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Bed-load discharge measurement by ADCP in actual rivers

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ABSTRACT: To overcome difficulty of bed-load discharge measurement, Yorozuya et al. (2009, 2010b) developed a bed-load discharge measurement system based on Acoustic Doppler Current Profiler (ADCP) and conducted it in an experimental flume. The authors applied the system in the actual river during medium flooding as well normal flow. The output of the system was compared with the conventional formula, which is commonly employed by Japanese engineers, as well as a sediment sampler. To compare the bed-load discharges from different methods, authors employed the bed-load velocity as agency for justification. As a result, authors indicated difficulty of conventional formula, since estimation of shear velocity is not easy. From this point of view, authors can concluded that the method presented in this paper has advantage, since most of the properties for estimation can be obtained by ADCP. Finally, the authors concluded the applicability of the current method as up to flat bed condition.

Keywords: Bed-load discharge, ADCP, Field measurements

1 INTRODUCTION

National institutes of Japan in hydraulics and hydrology have been engaged in the development of sediment-discharge measurement systems. Fixed-type systems have demonstrated their functions successfully. At the same time, they have shown some serious disadvantages, such as susceptibility to specific site conditions, immobility, and high cost. Mobile-type sediment samplers were used nationwide in the 1970s to measure bed-load discharge. However, observed results, especially those during large-scale flooding, were not accepted as appropriate (Yamamoto, K., and Nishio H., 1991) assumingly because of the landing condition of a sampler on a river bed or the heterogeneity of a river-bed form. In fact, field engineers have experienced different bed-load discharges by three or four orders of magnitude under similar hydraulic conditions. On the other hand, Dallas (1999) conducted field measurements with different sediment samplers, such as a Helley-Smith bed-load sampler and a Toutle-River-2 bed-load sampler (TR-2). He discussed about variances of obtained values with different parameters. He also presented different results with an order of 10^3 in similar hydraulic conditions.

Estimation of bed-load discharge rate was started by Du Boy in 1879; thereafter, many researchers have dedicated themselves to rate estimation studies (e.g., Howard Chang 1988). Since most prediction estimators are a function of shear stress, appropriate estimation of shear stress is considered to improve accuracy of estimating equations. Though shear stress can be easily defined in the experimental flume, that is not the case in actual rivers. In fact, Sime et al. (2007) conducted field measurements to compare shear velocities estimated based on water surface slopes and vertical velocity distributions obtained by acoustic Doppler current profilers (ADCP). Yorozuya et al. (2010a) also conducted an experimental study to make comparisons between shear velocities measured with ADCP and those based on water-surface slopes in unsteady flow conditions.

In any case, bed-load discharge, as well as shear velocity, cannot be easily defined in actual rivers. To overcome this difficulty, Yorozuya et al. (2009, 2010b) conducted experimental studies to examine the possibility of determination of bed-load discharge with ADCP. They developed an algorism for determining appropriate shear velocity while they indicated that bed-load discharge can change with an order of 10^2 in similar hydraulic conditions because of unsteady river-bed conditions. Based on this study, the authors confirmed the ambiguousness of traditional bed-load discharge values might be prevailed due to the authors' method. Thereafter, the authors conducted bed-load discharge measurements in actual rivers employing the exactly same system as the one tested in the experimental studies. The present paper introduces a brief explanation about the bed-load discharge measurement system, as well as one of the outputs from the field measurements.

2 METHOD

2.1 *Estimation of shear velocity*

Several different methods can be considered for determination of shear velocity (u_*). In this section, four types of shear velocity estimators are introduced.

The most traditional method is:

$$u_*(1) = \sqrt{ghI} \tag{1}$$

where g = gravitational acceleration, h = water depth, and I = water surface slope.

To estimate shear velocities based on ADCP-collected data, log-law with the entire data set is usually applied (Rennie, 2002; Sime et al, 2007). The equation is as follows:

$$u(z) = \frac{u_*}{\kappa}\ln(z) + \frac{u_*}{\kappa}\ln\left(\frac{30}{k_s}\right) \tag{2}$$

where $u(z)$ = velocity at the point of z, z = vertical elevation from the river bed, κ= von Karman constant, which is about 0.4, k_s = bed roughness. To obtain the values of shear velocity in Eq. (2), the authors selected curve fitting with natural log to determine a and b in the equation of $u(z) = a\ln(z) + b$. Then, a can be converted to u_*, which is namely $u_*(2)$.

On the other hand, Yorozuya et al. (2010a) pointed out the difficulty in the application of Eq. (2) from the entire data set when a bed form exists. Instead, they applied Eq. (2) from the river bed to the point where the local maximum exists, which is namely $u_*(3)$.

Additionally, Ashida and Michiue (1972) proposed the following equation for estimating effective shear velocity u_{*e}, which indicates that the equation is effective in terms of movement of sediment particle as follows:

$$\frac{U}{u_{*e}} = 6.0 + 5.75\log_{10}\frac{R}{d(1+2\tau_*)} \tag{3}$$

where U = vertical averaged velocity, u_{*e} = effective shear velocity, R = hydraulic radius. In this study, value τ_* is derived from $u_*(1)$, while U is obtained from ADCP, and d is employed from the observed value by the sediment sampler.

2.2 *Estimation of sediment discharge*

ADCP has a bottom trucking function to trace the movement of ADCP itself mainly for the navigation purposes. Conversely, it can measure the movement of river beds when ADCP is stationary. Rennie et al. (2002) was the first to apply this fun ction to measurement of bed-load discharge. Later, Yorozuya et al. (2009,2010b) introduced $u_*(3)$ and implemented the equation to determine thickness of bed-load layers, as proposed by Egashira et al. (2005). In this paper, the authors briefly describe the method as follows.

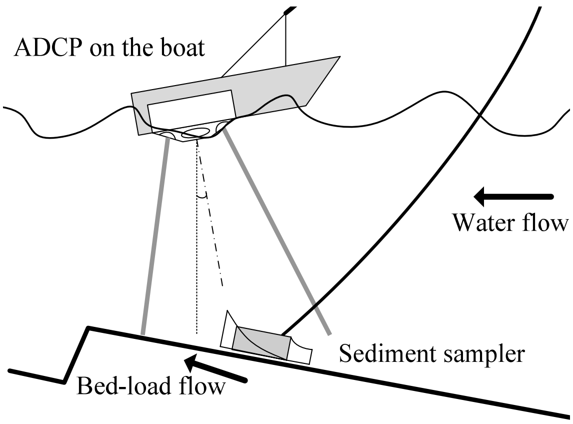

Figure 1 Conceptual figure of ADCP measurements and sediment sampler

The Bagnold type, a bed-load discharge estimator, translates bed-load into multiplication of sediment movement, thickness of bed-load layer, and sediment concentration of bed-load. Therefore, as Egashira et al. (2005) shows, it is defined as:

$$q_B = \int_0^{h_s} c \cdot u \cdot dz \cong v_s \cdot h_s \cdot c_s \tag{4}$$

where q_B = unit bed-load rate, c = sediment concentration, u = velocity of sediment, h_s = sediment layer. Also v_s = vertical averaged velocity of sediment, and c_s = vertical averaged sediment concentration. For taking advantage of

ADCP measurement, the authors assumed and applied the bed-load velocity as v_s ; even though velocity of sediment distributed. Additionally, the following equation for h_s from Egahisra et al (2005) was applied.

$$\frac{h_s}{d} = \frac{1}{c_s \cdot \cos\theta \cdot \left\{ \tan\phi_s / (1+\alpha) - \tan\theta \right\}} \tau_* \qquad (5)$$

where d = size of bed material, θ = bed slope, ϕ_s = internal friction angle, α = ratio of static and dynamic pressure, τ_* = non-dimensional shear stress. Based on Eq. (4) combined with Eq. (5), bed-load can be obtained. Note that most of the properties listed in the Eq. (4) and (5) can be obta ined by ADCP, which is the strongest part of this study, though Eq. (5) is an equation determined from for example Egahisra et al (2005).

Table 1. Setup of ADCP measurement

Measurement mode	WM1
Depth cell size	0.25 m
Number of Depth cell	59
Number of Water ping	5
Number of bottom ping	5

2.3 *Instruments*

Figure 1 shows a conceptual diagram of observation conducted by the authors. The figure illustrates two instruments, an ADCP on the boat and a sediment sampler on the river bed. Those instruments were tied with a wire or a rope to persons (or a carriage) on a bridge. Theoretically, the ADCP and the sediment sampler should observe the exactly same location. However, the ADCP measured the location about 10 m downstream from that of the sediment sampler for safety purposes. Detailed explanation about those two key instruments will be discussed in the following paragraphs.

The authors employed the Work Horse (WH)-ADCP with 1200 kHz manufactured by Teledyne RDI Instruments. Detailed setup information of the ADCP measurements are listed in Table 1. In addition, the Real Time Kinematic Global Positioning System (RTK-GPS) was employed, while Vector track an Speed over the Ground (VTG) information was also applied when the quality of RTK-GPS information was poor. Keeping the ADCP-mounted boat as stationary as possible (though movement of boat was kept tracking), the observation was conducted, especially for sediment movement. Actually, three daytime observations at a normal stage, as well as two 24-hours observations during flooding were conducted as one measurement (about 30 minutes) in a two hours in each, thereafter, total 80 measurements were obtained.

A sediment sampler, TR-2β, modified by the River Division of the National Institute for Land and Infrastructure Management (NILIM), the Ministry of Land, Infrastructure, Transport and Tourism of Japan, was employed for this study (For details, refer to Dallas, 1999). Major modifications by NILIM on the sampler are change of the nozzle expansion ratio from 1.4 to 1.0 for simple assembling and addition of weight on the nozzle to increase the angle of approach to the water surface. The authors also used a bag with a mesh size of 1 mm, since a sampler with a bag of 0.1 mm mesh caused clogging. Samplings with TR-2β were conducted two times within one ADCP measurement. Therefore, 160 points were obtained.

For measuring water-surface slopes, the authors employed six Cera Divers water gauges, as well as one for an atmospheric correction with an error range of 2 cm. They measured the water surface elevation at 5 minutes interval. In addition, six water gauges, three each in the left and right banks, were installed at 500 m intervals.

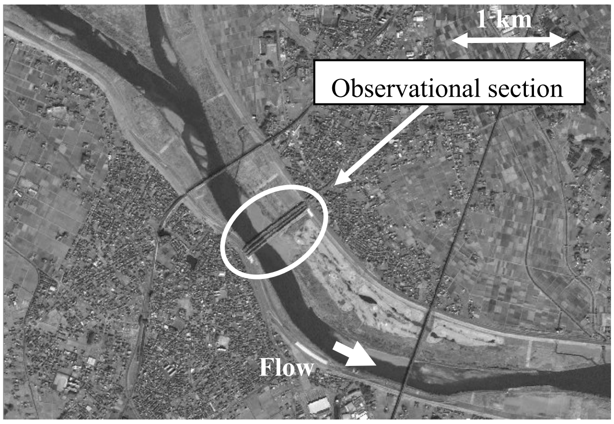

Figure 2 Aerial photo of the observatory ((c) RESTEC/included (C) JAXA)

2.4 *Site condition and experienced flooding*

Figure 2 shows the measurement site of this study. It is located near a bridge along the Tone River in Japan with a bed slope of about 1/4000, bed material of about 1 mm with d_{50}, and a maximum flow capacity of 20,000 m^3/s. This section had a compound channel with a 300 m long floodplain on the left side and a 300 m long main channel on the right side. Point bars were located upstream, downstream and at the center of the observational section. During the daytime observations, water discharges were about 300 m^3/s (a normal stage) while about 1,000 m^3/s and 2,000 m^3/s during the two 24-hour observations.

2.5 *Application of conventional equation*

For verification purposes, the Ashida-Michiue formula (Ashida and Michiue, 1972), which is widely used by Japanese engineers, was selected:

$$q_{B*} = 17\tau_{*e}^{3/2}\left(1-\frac{\tau_{*c}}{\tau_*}\right)\left(1-\frac{u_{*c}}{u_*}\right) \tag{6}$$

where $q_{B*} = q_B \big/ \sqrt{(\sigma/\rho - 1)gd^3}$, q_B = bed-load discharge, σ = mass density of sediment, ρ = mass density of water, g = gravitational acceleration, d = median size of bed sediment, τ_{*e} = dimensionless effective shear stress computed by u_{*e}, τ_{*c} = dimensionless critical shear stress, τ_* = dimensionless shear stress determined as $u_*(1)$, u_* = shear velocity computed by $u_*(1)$, u_{*c} = critical shear velocity. Values calculated by Eq. (6) were named as AMF in the following discussion.

3 RESULTS

The sequence of the figures from 3 to 4 indicate the results obtained by the field measurements, as well as the results from the estimation formula based on the observed values. In those figures, the filled circles indicate the values obtained by the ADCP measurements; the filled squares by the sediment sampler; the open triangles by the AMF. The following paragraphs will explain about each figure.

The results from the sediment sampler scatter in great extents from 2 to 4 orders of magnitude. Several reasons might be considered for this dispersion. The first major reason is difficulties related to landing the sediment sampler on the river bed. The mesh size is also considered to have some influence on the results as well. Particularly, in the case of a smaller shear stress, only small-sized sediment particles move and flow into the sampler; therefore, particles smaller than the mesh size may pass through instead of remaining in the sampler. Actually, the results indicate a wider range of values with a smaller shear stress while a relatively narrower range with a higher shear stress. Though many adverse conditions for application of sediment sampling can be listed, overestimation may be the least considered. Therefore, instead of averaging similar shear velocities, an envelope curve may be suitable to assist engineer ing judgments to the results from the sediment sampler.

Figure 3 shows the relationship between the non-dimensional shear stress (τ_*) from $u_*(1)$ in the horizontal axis and the non-dimensional bed-load discharge (q_{b*}) in the vertical axis. As it indicates, the results of those three proportionally increase with the non-dimensional shear stress. The differences between the AMF and the ADCP measurements are in the range of the power of 10 though the results from the sediment sampler show a somewhat different trend.

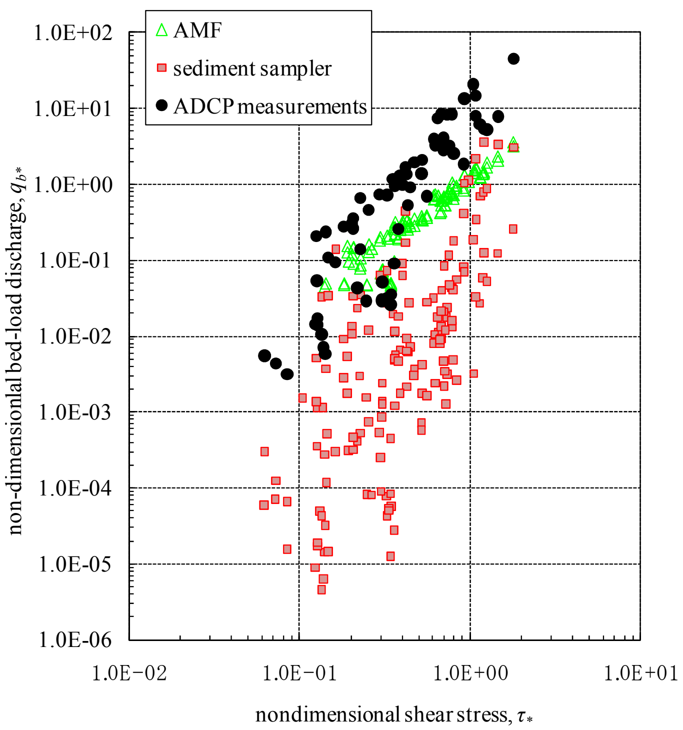

Figure 3 Relationship between non-dimensional shear stress and non-dimensional bed-load discharge

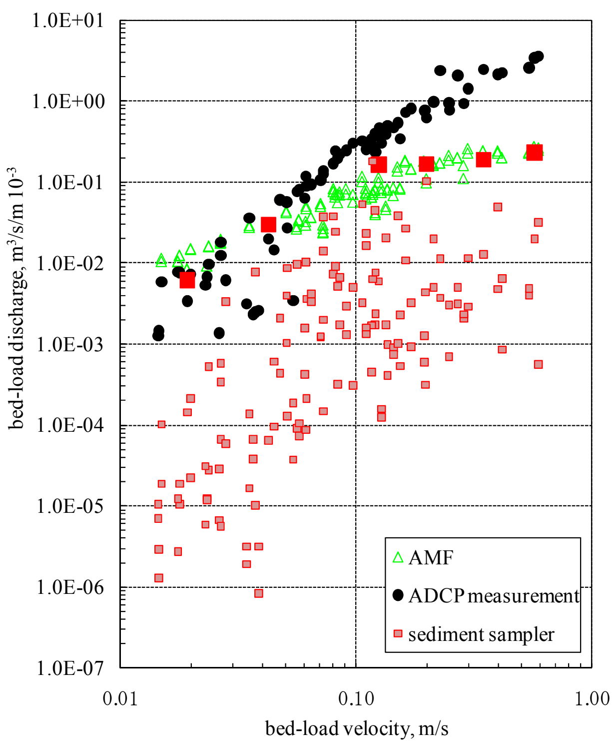

Figure 4 Relationship between the bed-load velocity and bed-load discharge (several dots of the sediment sampler highlighted as larger dots)

For further discussion, the authors re-plotted Figure 3 to Figure 4, which indicates the relationship between the bed-load velocity and bed-load discharge.

As Eq. (4) indicates, the bed-load velocity and the bed-load discharge have a directly proportional relation, so does the relationship between bed-load velocity and shear velocity. Therefore, the bed-load velocity should have a positively increasing function in respect to the bed-load discharge. From that point of view, as shown in Figure 4, the ADCP measurements and AMF show appropriate trends even though those two draw different slopes. Additionally, the ADCP measurements scatter only when the bed-load velocity is less than 0.05 m/s. Reasons for this tendency cannot be clearly explained at this moment though understandable because in general bed-load velocity is more difficult to measure when it is low than high. Otherwise, those two curves would have no discrepancy as seen in Eq. (4).

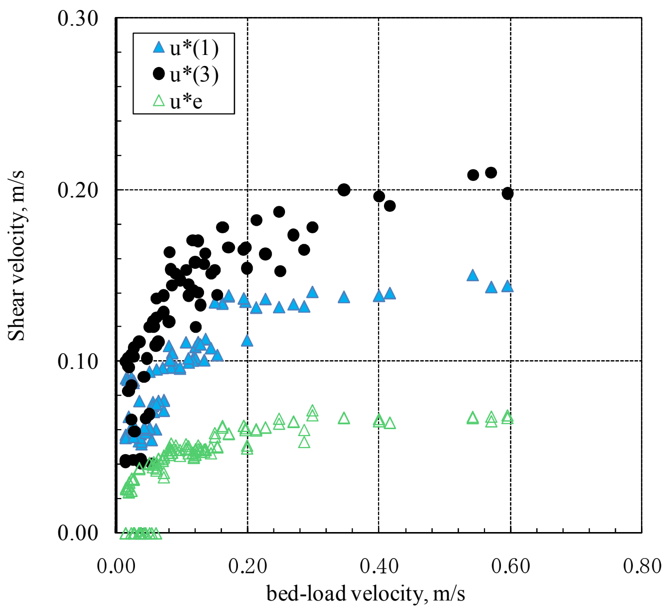

Figure 5 Relationship between the bed-load velocity and the shear velocities.

Associated with the sediment sampler, the authors intentionally plotted 6 large squares to show the envelope curve. The first 3 squares (less than 0.15 m/s) show a similar trend with the ADCP measurements. The trend of the remaining three squares appears similar to that of the AMF. However, the last 4 squares do not show an upward trend in line with the bed-load velocity, which indicates that they have somehow reached to the ceiling though q_B is supposed to show larger values.

Figure 5 shows the relationship between the bed-load velocity and the shear velocity. In this figure, the filled circles stand for $u_*(3)$; the filled triangles for $u_*(1)$; the open triangles for u_{*e}. The horizontal axis is a measured property while the vertical axis is an estimated one by several different equations as explained in section 2.1, i.e., $u_*(1)$, $u_*(3)$, and u_{*e}. From a river engineering point of view, shear velocity is supposed to increase along with bed-load velocity since it represents a hydraulic force while bed-load velocity is a consequence from the action of the force. Therefore, the relationship should be an increasing function. Actually the three estimated properties all satisfy this assumption though the increasing rates are different. In the case of $u_*(1)$ and u_{*e}, the increasing rates are very small especially when the bed-load velocity is more than 0.20 m/s. For example, when shear velocity u_{*e} is 0.06 m/s, the bed-load velocity is between 0.2 and 0.6 m/s. Shear velocity $u_*(1)$ exhibits a similar trend. From this point of view, $u_*(1)$ and u_{*e} appear open to question. In other words, the authors could consider that estimation of shear velocity by the water surface is not appropriate, especially when the bed-load velocity is higher than 0.20 m/s. Since Eq. (6) is a function of $u_*(1)$ and u_{*e}, AMF in Figures 3 and 4 is also inappropriate.

The primary reason for applying AMF is verification of the ADCP-based method, currently proposed by the authors. However, the application of AMF in actual rivers is not easy unless an appropriate shear velocity is estimated from the water surface. The estimation of shear velocity has not been well discussed yet, e.g., in terms of relative distance of water gauges and sampling time. It may also depend on characteristics of river channels. Therefore, bed-load estimators (in this discussion, referring to not only AMF; Eq.(6), but another estimator whichever bed-load discharge is derived from) cannot be easily applied unless shear velocity is determined appropriately. On the other hand, the current method with Eq. (4) and (5) can be determined by flow properties obtained from actual ADCP measurements. From this reason, the current method has strong advantages for measuring bed-load discharge, compared with any other conventional estimators.

4 DISCUSSION: LIMITATION OF PRESENT STUDY

Concerning the limitation of this method, a few points need to be discussed; 1) determination of shear velocity, as well as 2) determination of h_s, and 3) practical points of view. Each discussion will be as follows.

Firstly, $u_*(3)$ already can take care about velocity distribution when dunes exist. When plane bed appears, velocity distribution is most likely better fit to the log law. Therefore, $u_*(3)$ can be applied. However, $u_*(3)$ cannot be applied to the case of anti-dunes with standing waves, since velocity distribution has not been well described yet.

Secondary, the applicability of Eq. (5) needs to be considered. This relation is well examined in the range between 0.1 and about 4 in terms of non-dimensional shear velocity, e.g., Egashira (2005).

A practical aspect is the most restrictive. Actually, the authors have successfully conducted the ADCP measurements with a tethered ADCP platform where standing waves existed (Yorozuya et al., 2010c). The tethered ADCP platform was 1.5 m long and 1.2 m wide. This size of the platform was selected since portability and operationality were prioritized in conducting the measurements. Additionally, the height of the standing waves was about 0.5 m with a wave length of about 2.0 m. The authors have confidence about executing such measurements when the wave length is almost the same size as the platform. However, if standing waves are much longer than the platform during flooding, the authors will hesitate to execute measurements. Therefore, the limitation of the method is the flow condition with larger standing wave.

Finally, based on the theoretical as well as practical aspects, the authors can conclude that the method is applicable up to the dune as well as flat-bed conditions, but not the anti-dune condition.

5 CONCLUSION

The following conclusion can be derived from this paper:

1) the bed-load discharge measurements have conducted with TR-2β as well as the method developed by Yorozuya et al. (2009,2010b). Also, the obtained values from the field measurements were compared with the conventional formulas,

2) The differences between the AMF and the ADCP measurements are in the range of the power of 10,

3) the bed-load discharge obtained by sediment sampler scatter from 2 to 4 orders of magnitude,

4) the bed-load velocity from the bottom tracking function provides valuable information for consulting applicability of bed-load discharge estimator, as well as shear velocity,

5) only $u_*(3)$ was recognized appropriate estimator of shear velocity,

6) this study cannot deriver the conclusion about whether the author's method is better estimator compared with AMF. However, authors indicate difficulty of application of AMF in actual flooding, because of difficulty of estimating shear velocity. From this point of view, the method presented in this paper has advantage, since most of the properties for estimation can be obtained by ADCP,

7) the authors concluded the applicability of the current method as up to flat bed condition, in terms of theoretical as well as practical points of view.

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