DISCHARGE ESTIMATION BY STIV COMBINED WITH THE MAXIMUM ENTROPY METHOD

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ABSTRACT

The space-time image velocimetry (STIV), which can measure surface velocity distributions from river surface videos, has come to be introduced in Japan as a non-contact discharge measurement technique in recent years. River discharge is usually obtained by integrating local mean velocities estimated by multiplying a surface velocity coefficient. Conventionally, a constant value of 0.85 is used for the surface velocity coefficient, but its validity depends on the estimation of the vertical velocity distribution. Furthermore, its value can be different in transverse direction. Although various types of formula representing a vertical velocity distribution are available, none of them can reproduce a distribution including a velocity dip, except for the formula based on the maximum entropy method (MEM) proposed by Chiu. The advantage of the formula is that it can represent a velocity distribution for a whole depth with a single equation even when the distribution has a velocity dip. In order to examine the performance of STIV with MEM, snowmelt floods of the Shinano and Uono Rivers were measured by ADCP. Firstly, the entropy parameter M, which is a function of the maximum velocity and the cross-sectional mean velocity and assumed to be constant for a channel section, was determined by the ADCP. Secondly, a surface velocity distribution measured by STIV is used to estimate the discharge with the information of M. The proposed method yields discharges comparable to ADCP successfully. In addition, transverse distributions of the surface velocity coefficient and the location of the velocity dip were obtained.

Keywords: discharge measurement, STIV, MEM, snowmelt flood

1. INTRODUCTION

River discharge measurement in Japan has long been carried out by a float method. The float method measures the surface velocity by throwing a float into a river and measuring the time it takes to flow down a certain distance. However, it sometimes becomes difficult even to come close to the river in case of a huge flood, and the peak flow discharge is frequently missing due to the frequent heavy rainfalls in recent years. Therefore, safety and reliability of discharge measurements have been regarded as a problem. In the light of such present status, the Japanese government has just started a project, ‘an innovative river technology project’, aiming at developing a reliable and labor-saving system for discharge measurements.

Under these circumstances, the Space-Time Image Velocimetry (STIV) developed by Fujita et al. (2007, 2011) was proposed as a method of non-contact surface velocity measurement (Fujita et al. 2018; Koutalakis et al. 2019) and it has been used in Japan and overseas. This method has a great potential to overcome the above-mentioned problems by effectively utilizing river monitoring cameras installed at many rivers in Japan. Since this is the method to estimate the surface velocity distribution from the image of the river surface, it is necessary to convert it to the depth-averaged velocity when calculating the discharge. Normally, the depth-averaged velocity is calculated by multiplying the surface velocity coefficient to the surface velocity, but the surface velocity coefficient can’t always be constant in the transverse direction, or rather it should vary with a distance from the riverbank. Moreover, as discussed by Yang et al (2004), the maximum velocity may occur below the water surface depending on flow conditions, which is called a velocity dip phenomenon. Hence, the surface velocity coefficient has to be varied for improving the measurement accuracy. For that purpose, we applied a vertical velocity distribution formula based on the maximum entropy method proposed by Chiu et al (1987) to improve the accuracy of discharge measurements. Conventional vertical velocity distribution formulas are the logarithmic law and the power law, but these can’t express the velocity dip. On the other hand, the main feature of Chiu's formula can express the velocity dip well, and the reproducibility for the vertical distribution is higher than the other formulas.

2. VERTICAL VELOCITY DISTRIBUTION BASED ON THE MAXIMUM ENTROPY METHOD

2.1 Existing vertical velocity distribution formula

The vertical velocity distribution of open channel turbulence has been related to the resistance law, and studies such as Nakagawa and Nezu (1993) have been conducted in the past decades. In recent years, it has become possible to measure detailed vertical velocity distributions not only in laboratory flumes but also in actual rivers by improving the measurement instruments. With these instruments, it has become possible to verify the existing velocity distribution models. The well-known model is the following logarithmic distribution formula

$$\frac{u(y)}{u_*} = \frac{1}{\kappa} ln \frac{y}{y_0} + \phi\left(\frac{y}{D}\right) \tag{1}$$

and the following power law.

$$\frac{u(y)}{U_s} = \left(\frac{y}{D}\right)^{1/m} \tag{2}$$

where $u(y)$ is the streamwise velocity at a height y from the riverbed, u_* the shear velocity, κ the Karman constant, y_0 the riverbed height where $u = 0$, D the depth, m a parameter. ϕ is the term for correcting deviation from the logarithmic law, and generally given by the wake function of Coles (1956).

$$\phi\left(\frac{y}{D}\right) = \frac{2\Pi}{\kappa} sin^2\left(\frac{\pi y}{2D}\right) \tag{3}$$

where Π is the wake intensity parameter.

The main feature of these equations is that the maximum velocity always occurs at the water surface. However, a velocity dip where the maximum velocity appears below the water surface can occur in a channel with a small aspect ratio or a channel section near the riverbank even for a wide river. Therefore, various velocity distribution formula have been proposed in the past to reproduce the velocity dip. For example, Finley et al (1966) replaces Eq. (3) with

$$\phi\left(\frac{y}{D}\right) = b_1\left(\frac{y}{D}\right)^2\left(1-\frac{y}{D}\right) + b_2\left(\frac{y}{D}\right)^2\left(3-2\frac{y}{D}\right) \tag{4}$$

Yang et al (2004) suggested the following equation.

$$\phi\left(\frac{y}{D}\right) = \frac{\alpha}{\kappa}\left(1 - log\frac{y}{D}\right) \tag{5}$$

$$\alpha = 1.3exp\left(-\frac{z}{D}\right) \tag{6}$$

where b_1 and b_2 are model parameters, z the distance from the side wall. All of the above model equations are empirically proposed based on measured values.

2.2 Vertical velocity distribution formula based on the maximum entropy method

Chiu (1987, 1989) and Hossein (2008) theoretically derived the vertical velocity distribution instead of the above empirical formula. Among them, Chiu (1987, 1989) theoretically induced the velocity distribution using the concept of entropy, and recently Moramarco et al. (2004, 2017) proposed a simplified formula. This simplified formula has increased its practicality significantly. Focusing on the fact that velocity dip can be easily estimated from the surface velocity, and the applicability of the formula to the rivers in Japan was investigated. There are no study examples of such a proposed formula in Japan.

In the model of Chiu (1987), the velocity distribution equation is expressed as follows.

$$\frac{u}{u_{max}} = \frac{1}{M}\ln\left[1 + (e^M - 1)\frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right] \tag{7}$$

where,

$$\xi = \frac{y}{D-h} exp\left(1 - \frac{y}{D-h}\right) \tag{8}$$

is a dimensionless coordinate such that the coordinates of velocity = 0 are $\xi = \xi_0$ and the coordinates of maximum velocity are $\xi = \xi_{max}$, and h is the depth of the velocity dip from the water surface. As shown in Chiu (2002), M is an entropy parameter and is said to have a unique value for each river section. Eq. (8) can express the flow velocity distribution at a cross section centered on the maximum velocity point, but Moramarco et al. (2017) simplified it to a form that can be used at each vertical survey line in order to improve the efficiency.

$$u(x_i, y) = \frac{u_{maxv}(x_i)}{M} \times ln\left[1 + (e^M - 1)\frac{y}{D(x_i) - h(x_i)} exp(1 - \frac{y}{D(x_i) - h(x_i)})\right] \tag{9}$$

where, x_i is the distance from the side wall to survey line i, $u_{maxv}(x_i)$ the maximum velocity at a survey line i, $h(x_i)$ the depth of velocity dip at survey line i. The entropy parameter M is determined from the ratio of the maximum velocity to the depth average velocity in the cross-sectional field using the following equation.

$$u_{mean} = \left(\frac{e^M}{e^M - 1} - \frac{1}{M}\right) u_{max} = \phi(M) u_{max} \tag{10}$$

The magnitude of the velocity dip is estimated as follows from the equations of Yang et al. (2002) and, Moramarco et al. (2017).

$$\delta(x_i) = \frac{D(x_i)}{D(x_i) - h(x_i)} = 1 + 1.3exp\left(-\frac{x_i}{D(x_i)}\right) \tag{11}$$

The maximum velocity $u_{maxv}(x_i)$ can be estimated from the following equation using the surface velocity and the entropy parameter M.

$$u_{maxv}(x_i) = \frac{u_{surf}(x_i, D(x_i))}{\frac{1}{M} ln[1 + (e^M - 1)\delta(x_i) e^{1-\delta(x_i)}]} \tag{12}$$

3. APPLICATION OF MEM TO FLOOD FLOW DISCHARGE ESTIMATION

3.1 Overview of field observation

In this section, the velocity distribution and discharge were measured by applying the vertical velocity distribution formula based on MEM to actual rivers, and the estimation accuracy was verified and considered.

The field observation was carried out at two sites of the Shinano River and its tributary the Uono River. As for the Shinano River, the data observed at the Asahi Bridge in April 2017 is used. A video camera was installed on the left bank upstream of the bridge to capture images of river surface flows. Figure 1 shows the flow image of the observation site. The video data of the Uono River was taken at Negoya Bridge in April 2014. A video camera was installed on the left bank downstream of Negoya Bridge as shown in Figure 2. Both data were acquired when a snowmelt flood occurred in April and the flow rate was higher than normal condition. In both observations, measurements by ADCP (Acoustic Doppler Current Profiler) were also performed at the same section of the image.

3.2 Discharge calculation procedure

When applying MEM to an actual river, the parameter M has to be estimated from Eq. (10) from the average velocity and the maximum velocity of the entire cross-section by using the ADCP data. Chiu and Tung (2002) showed that the parameter M has a unique value for a section over a wide range of flow conditions. The velocity dip is estimated from Eq. (11). According to Eq. (11), the velocity dip is affected up to about 5 times the depth from the riverbank. The maximum velocity u_{maxv} is calculated by Eq. (12), and the vertical velocity distribution is determined by Eq. (9). The discharge is obtained by integrating vertical velocity distributions determined by the above procedure.

Figure 1. Observation point at Shinano River

Figure 2. Observation point at Uono River

3.3 Result of estimation of snowmelt discharge at Shinano River

At the measurement section, the surface velocity distribution is first obtained by using STIV from the obliquely viewed video images. Details of the technique are indicated in the papers of Fujita et al. (2007, 2011, 2019). A commercial software KU-STIV was used for the STIV analysis. Figure 3 shows the surface velocity distribution obtained at the cross section in Figure 1. Figure 4 compares the cross-sectional velocity distributions measured by ADCP and that by applying MEM. The parameter *M* was 1.17 in this case. Comparing two figures in Figure 4, the velocity about 3.5 m/s flowing from about 20 to 50 m from the left bank in MEM was an overestimation for the ADCP. Here, the maximum error was about 50 cm. Since it is the value of the parameter *M* that determines the vertical velocity distribution, it is necessary to further study the true value of *M*, including the measurement error of ADCP and the interpolation method of unmeasurable areas. The dashed line in the MEM results indicates the position where the velocity dip occurs. The velocity dip might have occurred up to the distance about 5 times the water depth from the bank. To compare the discharges, ADCP yielded 755.0 m^3/s , MEM 791.7 m^3/s. In addition, the surface velocity coefficient obtained from the ADCP was 0.80, which was slightly smaller than the default value of 0.85. The discharge obtained by STIV and using surface velocity coefficient 0.80 was 797.8 m^3/s. As a result, the relative error was about + 4.9% for MEM and about + 5.7% for the conventional method, and the discharge estimation by MEM could be estimated equal to or better than conventional method. The discharge is usually calculated by multiplying the surface flow velocity by a constant value, but its value can be different in transverse direction, and varies significantly depending on the water depth, so this is convenient procedure. As shown in Fig. 4, the velocity dip is limited to the region near the side wall, so it may be possible to ignore it when converting to the total discharge, depending on the distribution pattern. However, the vertical velocity distribution and the surface velocity coefficient for each section can be grasped in detail, by applying the velocity distribution by MEM, so it can be said that there is significance in correctly understanding the discharge. Figure 5 shows the cross-sectional distribution of the surface velocity coefficient calculated from the MEM, which is not constant in the transverse direction.

3.4 Result of estimation of snowmelt discharge at Uono River

The same procedure was applied to the Uono River. Figure 6 shows the surface velocity distribution obtained from the STIV. Figure 7 shows a comparison between the velocity distribution measured by ADCP and the velocity distribution estimated by MEM. The value of the parameter *M* was 2.23. It is obvious again that MEM can reproduce the ADCP data better than the conventional method; the discharge was 254.3 m^3/s for ADCP, 259.4 m^3/s for MEM, and 263.3 m^3/s by the conventional method. The relative error to ADCP was + 2.0% for MEM and + 3.5% for the conventional method. Assuming that the value of the parameter *M* is kept constant for a wide range of discharges, it becomes possible to estimate the discharge simply by applying STIV to the surface flow.

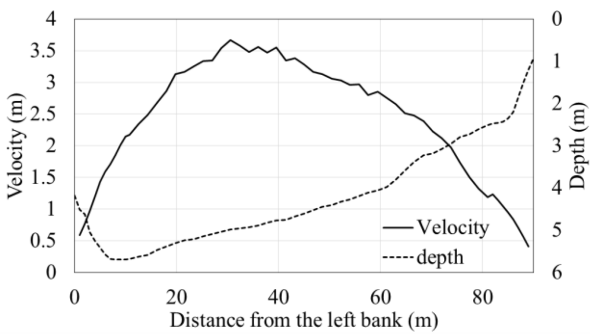
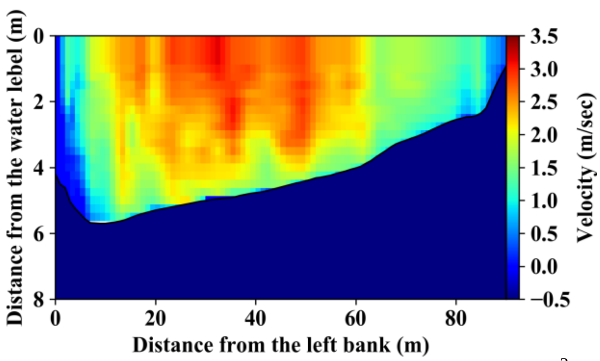


Figure 3. Surface velocity distribution at Shinano River



Velocity Distribution measured by ADCP: 755.0m^3/s

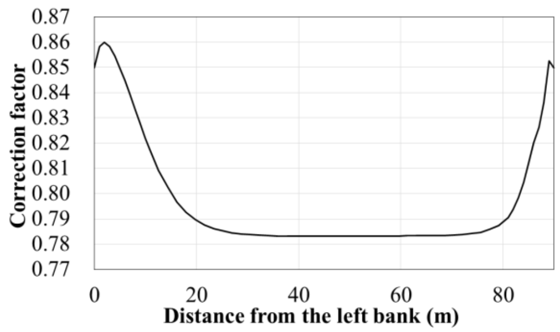


Figure 5. Cross-sectional distribution of the surface velocity coefficient

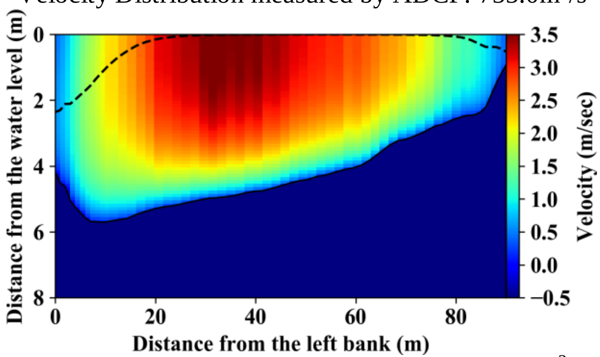


Figure 4. Distribution estimated by MEM: 791.7m^3/s (Dashed line: Position of velocity dip)

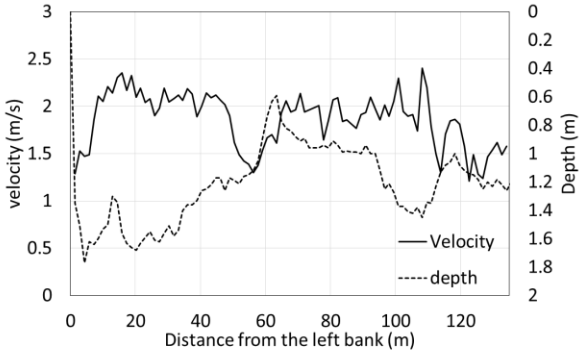


Figure 6. Surface velocity distribution at Uono River

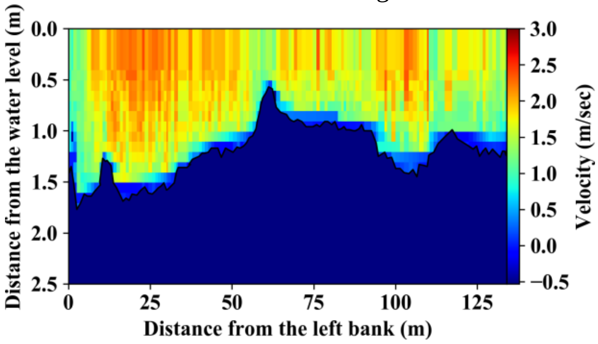
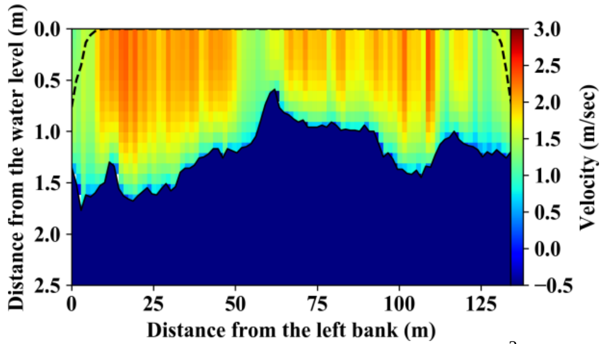


Figure 7. Velocity Distribution measured by ADCP: 254.3m^3/s



Distribution estimated by MEM: 259.4m^3/s (Dashed line: Position of velocity dip)

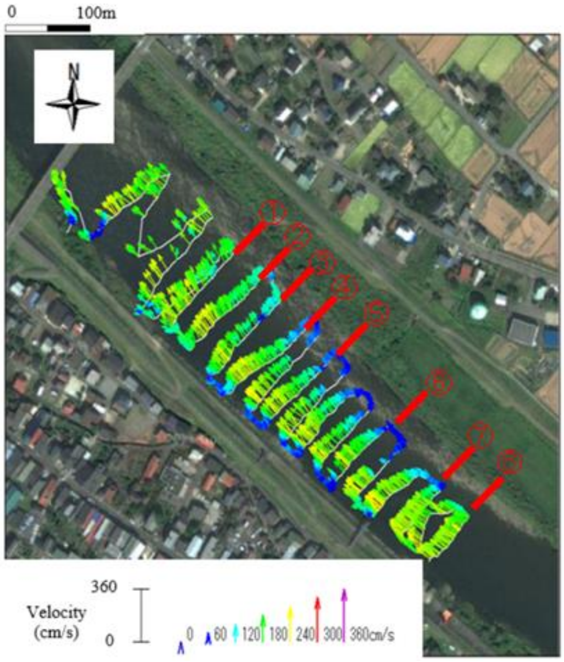


Figure 8. Routes of ADCP

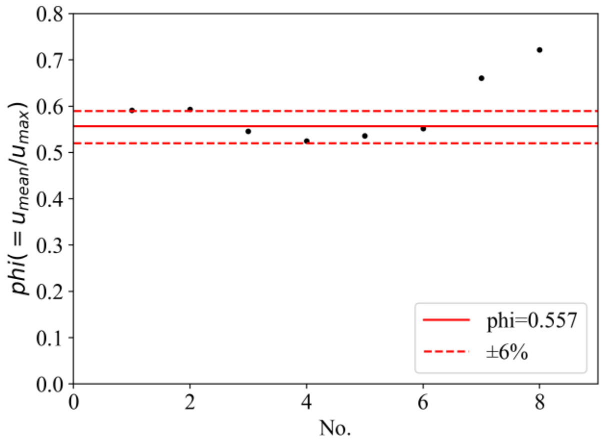


Figure 9. Distribution for each side line

4. EXAMINATION OF THE UNIVERSALITY OF PARAMETER *M*

As described above, Chiu and Tung (2002) show that the value of the parameter M is almost constant at the section for a wide range of flow conditions, including forward and reverse flows. However, this fact has not been proven in rivers in Japan. The data used for the examination was obtained by traversing a boat-mounted ADCP in a zigzag manner as shown in Figure 8. The sections were numbered sequentially from one to eight. The vectors in the figure show the velocity distribution of the top layer 0.35m below the water surface obtained by ADCP. Table 1 shows the average velocity, maximum velocity, and other parameters for each section. The value of the entropy parameter M is almost constant. At the sections from No.1 to No.6, which are within a range 425m from Negoya Bridge, the value of ϕ converged to almost the same value as indicated in Figure 9. The red line in the figure indicates the line with an average value of ϕ = 0.557. With this ϕ, M takes a value of 0.94. On the other hand, the section No. 7 yielded ϕ different from the above data by about 0.1, and the section No. 8 yielded 0.15 or more. When ϕ increases by 0.1, the value of M increases by about 1.3. The error of No.1-6 was within ± 6% from ϕ = 0.557, but the errors in No. 7 and 8 are considerably large, and it is considered that the same parameter M cannot be used in the entire range. The cause of the difference is attributed to the difference of the transverse bottom shape. The cross section No.7, 8 was affected by the meandering part in the upstream, and the transverse bottom shape was significantly different from No. 1-6. In this result, parameter M did not converge to one value in a wide flow regime of a single river as shown by Chiu and Tung (2002). However, focusing only on certain sections (No. 1-6) where the transverse bottom shape is uniform, parameters could be set for flow measurement with a single parameter M.

5. CONCLUSIONS

In this study, the river discharge measurement was executed by combining STIV for surface flow measurement and MEM for estimating vertical velocity distributions. The results showed discharge estimations better than the conventional method using a constant surface velocity coefficient. Although the universality of the parameter M has not been confirmed for rivers in Japan, the combination of STIV and MEM could improve the measurement accuracy significantly once the value of M is fixed by measurements for different flow rates. In that sense, M could take the role similar to the roughness coefficient at the section. Furthermore, detailed measurement at different stages by ADCP is required to determine M and to examine the dip depth in the actual rivers.

Table 1. Velocity and parameter at each section

No.	1	2	3	4	5	6	7	8
Distance from the bridge(m)	150	205	245	265	325	425	485	525
Cross section (m^3)	166.6	166.7	160.1	189.1	183.4	178.9	151.3	139.29
Maximum Velocity u_{max}(m/s)	2.58	2.57	2.60	2.56	2.59	2.59	2.54	2.53
Average Velocity u_{mean}(m/s)	1.53	1.53	1.42	1.34	1.39	1.42	1.68	1.83
ϕ (=u_{mean}/u_{max})	0.591	0.593	0.546	0.525	0.536	0.552	0.661	0.722
M	1.11	1.14	0.55	0.30	0.43	0.63	2.10	3.30

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