ADCP MEASUREMENTS OF VERTICAL FLOW STRUCTURE AND COEFFICIENTS OF FLOAT IN FLOOD FLOWS

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ABSTRACT

To check the accuracy of coefficients of float, which are widely used in discharge measurements with float and image processing, we examine the coefficients of float by conducting ADCP measurements for flood flows in the Edo River and the Ara River in Japan. We compare the observed results for vertical flow structure with classical well-known velocity distributions, such as the logarithmic profile and Aki's theory. The latter theory is used to evaluate general coefficients of float. The observed velocity distributions are in better agreement with the logarithmic profile than Aki's theory. Note that the observed coefficients of float show a decreasing trend as the water depth increases and the average coefficients of float are less than the general values. These results for the coefficients of float are also in good agreement with those evaluated with the logarithmic profile

Keywords: Coefficient of float; Discharge measurement; ADCP; Float; Logarithmic profile; Vertical flow structure

1 INTRODUCTION

River discharge is important for river planning and management. Monitoring of river discharge has been conducted using various sensors and techniques, such as the Price current meter, the electromagnetic current meter, the rod-float, the acoustic Doppler current profiler (ADCP), the radio current meter, and the image processing technique (*e.g.*, Muller, 2002). Among these sensors and techniques, the rod-float, the radio current meter, and the image processing technique can measure surface velocity. To evaluate the depth-averaged velocity and the discharge from the surface velocity, it is necessary to adopt a coefficient of float, which is a ratio of a depth-averaged velocity to a surface velocity (Rantz, 1982).

Table 1 indicates general coefficients of float, which have been set up in line with Aki's theory for vertical velocity distribution (Aki, 1932). Although the coefficients of

Table 1 Coefficients of float generally used in Japan.

Water depth	Draft of float	Standard values
～0.7 m	water surface	0.85
0.7～1.3 m	0.5 m	0.88
1.3～2.6 m	1.0 m	0.91
2.6～5.2 m	2.0 m	0.94
5.2 m～	4.0 m	0.96

float have been confirmed through various laboratory experiments, few field data have been reported for the coefficients of float because no appropriate technique for measuring the vertical velocity profile in rivers has been developed. On the other hand, acoustic Doppler instruments like ADCP that are generally used in flow monitoring in oceans can measure vertical velocity profile and water depth simultaneously (*e.g.*, Pettigrew et al. 1986). Therefore, the ADCP is appropriate to obtain field data for the coefficients of float.

In order to check the accuracy of coefficients of float through field measurements, in the present study, we attempt to examine the coefficients of float by conducting ADCP measurements for flood flows in large rivers. We compare the observed results for vertical flow structure with classical well-known velocity distributions, such as the logarithmic profile and Aki's theory, which is used in the evaluation of the general coefficients of float. Furthermore the measured coefficients of float are also compared with the theoretical values.

2 METHODS OF FIELD MEASUREMENTS AND DATA ANALYSIS

2.1 FIELD OBSERVATIONS

The river-flow measurements with the ADCPs were performed in the Edo River and the Ara River, which flow into Tokyo Bay in Japan. As shown in Fig. 1, a total of six measurement stations (Stns. E1, E2, and E3 on the Edo River and Stns. A1, A2, and A3 on the Ara River) were chosen. The average widths of compound cross sections in both rivers are 400-700 m.

A 1,200 kHz ADCP (Teledyne RDI) was used for river-flow monitoring in the present field measurement. The ADCP can measure the vertical distribution of the three-dimensional velocity with fine vertical resolution in which the minimum cell size is 1 cm. On the Edo River, a down-looking ADCP was set up near the water surface while a

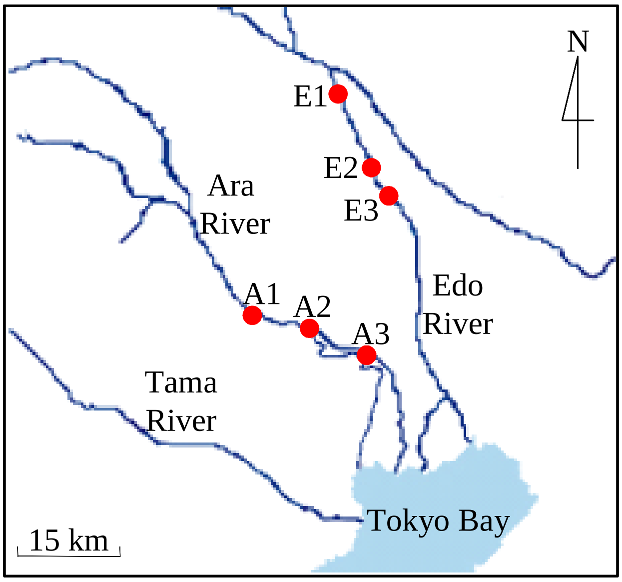


Fig. 1 Map of measurement stations

Table 2 Hydrologic events in which field measurements were conducted. Y. P. (Yedogawa Peil) and A. P. (Arakawa Peil) are the base levels in the Edo River and Ara River, respectively.

No.	Period	Stations	H.W.L.
1	Aug. 9～12, 2003	Edo River: Stn.E3	7.45 [Y.P.m]
2	Oct. 6～8, 2004	Edo River: Stns.E1 and E3	7.63 [Y.P.m]
3	Oct. 9～11, 2004	Ara River: Stns.A1, A2 and A3	3.24 [A.P.m]
4	Oct. 21～23, 2004	Edo River: Stns.E1 and E3	8.74 [Y.P.m]
		Ara River: Stns.A1, A2 and A3	3.27 [A.P.m]
5	July 27～28, 2005	Edo River: Stn.E3	8.02 [Y.P.m]
6	June 16～17, 2006	Edo River: Stn.E2	7.68 [Y.P.m]
7	July 19～20, 2006	Edo River: Stn.E2	9.21 [Y.P.m]

bottom-mounted, up-looking ADCP was used for continuous flow measurements in the Ara River. The cell sizes in the vertical direction are 20 cm and 10 cm in the Edo River and the Ara River, respectively. Table 2 lists seven hydrologic events in which the field measurements were conducted.

2.2 DATA ANALYSIS

To evaluate the coefficient of float, which is the ratio of the depth-averaged velocity to the surface velocity, we need the vertical velocity profile from the water surface to the riverbed. As shown in Fig. 2, the ADCP may not measure the velocity in the surface and bottom layers due to the measurement performance of the ADCP. When

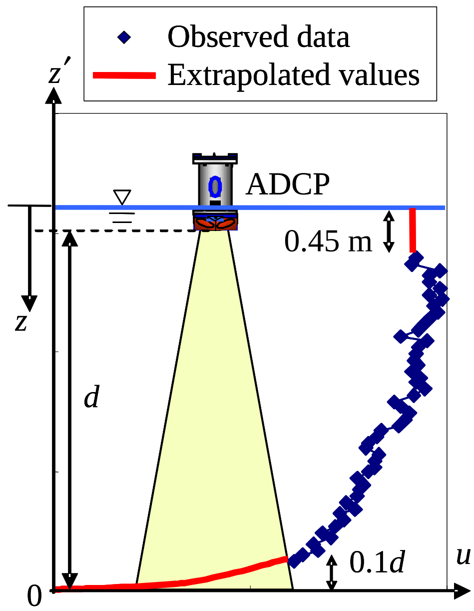


Fig. 2 Extrapolation procedure of velocities in the surface and bottom layers.

the ADCP are set near the water surface as depicted in the figure, the blank length, including the draft of the ADCP, is 0.45 m. Since, in this case, the acoustic signal transmitted from the sensors is received on the riverbed, there is a significant measurement error in the bottom layer, which has a thickness of 0.1*d*. It is therefore necessary to extrapolate the velocity in the surface and bottom layers. Then, the velocity in the surface layer is extrapolated to be the same as that in the upper layer of the measurement region. On the other hand, the bottom velocity is evaluated with the approximation of the logarithmic profile.

2.3 THEORY FOR VERTICAL VELOCITY DISTRIBUTION

The vertical distribution of velocity presented by Aki (1932), which is used to evaluate the general coefficients of float, as mentioned above, is expressed as

$$u = \sqrt{Ih}\left\{C + \frac{20}{3} - 20a + 40a\frac{z}{h} - 20\left(\frac{z}{h}\right)^2\right\}, \tag{1}$$

where I is the slope of the water elevation, z is the depth from the water surface, C is Chezy's coefficient ($= h^{1/6}/n$, h and n are the water depth and Manning's roughness coefficient, respectively), and a is the relative depth of the peak velocity. When evaluating the general coefficients of float, the relative depth of the peak velocity a is given as the function of the water depth h: *i.e.* a = 0, 0.1, 0.2, and 0.3 for h < 1 m, 1 < h < 2 m, 2 < h < 4 m and 4 m < h, respectively. From Eq. 1, the velocity profile normalized by the depth-averaged velocity u_m $(= C\sqrt{Ih})$ is given as

$$\frac{u}{u_m} = \frac{1}{C}\left\{C + \frac{20}{3} - 20a + 40a\frac{z}{h} - 20\left(\frac{z}{h}\right)^2\right\}. \tag{2}$$

The coefficient of float α_z is derived from Eqs. 1 and 2 as follows:

$$\alpha_z = \frac{u_m}{u_{mz}} = \frac{C}{\left\{C + \frac{20}{3} - 20a + 20a\frac{z}{h} - \frac{20}{3}\left(\frac{z}{h}\right)^2\right\}}, \tag{3}$$

The other theory of the vertical velocity profile is the logarithmic profile for rough-bottom turbulent flow, which is expressed as

$$\frac{u}{U_*} = \frac{1}{\kappa}\ln\frac{z'}{k_s} + A_r , \tag{4}$$

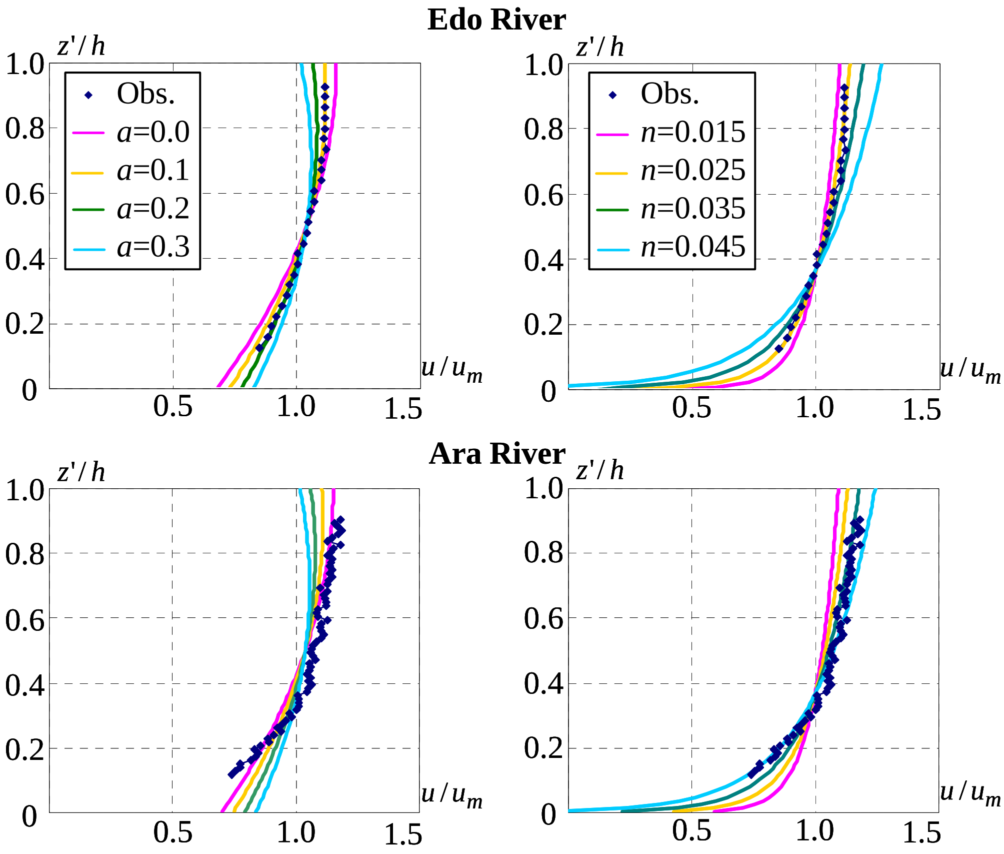
where U_* is the friction velocity, A_r is the constant (= 8.5), z' is the height from the bottom, and k_s is the equivalent roughness height. The normalized velocity profile and the coefficients of float are evaluated from Eq. 4.

3 RESULTS AND DISCUSSION

3.1 VERTICAL FLOW STRUCTURE

To compare the theoretical and observed results for vertical velocity profiles, Fig. 3 shows the vertical distributions of the normalized velocity u/u_m . As typical examples of the observed data, we choose the vertical velocity distribution at Stn. E2 (Edo River) in Event No.7 and that at Stn. A3 (Ara River) in Event No.3. In these cases, the water depths are 6.24 m at Stn. E2 and 9.04 m at Stn. A3. Aki's theory and the logarithmic profile, based on Eqs. 2 and 4, respectively, are also indicated here. In Aki's theory, Manning's roughness parameter *n* is given to 0.0325 $m^{-1/3}s$, while the relative height of the peak velocity *a* is given at 0.0, 0.1, 0.2, and 0.3. In the logarithmic profile, *n* is set at 0.015, 0.025, 0.035, and 0.045 $m^{-1/3}s$.

Figure 3(a) indicates the fundamental property of Aki's theory, whereby the peak velocity appears on the water surface at *a* = 0 and the depth of the peak velocity increases with *a*. It is also noteworthy that Aki's theory does not satisfy the no-slip condition on the bottom boundary. In other words, the velocity on the bottom is not zero. Comparison of the observed results and Aki's theory indicates that the theoretical values at *a* = 0.0 or 0.1 have better agreement with the observed data at Stn. E2. In the case of Stn. A3, close agreement between the observed and theoretical results is not



(a) Aki's theory (n = 0.0325 m$^{-1/3}$s) (b) Logarithmic profile

Fig. 3 Vertical distributions of the normalized velocity at Stn. E2 (Edo River) in Event No.7 and at Stn. A3 (Ara River) in Event No.3. The solid lines and dots show the theoretical and observed values, respectively. The unit of n is described with SI units.

obtained. Since the water depths are larger than 4 m in these cases, the general coefficients of float are evaluated with a = 0.3. However, the observed results agree better with the theoretical results at a = 0.0 or 0.1 than those at a = 0.3. On the other hand, the comparison of the observed results and the logarithmic profile reveals that the observed data agrees better with the theoretical values when n = 0.025 m$^{-1/3}$s at Stn. E2 and n = 0.035 or 0.045 m$^{-1/3}$s at Stn. A3. From the above comparison, note that the observed data generally conforms better to the logarithmic profile than Aki's theory.

To examine the relative depth of the peak velocity a in detail, the contour of the streamwise velocity at Stn. A3 is shown in Fig. 4. In the figure, the result at Event No.3 is chosen. The velocity in the surface and bottom layers is not depicted because, as mentioned above, the ADCP cannot measure the velocity in the surface and bottom layers. The solid lines corresponding to the heights of a = 0.1 and 0.3 are also shown here. Since Stn. A3 is located in a tidal reach, the tide influences the water elevation. As

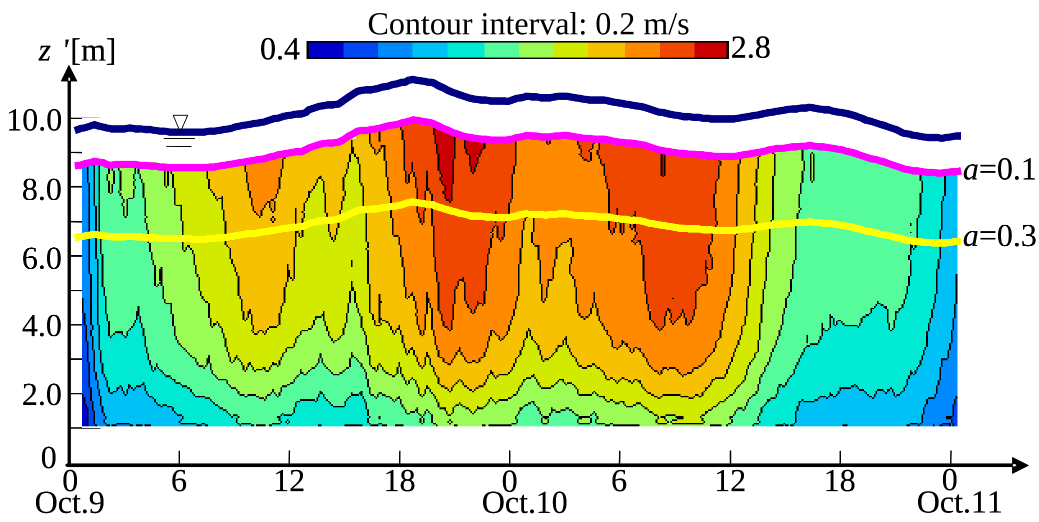


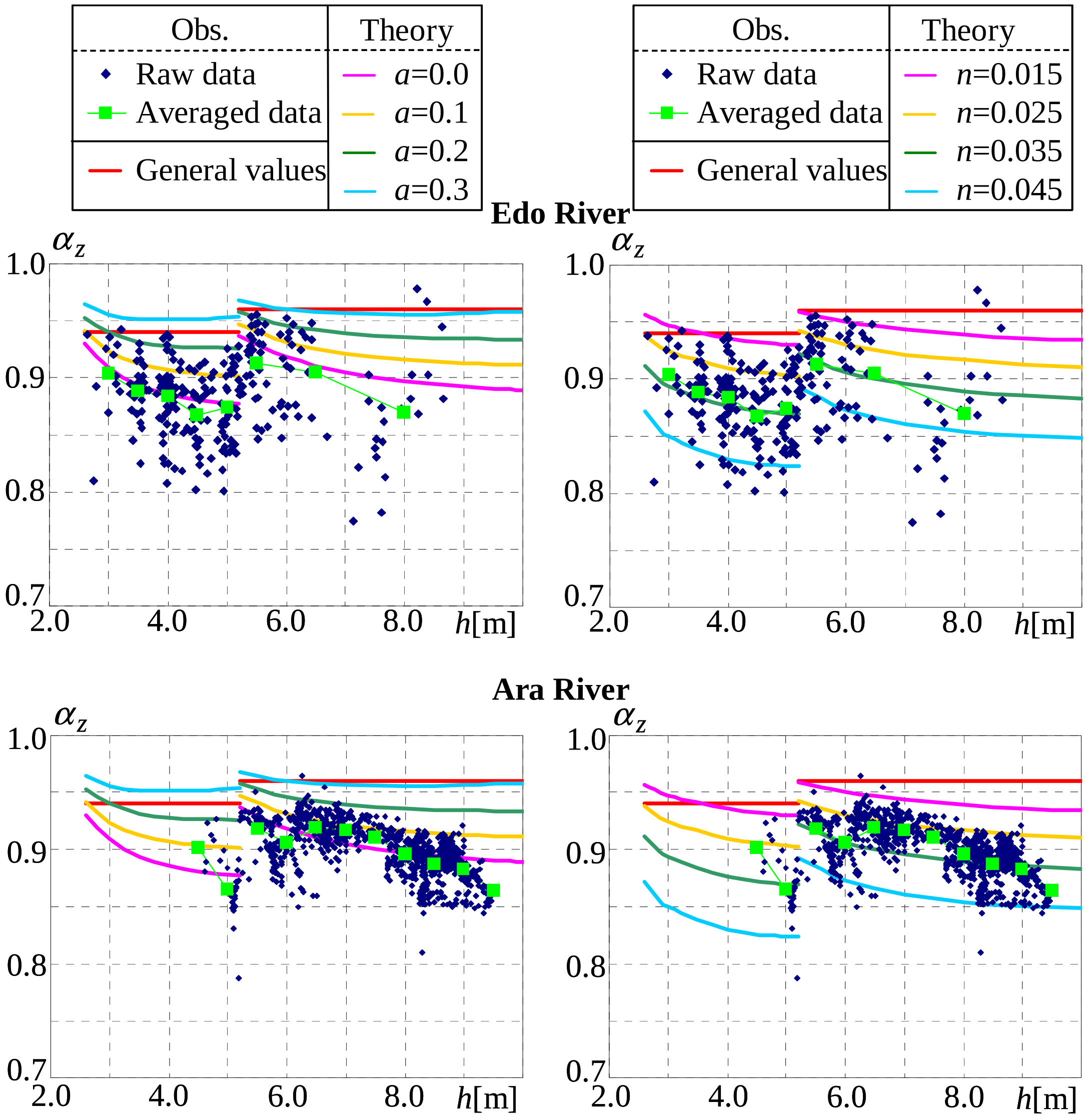
Fig. 4 Contour of the streamwise velocity at Stn.A3 for Event No.3.

such, there appeared several peaks in water elevation, as shown in Fig. 4. The streamwise velocity became maximum not at the rising stage, but at the falling stage just after the high water level. This is attributed to the superposition of the ebb-tide current and flood flow. Note that the relative depths of the peak velocity are located above the upper measurement region, *i.e.*, $0 < a < 0.1$. Therefore, no peak in the velocity appears at $a = 0.3$. This corresponds to the above discussion for Fig. 3.

3.2 COEFFICIENTS OF FLOAT

To compare the observed and theoretical values for the coefficients of float α_z, Fig. 5 indicates the correlations between the water depth and the coefficients of float in both rivers. In line with Table 1, the coefficients of float of 4 m and 2 m in length are evaluated with $h > 5.2$ m and 2.6 m $< h < 5.2$ m, respectively. In the figure, the moving-averaged values for α_z are plotted as points. Furthermore, the general values of α_z indicated in Table 1 are shown. In Aki's theory, n is selected at 0.0325 m$^{-1/3}$s in the figure. The common results for the Edo and Ara Rivers are that most of the observed coefficients of float are less than the general values of α_z. The observed values of α_z for the draft of 4 m in length are 0.87-0.91 for the Edo River and 0.86-0.92 for the Ara River, indicating that the general value of α_z for the draft of 4 m in length (= 0.96) is 0.04-0.10 larger than the observed data.

In both theories, the coefficients of float α_z show a decreasing trend as water depth increases. This trend agrees well with the moving-averaged values for the observed α_z. In Aki's theory, the theoretical values at a = 0 or 0.1 are in relatively



(a) Aki's theory (n = 0.0325 $m^{-1/3}s$) (b) Logarithmic profile

Fig. 5 Correlations of the water depth and the coefficients of float α_z.

better agreement with the observed data. On the other hand, in the logarithmic profile, the observed α_z has better agreement with the theoretical values with n = 0.035 $m^{-1/3}s$ for the Edo River and n = 0.025 or 0.035 $m^{-1/3}s$ for the Ara River. The observed coefficients of float are also in better agreement with those evaluated with the logarithmic profile than with Aki's theory. Furthermore, appreciable differences appear between the observed and theoretical values for α_z when, in Aki's theory, a is set to 0.3, which is adopted in order to evaluate the general coefficients of float. This fact demonstrates that the accuracy of the general coefficients of float is appreciably influenced by the evaluation of the relative height of the peak velocity a.

4 CONCLUSIONS

To check the accuracy of coefficients of float, which are widely used in discharge measurements with float and image processing, we examine the coefficients of float by conducting ADCP measurements for flood flows in the Edo and Ara Rivers in Japan. We compare the observed results for the vertical flow structure with classical well-known velocity distributions, such as the logarithmic profile and Aki's theory, which is used in the evaluation of the general coefficients of float. The observed velocity distributions are in better agreement with the logarithmic profile than with Aki's theory. It is noteworthy that the observed coefficients of float show a decreasing trend as the water depth increases and the averaged coefficients of float are less than the general values. These results for the coefficients of float are also in good agreement with those evaluated with the logarithmic profile.

The above knowledge is useful for the Edo River and Ara River under the flood flows presented here. However, there is no positive proof that these results can be applied to other rivers. Therefore, it is necessary to collect field data for the vertical velocity distribution and the coefficients of float under various flood-flow conditions and for various field sites.

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