May 9-12
Kyoto-Japan
2017

2^{nd} International Workshop on
Sediment Bypass Tunnels

Measurement of shear velocity and bed load discharge

Hiroshi Koseki, Atsuhiro Yorozuya, Shun Kudo, Takashi Kitsuda and Yoichi Iwami

Abstract

Most of bed load formulas employ shear velocity to predict bed load discharge. However, it is very difficult to measure local shear velocity over the bed with sand waves because flow resistance over sand waves is composed of grain roughness and form roughness and have been evaluated in one wavelength. A new method is introduced to determine the local shear velocity for evaluating bed load discharge. The bed load discharge predicted by the new method is compared with results obtained from an experiment using aDcps and a multibeam echo sounder in an experimental flume nearly as large as an actual river. We also found that bed load discharge estimated using the local shear velocity can successfully reproduce bed load calculated based on a longitudinal riverbed elevation profile observed by a multibeam echo sounder.

Keywords: acoustic Doppler current profiler, Multi-beam echo sounder, measurement of bed load discharge, shear velocity

1 Introduction

The estimation of bed load discharge in a river channel is necessary to predict river morphology. Bed load formulas have been studied for many years (Meyer-Peter and Müller 1948, Ashida *et al*. 1972, Egashira *et al*. 1997, 2005) since the first one presented by Du Boy (1897).

On sand waves, the local shear velocity is defined as grain roughness caused by grain unevenness and one factor of flow resistance as well as form roughness caused by bed form in depth scale. Although the relationship between a bed load discharge and the local shear velocity is established based on results from studies in experimental flumes, the local shear velocity itself has only been introduced conceptually and evaluated averaging in one wavelength on sand waves.

In actual rivers, predicting methods of bed load discharge have been studied. For example, Yorozuya *et al*. (2010) proposed a method for evaluating the local shear velocity using vertical velocity profiles, and predicted bed load discharge introducing bed load layer thickness using bed load formula proposed by Egashira *et al*. (1997, 2005). Meanwhile, sampling of bed load discharge has also been studied (e.g., Shimada *et al*. 2008, Okada *et al.* 2014). However, because horizontal profiles of riverbed elevation are not sufficiently available, it has been difficult to evaluate the validity of the local shear velocity used in the estimation and that of the resulting bed load discharge.

To discuss prediction of the local shear velocity, we conducted observation for sediment accumulation in sand pit and sand waves behaviour in an experimental flume nearly as large as an actual river using two latest measurement devices. One is a multi-beam echo sounder, which is capable of observing horizontal profiles of bed load discharge by measuring temporal changes. The other is an acoustic Doppler current profiler (aDcp), which is capable of observing both velocity distribution and bottom track velocity. In this paper, we discuss an estimation method with which bed load discharge and the local shear velocity predicted using bottom track velocity obtained from the observation.

2 Observation

The experiment was conducted in 2015 at Chiyoda Experimental Channel in Tokachi, Hokkaido, Japan. Figure 1 shows the details of the flume used in the experiment. It is an 8-meter-wide, low-flow channel with steel sheet piles erected vertically along the left side of the channel and 1/2-sloped concrete bank protection applied over the right side of the channel. Seven water-level gauges (indicated as "◇" in the figure) are installed along a 50-meter-long section of the channel. The numbers following the letter P indicate the distance from the gate that was operated to control the water discharge.

Two boats are used for this observation: Boat 1 carries Workhorse ADCP 1200 kHz manufactured by Teledyne RDI, and Boat 2 carries a multibeam echo sounder called MB1 made by Teledyne Odom and River Pro ADCP by Teledyne RDI (Figure 2). Boat 1 is kept at P453.5 for fixed-point observation while Boat 2 is operated round trip in downstream of Boat 1 to simultaneously observe horizontal profiles of riverbed elevation and vertical water velocity profiles at intervals of a few minutes. Refer to Kitsuda *et al.* (2017) for the detailed specifications of the measurement devices.

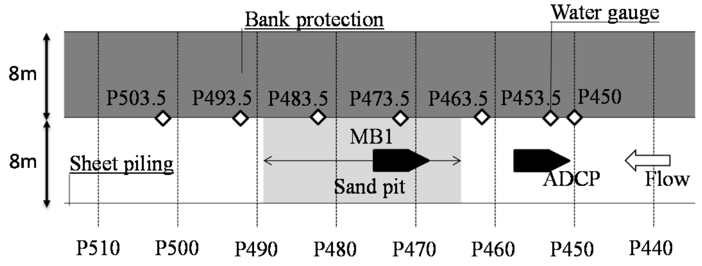

Figure 1: Top view of quasi-river scale open flume.

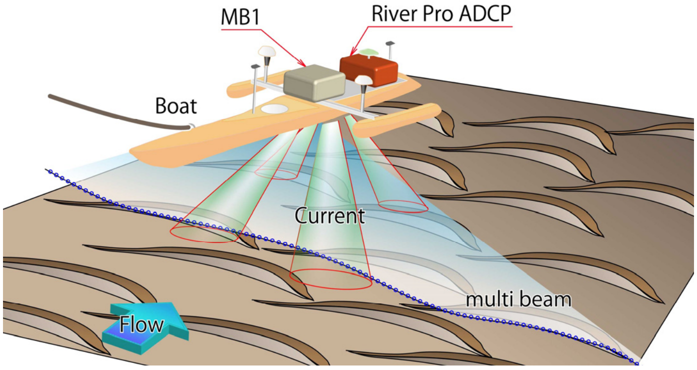

Figure 2: Sketch of measurement system

3 Estimation of local shear velocity using bottom track velocity

The method is designed to estimate the local shear velocity using the bed load discharge formulas proposed by Egashira *et al*. (1997, 2005) and bottom track velocity u_b observed by an aDcp. The following is the bed load discharge formulas used in this study:

$$q_b = \int_0^{h_s} c \cdot u \cdot dz \cong u_s \cdot h_s \cdot c_s \tag{1}$$

where q_b is the unit-width bed load discharge, u_s is the thickness-average moving velocity of a bed load layer, h_s is the thickness of a bed load layer, c_s is the average sediment concentration (= $c_*/2 = 0.3$, with c_* as 0.6). In this estimation method, u_s is defined using u_b as follows:

$$u_s = \alpha \cdot u_b \tag{2}$$

where α is the coefficient used to estimate thickness-average velocity u_s from surface moving velocity u_b of a bed load layer. α is computed to be 0.65 from Eq. [3] as follows:

$$\frac{u(z)}{u_*} = A_s \left\{ 1 - \left(\frac{h_s - z}{h_s} \right)^{3/2} \right\} \tag{3}$$

where u_* is shear velocity, A_s is a function of c_s, θ and φ_s. Eq. [3] shows velocity vertical profiles in a bed load layer. Since Eq. [3] appears to be a linear function, bed load discharge is also predicted and sensitivity analysis is performed as well, even when 0.5 is applied as the coefficient. u_s is calculated using the following equation:

$$\frac{u_s}{u_*} = \frac{4}{15} \frac{K_1 K_2}{\sqrt{f_d + f_f}} \tau_* \tag{4}$$

where τ_* is dimension shear stress, K_1 is the coefficient of slope, K_2 is the coefficient of relative water depth, f_d is the coefficient of particle collision, f_f is the coefficient of pore water. These coefficients can be calculated theoretically without calibration using results obtained in experiments.

In addition, the thickness of a bed load layer h_s is defined as follows:

$$\frac{h_s}{d} = \frac{1}{c_s \cdot \cos\theta \cdot \{\tan\varphi_s - \tan\theta\}} \tau_* \qquad [5]$$

here d is the average grain size, θ is the slope of a riverbed in the flow direction, and φ_s is the internal friction angle of sand particles (= 38.5 degrees).

The proposed method is unique in using u_s to compute u_*, while it is a common practice to calculate u_s and h_s using u_* when estimating bed load discharge with Eq. [1], [4] and [5]. More specifically, in our method, bed load discharge is predicted based on u_b, θ and water depth that are measured with an aDcp and Eq. [1], [2], [4] and [5]. In the following sections, u_* resulting from the proposed method is indicated as u_{*b}.

4 Comparison of bed load discharge

The bed load discharge predicted from the proposed method is determined in two different ways: one is through comparison with the sediment accumulation in the sand-collecting pit, and the other is through comparison with bed load discharge produced when sand waves migrated.

4.1 Bed load discharge in the sand-collecting pit

To measure the sediment discharge in a sand-collecting pit, we created a pit about 1 meter deep in the section between P463.5 and P483.5 before discharging water to the experimental flume. After opening the water control gate, we navigated Boat 2 in both upstream and downstream directions at intervals of a few minutes to record temporal changes in distribution of riverbed elevation in the sand-collecting pit.

Figure 3 shows horizontal profiles of riverbed elevation in the sand-collecting pit observed by MB1 immediately (left bathymetry) and 660 seconds (right bathymetry) after the experiment started. The profiles indicate that the riverbed becomes higher in the middle of the observed section with the flow direction from left to right.

Figure 4 plots the longitudinal riverbed elevation along the center of the channel at different times of the experiment, based on the results exhibited in Figure 3. The horizontal axis is the longitudinal distance from the water level gauge at P450 while the vertical axis is elevation. The lines in different colors show temporal profile changes starting with black and ending with red. The riverbed becomes higher at several points located 16.5 m or farther downstream from P450 as the time passes: it rises up to about 50 cm higher than the initial elevation at the 18.0 m point. However, little change is observed in riverbed elevation in the section 20.5 m or farther downstream. This indicates that during the observation, the sediment from upstream of the 16.5 m point did not flow farther downstream than the 20.5 m point; i.e., the sediment remained in the section between 16.5 m and 20.5 m. This in turn suggests that the analysis method proposed in this study can be verified by comparing the bed load discharge in this section and the bed load discharge that is estimated using the proposed method and aDcp-observed data collected from the area upstream of the sand-collecting pit.

Figure 5 shows the results from the analysis of bed load discharge including the calculation results with α = 0.5 for reference. The results with α = 0.5 and 0.65 show almost the same trend. The results with α = 0.50 matches well with those of MB1 up to 410 seconds. On the other hand, the results with α = 0.65 is twice as those of MB1. All these results verify the bed load discharge estimated with our proposed method, and also confirms that α should be set less than 0.5.

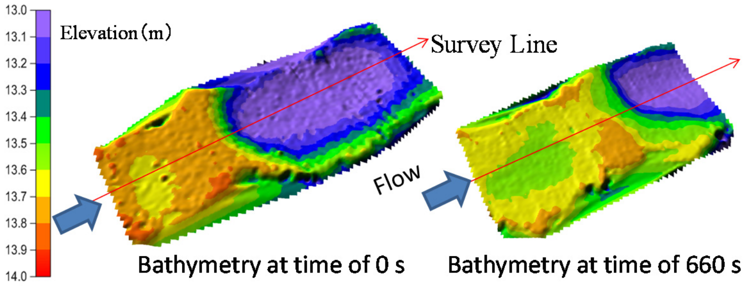

Figure 3: Bathymetry of sand pit

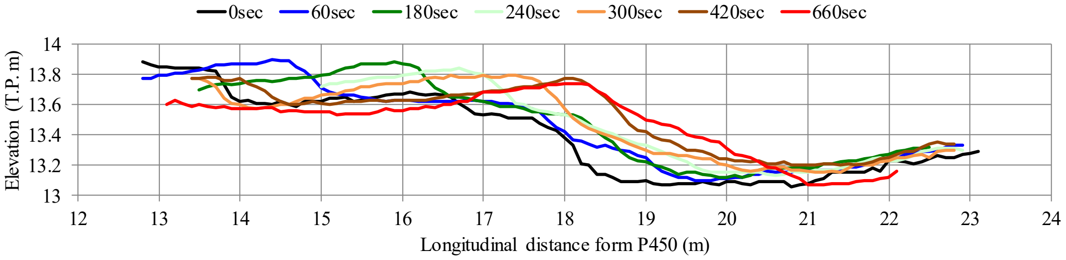

Figure 4: Temporal changes in longitudinal riverbed height profile

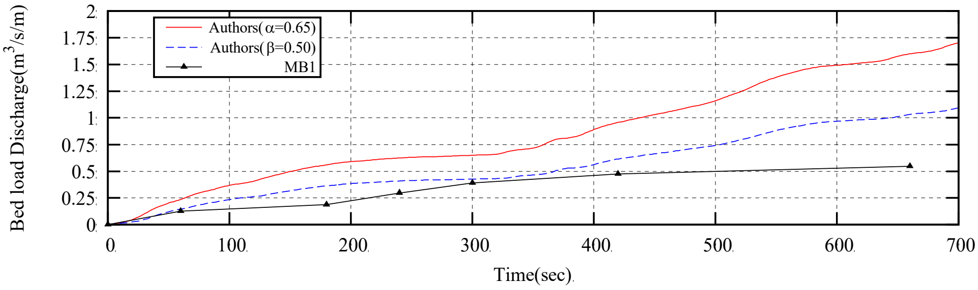

Figure 5: Time series variation of bed load discharge

4.2 Bed load discharge due to sand waves migration

Sand waves travel when bed load is transported downstream. Based on this observation, we tested our analysis method in conditions similar to those of actual rivers by comparing bed load discharge calculated using an aDcp at crest and bed load discharge calculated using the migration velocity and wave height of sand waves.

Kikkawa *et al.* (1985) proposed the following equation with bed load discharge q_b at crest of sand waves, migration velocity of sand waves U_w and wave height H:

$$U_w = \frac{q_b}{(1-\lambda)H} \qquad [6]$$

where λ is the porosity of sediment.

Analysis with Eq. [6] is conducted using the results from observation of sand waves at intervals of 1.5-2 minutes after the riverbed of the experimental flume is leveled. Each wave height H is defined as difference of elevation between crest and the lowest at downstream of the crest. For using Eq. [6], H is averaged wave height using two MB1 measurements. U_w is also calculated using longitudinal position of crest and elapsed time in moving from the first position to the second position. The q_b using Eq. [6] and these results from MB1 measurements is called q_{bM}. On the other hand, estimated bed load discharge using the present method at crest is called q_{bA}.

Figure 6 shows time series variation of water level, wave height, migration velocity, bottom track velocity and q_{bA}/q_{bM}.

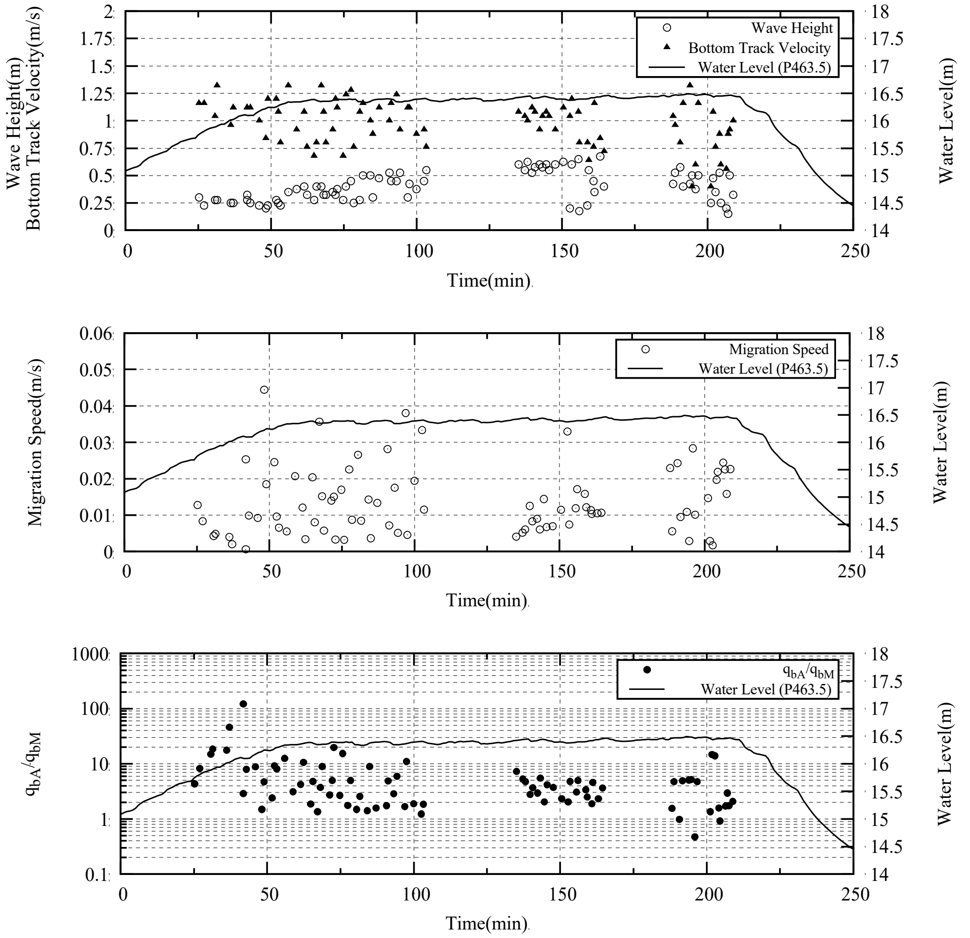

Figure 6: Time series variation of water level, wave height, migration velocity, bottom track velocity and q_{bA}/q_{bM}.

The time series are divided into three periods, 1) before 110 min, 2) between 130 min and 170 min, and 3) after 180 min. In the first period, water level is increased for 50 min and constant for 20 minutes, wave height is increased from 0.2 m to 0.6 m, and bottom track velocity, migration velocity and q_{bA}/q_{bM} are dispersed. In the second period with constant water level, wave height, bottom track velocity and migration velocity are almost constant, 0.6 m, 1.0 m/s and 0.01 m/s, respectively. q_{bA}/q_{bM} is distributed between 2.0 and 8.0 In the third period, despite water level is constant, wave heights decrease than values in the second period, and bottom track velocity, migration velocity and q_{bA}/q_{bM} are dispersed. In all period, bottom track velocity is almost 100 times as large as migration velocity. The rate of 100 times of q_{bA}/q_{bM} was possibly caused because bed load material didn't deposit downstream of crest where the bed load occurred. The longitudinal distribution of the bed load discharge is assumed that some of bed load discharge passes through to the downstream from the trough. It was also assumed that fine sediment is taken up to suspended sediment, however, the possibility of suspended sediment is low because the grain size distribution of less than 2 mm is less than 10 % in the channel.

5 Conclusions

The following three findings have been revealed through the discussions in this paper.

1. Bed load discharge is successfully calculated using bottom track velocity u_b observed with an aDcp and the bed load formulas proposed by Egashira *et al*. (1997, 2005). The results shows that α should be set less than 0.5.
2. The new method made it possible to estimate the local shear velocity u_{*b} using bottom track velocity u_b measured with an aDcp. The validity of the estimated local shear velocity was confirmed by verifying bed load discharge comparing with bed load discharge in sand-collecting pit.
3. Comparison between q_{bA} and q_{bM} suggested that, in unsteady flow, bottom track velocity, wave height and wave migration speed are also unsteady, vice versa. q_{bA}/q_{bM} is larger than a few times.

Acknowledgement

We would like to express our gratitude to experts and organizations that provided great help for our research. The Obihiro Development and Construction Department of the Hokkaido Regional Development Bureau kindly let us use the Chiyoda experimental channel and provided useful data. Mr. Takuya Inoue of Environment & Hydrology, a private firm, helped us a great deal with the modification of the observation boats. Dr. Shinji Egashira, the research and training advisor of the International Centre for Water Hazard and Risk Management, always gave us insightful advice.

References

Ashida K., and Michiue M. (1972). Study on hydraulic resistance and bed load transport rate in alluvial streams. *Journal of Japan Society of Civil Engineers*, Vol.206, pp.59-69.

Egashira S., Miyamoto K and Itoh T. (1997). Constitutive equations of debris-flow and their applicability. *Proc. of 1st International Conference on Debris-flow Hazards Mitigation, C. L. Chen (Eds.),* ASCE: NewYork, pp.340-349.

Egashira S. (2005). Importance of Sediment in Rivers, and Issues in Sediment Transport Mechanics. *Nagare*, The Japan Society of Fluid Mechanics, Vol.24, pp.581-592.

Engelund, F. (1967). Closure to “Hydraulic Resistance of Alluvial Streams.” *Journal of the Hydraulics Division*, ASCE, Vol.93, No.HY-4, pp.287-296, July,

Kikkawa H. (1985). Sediment hydraulics, Maruzen Publishing Co. Ltd, p.176.

Kitsuda T., Yorozuya A., Kudo S., Koseki H. (2017). Development of a measurement system for bed-forms and vertical velocity profiles; observation of the sand-waves behavior, *Annual Journal of Hydraulic Engineering*, JSCE, Vol.61, I_763-I_768.

Meyer-Peter, E. and Muller, R. (1948). Formulas for Bed load Transport, I.A.H.R., Stockholm.

Okada S., Izumi M., Takeuchi J., Yorouzya A., Kitsuda T. (2014). Consideration of the estimation method of bed load discharge besed on measured data using ADCP and RTK-GPS, *Annual Journal of Hydraulic Engineering*, JSCE, Vol.70, No.4, I_631-636.

Shimada T., Watanabe Y., Yokoyama H., Ishikawa S., Kiryu T., Takeda A., Oshima S. (2008). Basic study on sediment behavior in Chiyoda experimental channel, *Annual Journal of Applied Mechanics*, Vol.11, pp.699-707.

Rennie, C.D., Millar, R.G. and Church M.A. (2002). Measurement of bed load velocity using an Acoustic Doppler Current Profiler, *J. Hyd. Eng.*, Vol.128, No.5.

Yorozuya A., Okada S., Ejima K., Kanno Y., and Fukami K. (2010). Method for estimating shear velocity and bed load discharge with acoustic Doppler current profiler, *Annual Journal of Hydraulic Engineering*, JSCE, Vol.54, pp.1093-1098.

Authors

Hiroshi Koseki (corresponding Author)
Atsuhiro Yorozuya
Shun Kudo
Yoichi Iwami
Public Works Research Institute, Ibaraki, Japan
Email: h-koseki@pwri.go.jp

Takashi Kitsuda
Hydro System Development Inc., Osaka, Japan