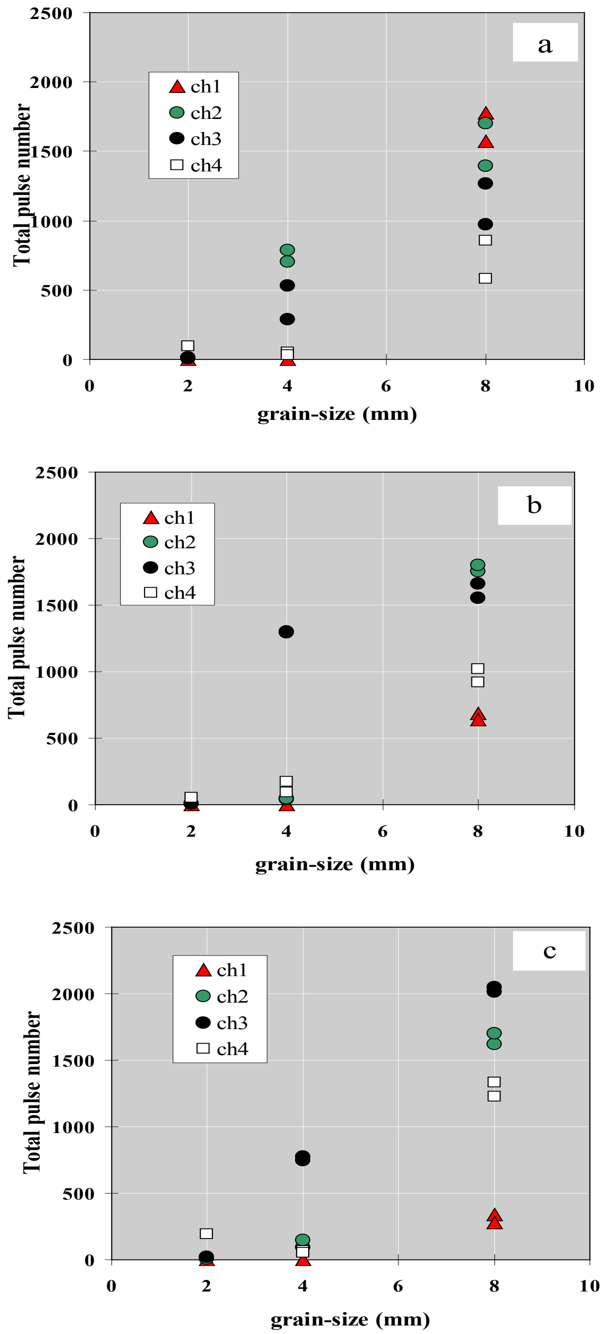

Figure 8. Variation of total number of pulses with bedload grain-size for the tip (a), center (b) and root (d).

For particle size 4.0 mm, channel 3 produced a reasonable response, recording a larger number of pulses in the center relative to the tip, though the number decreased instead of increasing for the root (Fig 8). Bedload discharge was too high to record pulses in the highest sensitivity channel 4, likely caused by reverberant sound or vibration of the metallic tube. In fact, pulse identification is possible when the sound collisions are lower than the threshold value, such that under conditions of high sensitivity these sounds remain detectable. Therefore, it is likely that under this condition, the collision sound level was above the set threshold, resulting in the inability to count pulses. It was also almost impossible to detect pulse at the lowest sensitivity in channel 1 (Figs 8 a-c)

For a grain size of 8.0 mm, the number of pulses increased with increase in channel sensitivity for each of the locations of the microphone (Fig 8a-c). This was the largest particle size with a lower bedload discharge in comparison with the other three runs.

The results of this experiment demonstrate that the pipe hydrophone system has a lower threshold of detecting bedload grain-size. For the pipe used in these experiments this lower threshold in 8 mm.

CONCLUSIONS

The objective of this study was to determine which geophone characteristics affect the extent to which bedload flux and ultimately bedload texture can be determined by surrogate bedload monitoring using a Japanese pipe geophone. The experiments have shown the following effects:

1. The length of the segment of pipe where collisions are recorded affects the number of pulses more than the length of the pipe.
2. Location (tip, center or root) where collisions are recorded affects the number of recorded collisions, increasing towards the root.
3. Lowering microphone sensitivity allows recording at higher bedload discharges.
4. Monitoring of high bedload discharge requires the use of lower channel sensitivity.
5. Bedload discharge of varying grain-size can be monitored by the Japanese pipe-geoophone. However, this acoustic system has a lower truncation grain-size threshold of detection; with the pipe characteristics used in these flume runs, the lower threshold is 8 mm.

Based on the geophone characteristic discussed above, it is likely that bedload monitoring may be improved by using (1) lower (than hitherto used) sensitivity channels in conjunction with still higher sensitivity channels; (2) shortening the length of the pipe portion on which particles collide; and (3) decreasing microphone sensitivity.

Further planned research is scheduled to include constructing a geophone monitoring system that may deal with higher bedload discharges: this will include changes to the construction of the pipe and microphone as well as, a variety of electronic amplification and signal filtering. Indeed, advanced signal processing may turn out to considerably embetter such a system as ours for the continuous and automatic surrogate monitoring of bedload.

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