Experimental and theoretical tools for estimating bedload transport using a Japanese pipe hydrophone

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A Japanese pipe hydrophone is an acoustic sensor that is widely used in Japan to measure bedload transport. Here we report experimental and theoretical tools for calculating bedload transport using a Japanese pipe hydrophone, and discuss the limitations based on laboratory tests. We found a linear relationship between the momentum of colliding particles and the maximum amplitude of the acoustic wave, and found that the grain size can be calculated using this linear relationship. We determined the range over which this linear relationship holds, and found that it depended on the amplifier gain; we then used it to calculate the maximum flow depth. The median frequency and the form of the frequency distribution of the acoustic wave depended on the grain size, slightly on the flow discharge. The bedload transport rate can be calculated using the velocity of the bedload and the sediment volume in the bedload layer using the linear relationship between the momentum of the colliding particles and the maximum amplitude of the acoustic wave.

Key words: bedload, flume tests, Japanese pipe hydrophone, laboratory tests

1. INTRODUCTION

The bedload is the part of the total sediment load that is transported by rolling, saltation, or sliding on a streambed [e.g., ASTM International, 1998]. It is significant in determining the morphology of river channels [e.g., Gomez et al., 2006], and monitoring and measuring bedload transport rates and grain sizes is necessary for comprehensive management of sediment transport from mountain streams to river mouths.

Preliminary bedload monitoring and measurement has been carried out since the 1900s, and measurement systems have been attempted at calibrations using a bedload sampler, which traps bedload directly from near the riverbed since early 1930s [e.g., Gray et al., 2010]. In Japan, bedload monitoring and measuring began in the late 1950s, and has been carried out mainly based on the methods proposed by the United States Geological Survey (USGS). We may measure the bedload directly using those methods; however, they are limited in the bedload volume that can be captured.

Methods of monitoring and measuring bedload in Japan were reviewed and summarized in the 1970s [Study Group of Sediment Measurement Techniques, 1971]. Some methods were proposed, including direct and indirect techniques. The Japanese pipe hydrophone is an acoustic sensor that can be used as part of an indirect measurement of bedload transport. It is advantageous compared with indirect measurements using supersonic sensors and radar, because it is difficult to discriminate the bedload signal from noise in these techniques.

In Switzerland, indirect measurements have been carried out using the vertical component obtained using an accelerometer (geophone) and sampler since the 1980s [Rickenmann, 1997; 1998; Rickenmann et al., 2007; 2012; 2013].

The Japanese pipe hydrophone uses the acoustic wave generated when sediment particles collide with the pipe to calculate the bedload transport rate.
The number of colliding sediment particles can be extracted from the acoustic wave. The technique can be calibrated using a known number of colliding sediment particles, and the weight of the transported bedload can be measured using a Reid-type slot sampler [Reid et al., 1980; Mizuyama et al., 2010]. This method cannot be used to characterize the grain size of the sediment particles. Instead, an empirical approach based on the number of colliding sediment particles is used to calculate the bedload transport rate. However, a theoretical approach is necessary to calculate the bedload transport rate and grain size of colliding sediment particles.

The bedload transport rate per unit width is defined as the product of the sediment volume per unit area in the bedload layer and the mean velocity of the bedload layer. The volume of the bedload can be calculated using the grain size and the number of colliding sediment particles. When measuring the bedload using a Japanese pipe hydrophone, information about the grain size and the velocity of the colliding particles is important to calculate the bedload transport rate.

When the grain size of the colliding sediment particles is calculated using the measured acoustic wave from the Japanese pipe hydrophone, it is necessary to use a correlation between the velocity of the colliding sediment particles and some characteristics of the signal. Parameters describing sediment particles movements include the momentum and kinetic energy of the sediment particles, and the characteristics of the acoustic wave include the maximum, minimum, or integrated amplitude. If the correlation between the momentum of the sediment particles and maximum amplitude is linear, the momentum can be inferred. The size of the colliding particles can be calculated from the momentum and the velocity of the sediment particles. Additionally, it is necessary to determine the threshold for the linear relationship, which represents a limitation of a Japanese pipe hydrophone, as well as a method to control this threshold.

Taniguchi et al. [1992] demonstrated experimentally a linear relationship between the momentum of colliding sediment particles and the maximum amplitude of the acoustic wave, and reported a good correlation between the circumferential components of the acoustic wave and the momentum, and were able to account for errors due to the distribution of the collision angle. They used a different microphone and amplifier from that used here, so we needed to characterize a similar linear relationship. We may expect a threshold for the linear relationship, but in 1992, no implement existed that could record the large amounts of data with a sufficiently high sampling rate in the field required to obtain the maximum amplitude of the acoustic wave. The most common method used to estimate bedload transport rate is involves calibration between the number of colliding sediment particles and the bedload weight using a sampler. As a result, few data are available to support the linear relationship, the threshold, or other limitations, such as the maximum flow depth. Recently, an implement was developed that can record large amounts of high data rate information from field measurements. The bedload transport rate and the grain size of the colliding sediment particles can be calculated using the linear relationship.

Here, experimental data were collected via laboratory tests involving stainless steel and nylon balls in air to obtain a linear relationship between the momentum of the colliding particles and the maximum amplitude of the acoustic wave. Here, we describe a method for calculating the grain size of sediment particles using this linear relationship. We also describe a method for calculating the limitations of the Japanese pipe hydrophone method, based on the threshold of the linear relationship and the theory of sediment hydraulics. We experimentally determined the effects of the amplifier gain on the threshold, and used the findings to control the limitations of the Japanese pipe hydrophone method. Here, we discuss experimental and theoretical tools for calculating the bedload transport rate using a Japanese pipe hydrophone based on the dependence of the grain size on the median frequency and the distribution of the maximum amplitude from flume tests.

2. JAPANESE PIPE HYDROPHONE SYSTEM

2.1 Eigenfrequencies in a pipe dut to sound pressure

The Japanese pipe hydrophone is typically installed across a riverbed on concrete (e.g., the spillway of a check dam). It consists of a stainless steel pipe that is 48.6 mm in diameter, 3 mm thick, and typically 2 m long. The amplitude of the oscillations generated by collisions of sediment particles onto the pipe is measured using a microphone attached to the end of the pipe.

Collisions between sediment particles and the pipe result in circumferential, radial, and axial components of sound pressure in a closed pipe. The
frequencies of the circumferential 1st mode $f_{10}$ as well as the radial $f_{01}$ and axial $f_z$ 1st modes are shown in Fig. 1. These can be represented as:

$$f_{10} = 0.298c/a,$$  \hspace{1cm} (1)

$$f_{01} = 0.61c/a$$  \hspace{1cm} (2)

and:

$$f_z = c/(2l).$$  \hspace{1cm} (3)

where $c$ is the speed of sound in air, $a$ is the radius, and $l$ is the length of the pipe. The coefficients in Eqs. (1) and (2) were theoretically derived for eigenfrequencies of the 1st mode [Blevins, 1979]. Equation (3) describes the eigenfrequency of the fundamental mode of the axial component in a closed pipe, as shown in Fig. 1.

Taniguchi et al. [1992] demonstrated the existence of a linear relationship between the momentum $M$ of the colliding sediment particle and the maximum amplitude $M_A$ of the eigenfrequency of the circumferential component. The amplitude of the oscillations in the 1st mode of circumferential component is almost independent of the location on the surface of the pipe of the colliding particle.

2.2 Specifications of the hydrophone system

Table 1 lists the properties of the Japanese pipe hydrophone system. This system is made by Hydrotec Co., Ltd. and has been widely used in Japan. We determined the effects of amplifier gain on the threshold using two amplifiers. The amplifier gain of the original system was 200, and the gain of the modified amplifier was 20.

The acoustic wave was sampled at 96 kHz using a Sony IC recorder. The amplitude at the eigenfrequencies of the circumferential components in the range 3.5–6.5 kHz was determined using Fourier transform processing, and the envelope was calculated from the acoustic wave following Fourier decomposition. The peaks of the envelope, i.e., the maximum amplitude of the eigenfrequency of circumferential mode, were detected using the Savitky–Golay method [Savitky and Golay, 1964].

3. LABORATORY TESTS

3.1 Acoustic wave due to colliding particles

Laboratory tests were carried out in air to obtain the relationship between $M$ and $M_A$. A Japanese pipe hydrophone was fixed on a concrete plate with clamps at both end of the pipe, as shown in Fig. 2. Stainless steel or nylon balls were allowed to roll down the 45 degrees slope and collide with the surface of the Japanese pipe hydrophone. Because $M_A$ is independent of the collision location [Taniguchi et al., 1992], the balls impinged 50 cm from the microphone. The impact velocity was analyzed using a high-speed camera, which was installed with the optical axis normal to the trajectory of the balls. The momentum of the colliding particles was calculated from the mass of each ball and the impact velocity.

3.2 Flume tests

Flume tests were carried out to obtain the frequency distribution of $M_A$ for each grain size and each flow discharge rate. The tests were carried out using the channel in Nippon Koei Co., Ltd., as shown in Fig. 3. This system was a fixed bed that was 0.8 m wide, 20 m long, and had a gradient of 1.5 degrees. The Japanese pipe hydrophone was installed 3.8 m from the downstream end of the}
channel, as shown in Fig. 4. This location was chosen to avoid secondary collisions with the bedload caused by the wake. Water discharge was measured using an electromagnetic flow meter (AXF-200G). The flow depth and velocity of the sediment particles were analyzed using a camera installed 4.0 m from the downstream end of the channel. Sediment was supplied 15.8 m from the downstream end of the channel. Table 2 lists the experimental conditions for the flume tests. Grain diameters were uniform, and were set at 3.32 mm, 11.8 mm, and 32.7 mm. Water discharge rates were set at 45 l/s, 60 l/s, 90 l/s, and 120 l/s.

![Fig. 3 The flume](image)

**Fig. 4 Installation of the pipe hydrophone in the flume**

4. RESULTS AND DISCUSSION

4.1 Linear relationship between M and MA

Fig. 5 shows the relationship between M and MA, which was linear for $0.04 < M < 30\ gms^{-1}$. Within this regime, the grain size of the bedload can be calculated, i.e., the value of M can be inferred from the velocity of collisional sediment particle and the measured value of MA, as shown in Fig. 5.

Let $M_{\text{min}}$ be the minimum detectable momentum of particles using the Japanese pipe hydrophone. The detectable grain size of the bedload can be calculated from the linear relationship. Mizuyama et al. [2010] showed experimentally using flume tests that the smallest sediment particle that could be detected was 4 mm in diameter.

Let $M_{\text{max}}$ describe the maximum momentum of particles that can be detected using the Japanese pipe hydrophone. This was limited by the maximum flow discharge rate and by the characteristics of the amplifier, as will be discussed in section 4.3.

![Fig. 5 Relationship between the momentum of the colliding particles, M, and the maximum amplitude of the circumferential mode, MA](image)

<table>
<thead>
<tr>
<th>Run</th>
<th>Flow discharge rate $Q$ (l/s)</th>
<th>Flow depth $h_t$ (mm)</th>
<th>Grain size $d$ (mm)</th>
<th>$h_t/d$</th>
<th>Critical shear velocity $u_*$ (m/s)</th>
<th>Dimensionless shear stress $\tau_*$</th>
<th>Flux sediment concentration $c_f$</th>
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4.2 Threshold of the linear relationship

The method used to calculate the threshold is as follows. There exists a critical shear velocity between the grain size of the bedload and the flow depth. This critical shear velocity leads to the flow discharge rate depending on the flow resistance.

The maximum momentum $M_{\text{max}}$ can be expressed as:

$$mu_s = M_{\text{max}}$$

where $m$ is the mass of a bedload sediment particle and $u_s$ is the velocity. From Fig. 5, we find $M_{\text{max}} = 30 \text{ gms}^{-1}$. The velocity of the sediment particle can be expressed as the averaged velocity in the bedload layer. The average velocity in the bedload is a function of $(u^* - u_c^*)$ [e.g., Simons and Snetürk, 1992] or $u^{1.5}$ [Egasira and Itoh, 2006]. It can be calculated as follows [Ashida and Michiue, 1973]:

$$\frac{u_s}{u_c^*} = A_r (1 - u_c^*/u_s)$$

Egashira et al. [1997] reported a similar expression, i.e.:

$$\frac{u_s}{u_c^*} = \frac{K_f K_s}{15} \frac{\tau_s}{f_f}$$

The terms in Eqs. (5) and (6) are defined as follows:

$$u_{c, \text{max}} = u_c^* + \frac{6}{(\sigma - \rho) \pi d^3} \frac{M_{\text{max}}}{A_r}$$

$$u_{c, \text{max}} = \left( \frac{M_{\text{max}}}{A_r} \frac{6 g}{\pi \rho K_s d^2} \right)^{1/3}$$

$$K_1 = \frac{1}{\cos \theta \tan \phi_s - \tan \theta}$$

$$K_2 = \frac{1}{c_s \left[ 1 - \frac{h_s}{h_f} \right]^{1/2}}$$

$$K_3 = \frac{4}{15} \frac{K_f K_s}{\sqrt{f_d + f_f}}$$

$$f_f = k_f (1 - c_s) \left( \frac{1}{\sigma / \rho} \right)^{1/3}$$

and:

$$\frac{h}{h_s} = \left( \frac{\sigma / \rho - 1}{c_s} \tan \phi_s - \tan \theta \right)$$

where $u_{c, \text{max}}$ is the maximum critical shear velocity, $u_c^*$ is the critical shear velocity, $\bar{u}_s$ is the averaged velocity of sediment particle in the bedload layer, $\sigma$ is the mass density of sediment particles, $\rho$ is the mass density of water, $\pi$ is the circular constant, $d$ is the grain size of the bedload, $A_r$ ($= 8.5$) is the universal constant in logarithmic flow resistance, $g$ is the acceleration of gravity, $\theta$ is the gradient of the bed, $\phi_s$ is the internal friction angle of the sediment particles, $c_s$ is the volumetric sediment concentration in the bedload layer, $h_c$ is the thickness of the bedload layer, $h_f$ is the flow depth, and $k_f = 0.0828$ and $k_f = 0.16$ are empirical constants [Egashira et al., 1997].

Figure 6 shows the relationship between the flow depth and the grain size of the bedload. The gradient of the riverbed was 1.5 degrees and the width was 1 m. The figure shows the flow depth as a function of the grain size of the bedload assuming that $M = M_{\text{max}}$.

If the linear relationship and the threshold between $M$ and $M_{\text{MA}}$ are checked preliminarily, the maximum flow depth and maximum flow discharge can be calculated according to grain size of the bedload; however, we arrive at three different values from the three different models. The velocity of sediment particles was calculated using the formula proposed by Ashida and Michiue [1973], and was found to be proportional to the shear velocity.
The velocity calculated using the formula of Egashira et al. [1997] was proportional to $u^3$. In these two formulas, the velocity of sediment particles was calculated assuming that the velocity of a mixed flow was the same as that of the sediment particles. This value may be selected depending on the field conditions.

4.3 The effects of amplifier gain on threshold

It is necessary to control the measurement range for each set of conditions in the field, because a Japanese pipe hydrophone is a piece of observational equipment. The threshold value of the linear relationship between $M$ and $MA$ was 30 gms\(^{-1}\), but it depends on the characteristics of the amplifier. Here, we discuss the dependence of the threshold value on the amplifier gain.

Figure 7 shows the relationship between $M$ and $MA$ for different amplifier gains with a gain of 200 and one with a gain of 20. The threshold of the linear relationship between $M$ and $MA$ was 3 gms\(^{-1}\) with an amplifier gain of 200, and was 30 gms\(^{-1}\) with a gain of 20. However, the gradient of the relationship was the same. It follows that the amplifier gain affects the threshold of the linear relationship, but not the gradient.

4.4 Grain size dependence of the maximum amplitude of the acoustic wave

Figure 8 shows the frequency distribution in the flume tests for different grain sizes and discharge rates. The momentum of the colliding sediment particles was smaller than the threshold of the linear relationship between $M$ and $MA$. The maximum amplitude is shown using the rank of maximum amplitude of the acoustic wave due to the colliding sediment particles.

The median frequency distribution depends on the grain size, slightly on the flow discharge rate. The forms of frequency distribution were similar, and depended on the grain size. The effects of the collision angle on the frequency can be calculated exactly, and Taniguchi et al. [1992] demonstrated that the effects of collision angle were within the error of the flume tests for uniform sediment particles.

4.5 Bedload transport rate

In this section, we describe experimental and theoretical tools for calculating the bedload transport rate using a Japanese pipe hydrophone, together with preliminary calculations and flume test data. The bedload transport rate per unit width is defined as the product of the sediment volume in the bedload layer per area on the bed and the average velocity of the sediment particles in the bedload layer, i.e.:

$$q_s = \int_0^h c_s u_s dz \approx c_s h \overline{u}_s$$ \hspace{1em} (15)

where $c_s h$ is the sediment volume in the bedload layer per unit width and length.

The sediment concentration of the bedload layer is $c_s$ at the bed surface and zero at the upper boundary of the bedload layer. When we evaluate the bedload transport rate in the flow over the movable bed, $c_s$ is approximated as:

$$c_s = \frac{1}{2} c^*$$ \hspace{1em} (16)

where $c^*$ is the sediment concentration in the non-flowing layer.

The value of $c_s$ cannot be determined uniquely from the flow over a rigid bed, and may be difficult to measure directly.

The number of sediment particles can be calculated from the bedload transport rate and the average volume of the particles, i.e.:

$$N \approx \frac{c_s h \overline{u}_s}{v_s} = \frac{q_s}{v_s}$$ \hspace{1em} (17)

For convenience, the bedload transport rate is calculated as the product of the number of colliding sediment particles per unit time and the volume of the particles $v_s$, i.e.:

$$q_s = v_s \cdot N$$ \hspace{1em} (18)
particles, i.e.:

The density of the particles assuming spherical sediment volume can be calculated from the mass calculated using the average velocity of the field tests. This linear relationship gives the shown in formula s reported by Ashida and Michiue [1973] or Egashira et al. [1997]. The mass of the sediment particles can be obtained in advance using the acoustic wave. The mass of the sediment particles as a function of the maximum amplitude of the acoustic wave. The number of colliding sediment particles can be calculated using the formulas reported by Ashida and Michiue [1973] or Egashira et al. [1997]. The grain size and sediment volume can be calculated from the mass and the density of the particles assuming spherical particles, i.e.:

\[ \nu_s = \frac{\pi}{6} d^3 (\sigma - \rho) \]  

(19)

and:

\[ d = \left( \frac{M}{\pi \cdot \frac{1}{(\sigma - \rho) \cdot \bar{r}_s}} \right)^{\frac{1}{3}}, \]  

(20)

where \( M \) is the momentum of the colliding sediment particle.

The number of colliding sediment particles can be calculated from the acoustic wave. The bedload transport rate can be calculated from the product of the number of colliding particles per unit time and the volume of the particles. For uniform sediment, the grain size and bedload transport rate can be calculated as described above. For non-uniform sediment, it is possible to calculate the grain size and bedload transport rate using a similar calculation process. Because the median of the
frequency distribution depends on the grain size of the sediment, slightly on the flow discharge rate, each grain size can be evaluated independently for non-uniform sediment.

The bedload transport rate calculated using the Japanese pipe hydrophone may differ from the actual bedload transport rate. There are three reasons. First, some sediment particles may pass over the pipe due to saltation; this should be taken into account, and the number of colliding sediment particles may underestimate the total movement of sediment particles. Second, the acoustic wave from individual impacts of colliding particles may merge when many sediment particles collide with the pipe in a short period of time. In principle this may be compensated for by defining an interference rate as the number of countable sediment particles to the total number of sediment particles. This rate depends on the characteristics of the acoustic measurement equipment. Third, there is a limit for detecting sediment particles, as described in section 4.2, which occurs due to the flow rate and grain size. This limit can be characterized by the rate of the number of detected sediment particles to the number of total sediment particles. Because it is difficult to separate these three factors, we obtained information for the macroscopic detection rate from flume or field tests to calculate the total bedload transport rate.

Table 2 lists the hydraulic conditions for the calculation. The number of sediment particles was calculated from the acoustic wave. The volume of sediment particles was calculated from the grain size. The average velocity of sediment particles was determined from the high-speed video camera used during the flume tests.

Figure 9 shows the relationship between the average velocity of the sediment particles and dimensionless shear stress:

\[ \tau_* = \frac{u_*^2}{(\sigma/\rho - 1)gd}. \] (21)

The average velocity of sediment particles was greater than the results of Eqs. (5) and (6), because the data were obtained from the flow over a rigid bed. The flow conditions were a small relative flow depth, which was in the range 0.1 < h/d < 1. It was difficult to compare directly the experimental data and the theoretical result, especially for large sediment particles with 1.0 < h/d < 2.0 and critical condition of bedload movement. Itoh et al. [2001] reported values calculated using Eqs. (5) and (6) and experimental data which were obtained for flow over a movable bed. The experimental data shown in Fig. 9 increased as a function of \( \tau_* \), and the gradient was similar to that calculated using Eq. (5). When \( \tau_* \) was larger than the criterion for sediment movement in the flow over the movable bed, the experimental data were similar to the results of Eq. (5). If \( \tau_* \) becomes the criterion for sediment movement in the flow over the movable bed, and the value takes \( \tau_* = 0.05 \). If the velocity of sediment particle increased by 10 times, the calculated grain size increased by a factor of 2.

Figure 10 compares the bedload transport rate calculated using Eq. (18) and the supplied bedload transport rate. The agreement was dependent on the grain size, and a correlation for each grain size was uniquely determined.

Figure 11 shows the estimated bedload transport rate calculated using Eq. (18) as a function of the dimensionless shear stress, \( \tau_* \). Here, we define the ratio of the calculated bedload transport to the supply of sediment particles, k. With a grain size of 3.32 mm, the calculated data were in

![Fig. 9 Relationship between the average velocity of sediment particles and dimensionless shear stress](image)

![Fig. 10 Comparison between estimated bedload transport rate and supplied bedload transport rate](image)
good agreement with the supplied bedload transport. If \( \tau^* < 0.05 \), \( k \) is approximately constant, whereas if \( \tau^* > 0.05 \), then \( k \) depends on \( \tau^* \). The form of the dependence of \( k \) on \( \tau^* \) can be expressed as follows:

\[
k \approx 10 \quad ( \tau^* < 0.05 )
\]

(22)

\[
k = 0.025 \left( \frac{1}{\tau^*} \right)^2 \quad (0.05 < \tau^* < 0.2)
\]

(23)

Figure 11 shows the macroscopic detection rate, defined as the ratio of the calculated number of sediment particles to the supplied number of sediment particles. The difference between the data shown in Fig. 11 and those shown in Fig. 12 is that in Fig. 12 we have removed the influence of volume or the grain size. The macroscopic detection rate, which depends on \( \tau^* \), is not always required because the gradient of the coefficient \( k \) was almost equal to the gradient of the macroscopic detection rate.

The bedload transport rate was calculated as the product of the number of colliding sediment particles per unit time and the volume of the particles. For \( \tau^* < 0.05 \), the results calculated using Eq. (18) were almost 10 times larger than the supplied sediment transport rate. When \( \tau^* > 0.05 \), the result of Eq. (18) depended on the dimensionless shear stress, \( \tau^* \).

5. Conclusions

Here, we described an experimental approach for calculating grain size and bedload transport rate using a Japanese pipe hydrophone, and proposed a combined theoretical and experimental toolset for calculating the bedload transport rate using the measured acoustic wave.
The experimental and theoretical tools described here for characterizing the bedload transport rate focused on uniform sediment; however, these tools can also be applied to bedload with a non-uniform particle size. We plan to address this in future work.

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