Discharge estimation using partially measured ADVM data

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This study shows some results from streamflow monitoring operation of side-looking ADVM installed at lower part of cross-section to meet the hydrologic situation of highly variable natural rivers which have much longer period of low flow than short flood season. To estimate sectional velocity distribution and discharge with partially measured ADVM data, Chiu's formulae are used. Calculated velocity data are roughly similar with measured ones. Calculated discharge by 10-cell scheme gives fairly good agreement with reference discharge of the dam below 800 m^3/s, while 5-cell scheme seems more suitable for higher discharge estimation. These characteristics are also shown in the plot of coefficient of determination and seem related with acoustic signal attenuation in high sediment concentration flow.

Keywords: Velocity, discharge, ADVM(acoustic Doppler velocity meter), Chiu's formulae

1 INTRODUCTION

In order to continuously monitor streamflow in highly variable natural rivers which have far longer period of low flow than short flood season, a fixed side-looking acoustic Doppler velocity meter (ADVM) is required to be installed at lower part of cross-section. In this condition, wide-shallowness and bed irregularity confines aspect ratio related to acoustic beams, then high frequency transducers of short reach length are used. Consequently, the ADVM only measure the relatively low-velocity outskirt rather than high-velocity core (Fig 3).

Though velocity data measured partially in the cross-section are not able to be used for discharge calculation by itself, they can be used practically either for index velocity rating, or with formulae simulating two-dimensional sectional velocity distribution. The latter may be the more cost-effective of the two in that it does not need many direct discharge measurements to develop rating.

A few two-dimensional sectional velocity distribution formulae have been reviewed [1, 2]. Among them, the formulae proposed by Chiu [1] are applied in this study. Calculated discharges are compared with ones by index-velocity rating and dam release discharges, and the results are discussed.

2 CHIU'S FORMULAE AND APPLICATION

2.1 Basic theory and formulae

Chiu [1, 3] proposed entropy-based two-dimensional probabilistic velocity distribution function for simulation in the river cross-section. His formulae are theoretically capable of reproducing maximum velocities occurring below water surface. By using Chiu's formulae, estimation of velocity distribution and discharge is possible with at least three measured point velocity data in the cross-section.

Two-dimensional velocity distribution formulae proposed by Chiu [1, 3] are composed of 1) isovelline-based coordinate (Fig. 1, Fig. 2) velocity distribution function based on the principle of maximum entropy, 3) relationship about hydraulic parameter M .

The first thing is isovelline-based $\xi - \eta$ coordinate in the cross-section (Fig 1). Of ξ and η, only ξ is necessary for calculation of velocity distribution and equation is written as follows.

$$\xi = Y(1-Z)^{\beta_i} \exp(\beta_i Z - Y + 1) \quad (1)$$

where, $Y = (y+\delta_y)/(D+\delta_y+h)$, and $Z = |z|/(B_i+\delta_i)$.

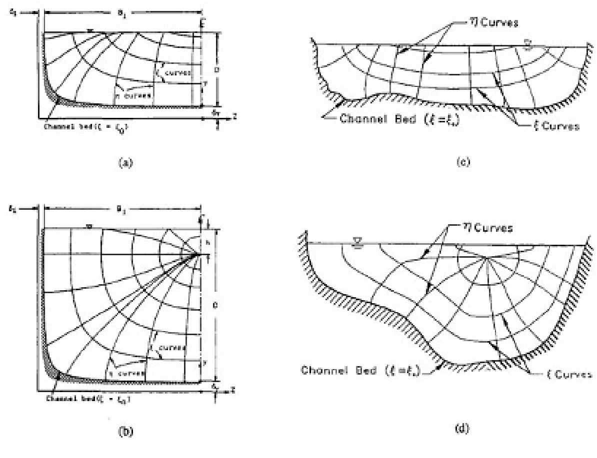

Figure 1: ξ-η coordinates in open-channels

The second is general velocity distribution function and is expressed by Eq.(2).

$$u = \frac{u_{max}}{M} \ln\left[1 + (e^M - 1)\frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right] \quad (2)$$

Thirdly, entropy parameter *M* which shows relationship between maximum and mean velocities is described as Eq.(3).

$$\phi(M) = \frac{\bar{u}}{u_{\max}} = e^M (e^M - 1)^{-1} - \frac{1}{M} \quad (3)$$

2.2 Determination of parameters

There are four parameters in Eq. (1). They are related to the shape of isovel (contour). Of them, *h* has physical meaning in the range of $-D < h \leq 0$ and represents vertical location below water surface along maximum velocity axis. Others (β_i, δ_i, δ_y) are variables relevant to shape of zero-velocity isovel and isovels near the boundary [4]. Considering range of values in [4], δ_i and δ_y are treated as zero, but β_i is determined in the range from 0 to 1. Parameter *h* and β_i are determined in two ways. First, *h* and β_i are determined according to a previous study by Lee et.al.[5] (Model_1). Second, *h* and β_i are considered as 0 and 1, respectively (Model_2). In case of *h*=0, it assumes that maximum velocity along the vertical axis occurs at water surface. The latter will be used for simple prediction for sites which do not have any hydraulic information in the cross-section. β_i is determined individually for the left (β_L) and right (β_R) half of the cross-section.

Parameter *M* in Eqs. (2) and (3) is an entropy one. It is only parameter related to hydraulic characteristics of the channel. It is related to maximum and mean velocity in the cross-section. *M* is also determined in two ways. It is determined either by Lee et.al. [5], or as 2.13 considering the study by Kim et.al. [6] and Moramarco et.al. [7].

Table 1: Applied parameters and discharge for cases in this study

Cases	Parameters (for Model_1)				Dam discharge (m^3/s)
	h	β_L	β_R	*M*	
C200707161806	0.05	0.58	1.0	2.36	16.8
C200707201900	0.00	0.58	1.0	2.36	39.1
C200707240839	-0.07	0.59	1.0	2.36	61.0
C200707241329	-0.52	0.59	1.0	2.36	321.2
C200707242130	-0.29	0.71	1.0	2.36	175.0
C200707250730	-0.17	0.64	1.0	2.36	106.1
C200708050429	-0.67	0.57	1.0	2.36	407.7
C200708050029	-0.77	0.55	1.0	2.36	626.6
C200708082229	-0.69	0.56	1.0	2.36	480.4
C200607161929	-1.13	0.47	1.0	2.36	830.2
C200607170229	-1.41	0.45	1.0	2.36	1,093.9
C200607162359	-1.56	0.44	1.0	2.36	1,307.3

2.3 Calculation of velocity distribution and discharge

Before calculating velocity distribution for discharge estimation by Chiu's formulae, four different schemes are individually treated according to settings of parameters and the ADVM multi-cell settings (Tab. 2).

Table 2: Applied parameters and discharge for cases in this study

Model	Parameter determination	Multi-cell scheme (ADVM setting)
Model_1	by Lee et.al.[5]	10 whole cells
		proximate 5 cells
Model_2	*h*=0, β_L=0, β_R=0, *M*=2.13	10 whole cells
		proximate 5 cells

Velocity distribution in the cross-section is substantiated by using both Eqs. (1) and (2), and rectangular grid network. Since simulated grid velocity values are non-dimensional, it is necessary to correlate them with real velocity values measured by ADVM. 10 or 5 observed multi-cell velocity data are used to establish linear correlation with non-dimensional velocity data calculated by Chiu's formulae. In this linear correlation relationship, slope of the fit line becomes maximum velocity and correlation coefficient presents index between calculated and measured velocity distribution. After determination of maximum velocity, all the non-dimensional grid velocity values are converted to real ones by Eq. (2). Total sectional discharge is computed by summation of all the grid discharge. For precise calculation of velocity distribution, size of each grid cell is 1 m in spanwise direction and 0.05m in vertical direction.

3 STUDY SITE AND ADVM SYSTEM

Streamflow monitoring system has been being operated at the reach of the Dalcheon river located near the center of South Korea. The river reach is an approximately 110 m wide and straight stable cobble-bed stream (Fig 2). There is the Goesan dam about 800 m upstream of the study reach. Its discharge release ranges from 5 m^3/s during low flow season, up to 1,700 m^3/s at severe flood. In this study, dam discharge is a reference for discharge comparison.

Figure 2: A view of the study site

The cross-section for streamflow monitoring is shown in Fig 3. Low water level ranges from 110.0 to 110.5 m above sea level and is maintained by the riffle crest located 450 m downstream from the cross-section, while high water level comes up to 115.0 m.

The ADVM is a Sontek's Argonaut-SL of 1.5MHz frequency. It is set up to measure 10 cells in the range from 10 to 20 m from the transducers. In order to unceasingly measure water velocity even during dry low flow season, the ADVM is installed near the lower right edge of the cross-section. Consequently, it can partially measure the velocity of the outskirt of the cross-section.

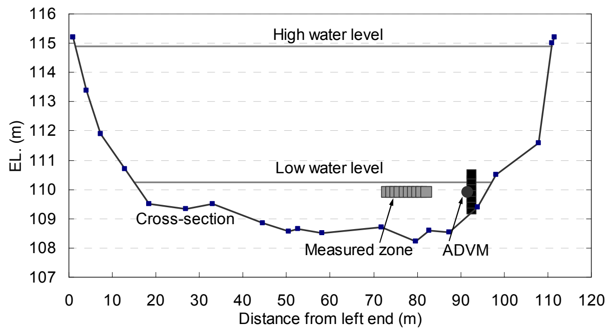

Figure 3: Cross-section and ADVM installation

4 RESULTS AND DISCUSSION

4.1 Velocity comparison

Fig. 4 shows lateral velocity distribution calculated by Chiu's formulae compared with measured by ADVM for the C200708050429 case (407.7 m^3/s). Upper plots are for 10-cell data, while lower ones for 5-cell data. For both scheme (10-cell and 5-cell), calculated velocity shows more gradual increase in magnitude than measured distribution. In general (including other cases), this discrepancy is similar, but for higher discharge cases (> 800 m^3/s), measured velocity of outer cells in the 10-cell scheme shows decrease in spite of discharge increase. It is likely to be attributed to acoustic signal attenuation caused by high suspended concentration [8].

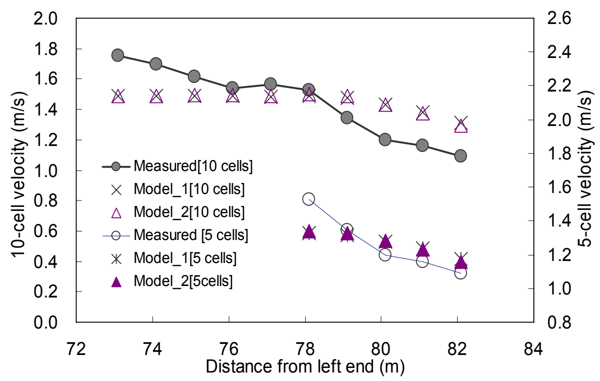

Figure 4: Comparison of velocity calculated by Chiu's formulae with measured velocity

There are very slight velocity differences calculated by model_1 and model_2. It is likely to be caused by similarity of parameters, especially hydraulic parameter *M*. In addition, it seems to be a cause that velocity is not measured near core, but in the outskirts.

4.2 Discharge comparison

Since streamflow monitoring in natural rivers depends on accuracy of discharge, more interest is focused on discharge. For range from 10 to approximately 800 m^3/s, calculated discharge by Chiu's formulae for 10-cell scheme shows roughly good agreement with dam discharge except a case of discharge 626.6 m^3/s (Fig. 5). Mean absolute relative differences with dam discharge are 5.7%, 7.0% for model_1 and model_2 of 10-cell scheme, respectively. On the contrary, for 5-cell scheme, they are 12.6% and 15.1% for model_1 and model_2, respectively. Consequently, discharge calculation using 10-cell data gives more accurate results. Mean absolute relative differences with index method are 5.6% and 8.2% for 10-cell scheme, 14.3% and 16.5% for 5-cell scheme.

For most cases, relative discharge differences with dam discharge show negative bias (-3.9%, -6.7% for 10-cell scheme, -12.6%, -15.1% for 5-cell condition). That is, 10-cell scheme can provide less negative bias than 5-cell condition. This is because the 10-cell condition has more possibility to get higher velocity by distant cells so that it estimates higher maximum velocity than in the 5-cell scheme. According to the results above, it can be inferred that if higher velocity near core is measurable, then estimated maximum velocity will be larger and negative bias in discharge calculation may decrease.

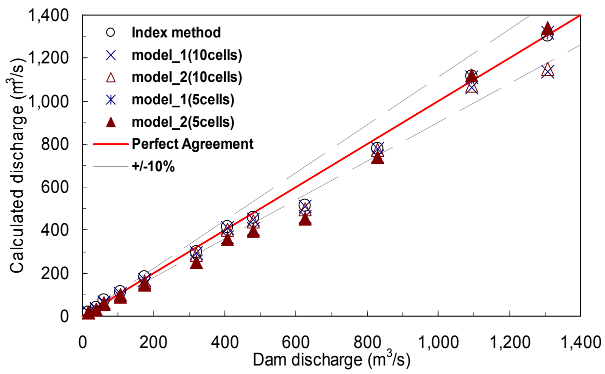

Figure 5: Comparison of discharge calculated by Chiu's formulae and index method with dam discharge

4.3 Coefficient of determination

C200607162359 case (discharge=1,307.3 m^3/s) for 10-cell scheme displays abrupt discharge decrease (Fig. 5). It seems to be attributed to abnormal velocity decrease in the distant cells, which is probably caused by signal attenuation just as occurs in lateral velocity distribution. Fig. 6 shows abrupt decrease of coefficient of determination between 800 and 1,100 m^3/s for 10-cell scheme. Since calculated maximum velocity by Chiu's formulae depends on linear correlation with partially measured 10-cell data by ADVM, this low coefficient of determination depreciates reliability of the calculated data. Therefore it is desirable that 10-cell scheme should be used at discharge below 800 m^3/s and above this discharge, another method is required to simulate velocity distribution and estimate reliable discharge.

In contrast to 10-cell scheme, coefficient of determination in the proximate 5-cell scheme presents more constant values because measuring cells are closer to the transducers in the 5-cell scheme. In addition, for discharge above 800 m^3/s, relative error compared with dam discharge becomes much smaller (1.1% for model_1 and 2.3% for model_2, respectively) than for discharges below 800 m^3/s. On the ground of both less erroneous discharge estimation and high coefficient of determination, it seems desirable to use calculated discharge by 5-cell scheme for discharge above approximately 800 m^3/s.

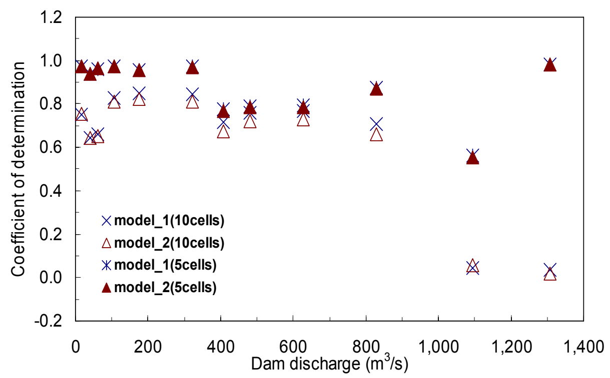

Figure 6: Coefficient of determination between calculated and measured velocity for 4 different conditions

5 CONCLUSIONS

In this study, we estimate lateral velocity distribution and discharge by using Chiu's entropy-based formulae with partially measured ADVM cell velocity data. The main outcome of this study is as follows:

For lateral velocity distribution, calculated values are roughly similar with measured data. But for higher discharge cases (> 800 m^3/s), discrepancy between calculated and measured velocity increases in outer cells.

Calculated discharge by 10-cell scheme gives fairly good agreement with reference discharge of the dam below 800 m^3/s, while 5-cell scheme seems more suitable for higher discharge. These characteristics are also shown in the plot of coefficient of determination.

This study shows another method for estimating velocity and discharge in natural rivers of irregular bed configuration. In addition, if a target river section has similar value for entropy parameter *M*, it is possible to estimate discharge for wide range without troublesome effort for developing conventional H-Q or index-velocity rating. But due to dampening of acoustic signal in water of high suspended sediment concentration, complementary method is necessary to meet higher flood condition.

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