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Evaluation of river velocity and discharge with a new assimilated method

YASUO NIHEI, *Associate Professor, Department of Civil Engineering, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba, 278-8510, Japan*

AKIRA KIMIZU, *Graduate Student, Department of Civil Engineering, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba, 278-8510, Japan*

ABSTRACT
To evaluate accurately river discharge by using the velocities observed at discrete points in a cross section, a new method is presented for data assimilation in which observed velocities are properly incorporated into a river-flow computation. In the present method, a shallow-water flow model is adopted, introducing a new additional term to incorporate smoothly the influence of the observed data into the numerical simulation over the whole cross section. The spatially observed velocities can then be interpolated in a cross section by satisfying dynamic principles for fluid motion. The present method is therefore referred to be here as a dynamic interpolation method. To confirm the fundamental performance of the dynamic interpolation method, the present method has been applied to the spatial interpolation of velocities in a cross section with the simulation data for a river-flow computation done by the authors. The interpolated results indicate that the present method can have high accuracy for the evaluation of river velocity and discharge.

Keywords: Data assimilation; river flow; discharge; dynamic interpolation method; ADCP.

1 Introduction

To realize river management taking account of flood control, irrigation and the environment, it is necessary to monitor the velocity and discharge in rivers with a high level of accuracy. Measurement for the velocity in rivers has been performed with floats, electromagnetic current meters, radio current meter, ADCP (Acoustic Doppler Current Profiler) and so on (e.g., Kinoshita, 1984). In estimating river discharges, the river velocities are normally measured at discrete points in a cross section of a river with these types of current meters, and the velocities are integrated over the cross section. For this purpose, it is necessary to interpolate spatially the river velocities observed at discrete points in the cross section. The accuracy of the evaluated river discharge is appreciably dependent on that of the spatial interpolation methods, and then simple spatial interpolation for velocities without considering hydrodynamic laws may cause significant errors for estimating the discharge.

To perform the spatial interpolation of discretely observed velocities with a proper physical background, one of the promising tools is to adopt data assimilations in which observed results for velocities are appropriately incorporated into numerical simulations for river flow. Such data assimilations are widely used in meteorology and oceanography (e.g., Lonenc, 1986; Robinson *et al.*, 1998). Concerning computations for river flows, however, there exist only a few applications of data assimilations (Sulzer *et al.*, 2002), and a general methodology of the data assimilation has not been established for river-flow computations.

In the present study, a new method is developed for the data assimilation, in which observed results for velocities are properly taken into account for river-flow computations. In the present method, the depth-averaged velocities are assimilated at discrete points in a cross section into a shallow-water flow model, and then the observed velocities are spatially interpolated in the cross section with satisfying the dynamic principles of fluid motion. The present method is therefore referred to herein as a dynamic interpolation method. To confirm the fundamental performance of the present method, the method has been applied to the spatial interpolation of velocities with simulation data for a river-flow computation (Yamasaki and Nihei, 2005).

2 Outline of the present method

2.1 Fundamental structure

The present method commonly used to evaluate the velocity and discharge in rivers consists of field measurements, numerical simulations and data assimilations, as shown in Fig. 1. Among these approaches, the combination of numerical simulations and data assimilations corresponds to the dynamic interpolation method. In the field measurements, the river velocities are recorded at discrete points in a cross section. For the measurement of the

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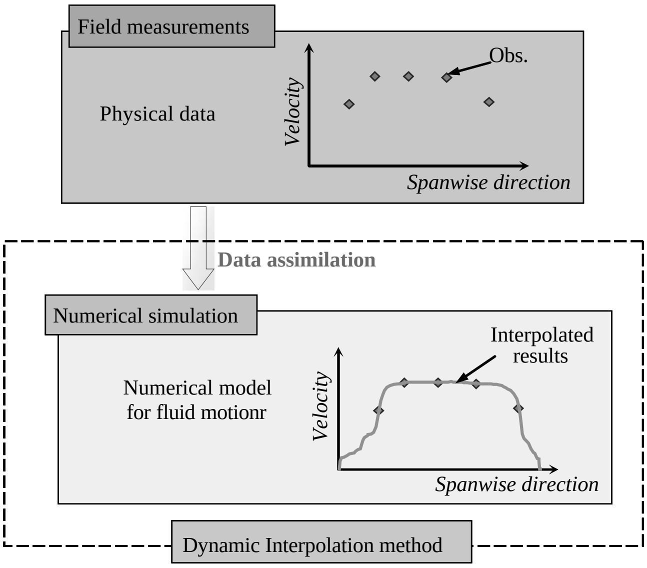


Figure 1 Fundamental structure of the present method.

river velocity, in the present study, a High Resolution Acoustic Doppler Current Profiler (HR-ADCP, RD Instrument) has been used to measure the vertical distribution of three-dimensional velocities with a high level of accuracy and a fine resolution. The depth-averaged velocity measured with the HR-ADCP is used for the data assimilation. In the numerical simulations a shallow-water flow model has been adopted, in which the governing equations are based on the depth-averaged two-dimensional mass and momentum conservation equations. To reflect rationally the observed results in the numerical simulations, a new approach for data assimilation is outlined below. In assessing the fundamental performance of the dynamic interpolation method, a simulation data study has been undertaken for a flood flow computation. Applications of the present method to the field data obtained using the HR-ADCP will be shown in near future.

2.2 Governing equation in the dynamic interpolation method

To outline the dynamic interpolation method, the governing equation used in this method is first detailed. A shallow-water flow model is used for the horizontally two-dimensional flow field, since the horizontal scale of river flows is generally much larger than the vertical scale. The depth-averaged momentum equation in the streamwise direction is expressed as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = gI + A_H\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \left(\frac{C_f}{h} + \frac{aC_D}{2}\right)u\sqrt{u^2+v^2}, \quad (1)$$

where t is time, x and y are the streamwise and spanwise coordinate directions, u and v are the depth-averaged velocities in the x and y directions, h is the water depth, g is the gravitational acceleration and I is the slope of the water elevation. The horizontal eddy viscosity A_H and the coefficient of bottom friction C_f in Eq. (1) are given as

$$A_H = \alpha U_* h = \alpha\sqrt{C_f}uh, \quad (2)$$

$$C_f = \frac{gn^2}{h^{1/3}}, \quad (3)$$

where α is a constant value, U_* is the friction velocity and n is the Manning roughness coefficient. The third term on the right-hand side of Eq. (1) includes the vegetation drag represented by the density of vegetation a and a drag coefficient of vegetation C_D in line with previous studies for river-flow computations (e.g., Nadaoka and Yagi, 1998). Since it is difficult to estimate the advective and horizontal diffusion terms in Eq. (1) only by using observed velocities at discrete points in a cross section, these terms are neglected in Eq. (1), giving:

$$gI + A_H\frac{\partial^2 u}{\partial y^2} - \left(\frac{C_f}{h} + \frac{aC_D}{2}\right)u^2 + F_a = 0. \quad (4)$$

The unsteady term is also neglected since this term is much less than the other terms in the above equation. Instead of these terms neglected here, an additional term F_a is introduced, which considers the effects of the neglected terms in Eq. (4). The additional term F_a is determined from the measured velocities as highlighted below.

2.3 Numerical procedure of the dynamic interpolation method

To obtain the solution of the river velocity u using Eq. (4), a finite difference solution has been adopted in the current study. Using a second-order central difference scheme for the horizontal diffusion term in Eq. (4), the finite difference equation is given as:

$$gI + \alpha\sqrt{C_{f_i}}u_i h_i\left(\frac{u_{i+1} - 2u_i + u_{i-1}}{(\Delta y_i)^2}\right) - \left(\frac{C_{f_i}}{h_i} + \frac{aC_D}{2}\right)u_i^2 + F_{a_i} = 0, \quad (5)$$

where the subscript i refers to the grid number and Δy is the grid interval in the spanwise direction. To evaluate the velocity and discharge in the cross section, Eq. (5) is then solved using the measured velocities at discrete points in the cross section through the following 4 steps:

1. F_a at each observational point is evaluated with Eq. (5) and measured velocities.
2. The spanwise distribution of F_a in the cross section is given by spatially interpolating F_a at the observational points.
3. The velocity in the streamwise direction $u(y)$ is given using Eq. (5) and the value of F_a obtained at step 2.
4. The calculation of the steps 1, 2 and 3 is repeated until the solution of Eq. (5) converges.

It should be noted that the present method for data assimilation can incorporate smoothly the influence of the measured data into the computational results over a whole cross section by introducing the additional term F_a into Eq. (4).

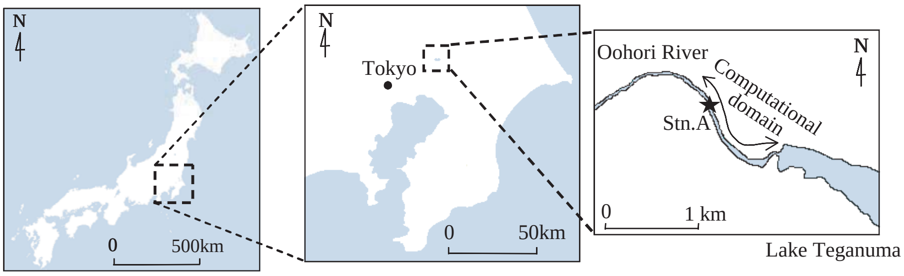


Figure 2 Site of the river-flow simulation.

3 Verification of the dynamic interpolation method

3.1 Outline of simulation data

To examine the fundamental performance of the dynamic interpolation method developed herein, the present method has been applied to the spatial interpolation of river velocities in a cross section with the simulation data obtained for a flood flow computation (Yamasaki and Nihei, 2005). As shown in Fig. 2, the site of the numerical simulations is the estuarine section of the Oohori River, located in the north-west part of Chiba Prefecture in Japan. The Oohori River, one of many typical urban rivers in Japan, is about 50 m wide and 0.8 m deep in the estuary under normal atmospheric conditions. The numerical simulations were performed for a hydrologic event from 20 to 21 May, 2004. The simulation data was selected from the data at 3:30 on May 21 in 2004 at which the peak water elevation appeared in the hydrologic event. The location of the simulation data was at Stn.A, as shown in Fig. 2, and about 1.0 km upstream from the river mouth. The cross-sectional details at Stn.A are depicted in Fig. 3(a), with Fig. 3(b) indicating the lateral distribution of the simulation data for the depth-averaged velocities in the streamwise direction. Further details of the numerical simulations are given in Yamasaki and Nihei (2005).

3.2 Computational conditions

The number of simulation data values recorded across the cross section is 15 as shown in Fig. 3(b). To examine the numerical accuracy of the present method for the spatial interpolation of river velocities, some of simulation data were interpolated spatially over the cross section using the present method. The coefficients in Eqs. (2) and (3) were given as $\alpha = 0.067$ and $n = 0.022\,\mathrm{m}^{-1/3}\,\mathrm{s}$. Vegetation drag was not considered in the numerical simulations. The number and interval of the computational grids in the spanwise direction were 65 and 2.92 m, respectively. The gradient of the water elevation I in Eq. (5) was set to be 0.004 in line with the simulated results.

In comparing the interpolated and simulated velocities, the accuracy for the spatial interpolation was checked using the present method. For comparison, the velocity distributions were evaluated by simply conducting the spatial interpolation for the simulated velocities, which are referred herein as the simple interpolation method. A linear interpolation for the velocities was used in the simple interpolation method.

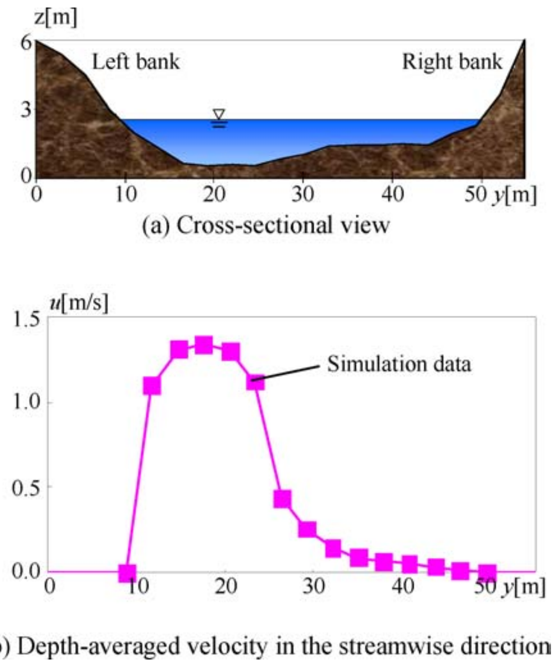
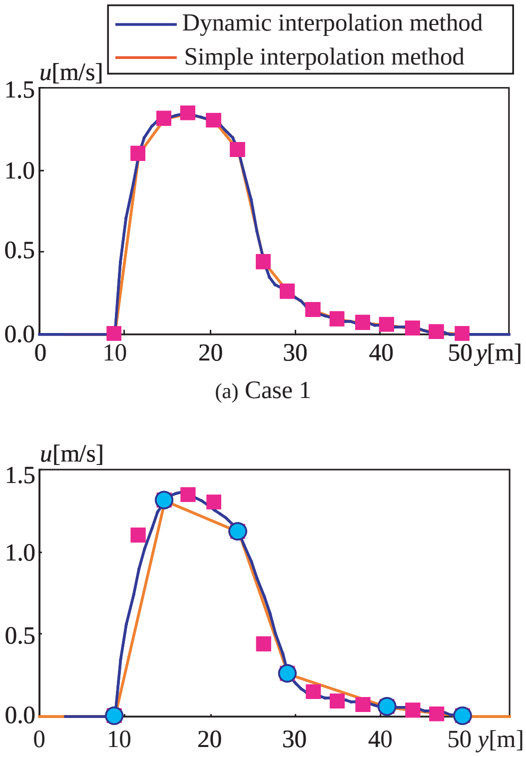


Figure 3 Simulation data for water depth and velocity in the cross section at Stn.A.

3.3 Results and discussion

Figure 4 illustrates examples of the interpolated velocities using the dynamic and simple interpolation methods for two cases. In Case 1, all simulation data were used to perform the spatial interpolation of the velocities in the spanwise direction. In contrast, for Case 2, only 6 of the data values, as shown by circles in Fig. 4(b), were used to interpolate spatially the velocities. The other simulated velocities, not used in the spatial interpolation, are expressed as squares in the figure. For Case 1, the results using both methods gave completely agreement with the simulated velocities. Also the lateral distribution of the interpolated velocities with the dynamic interpolation method varied smoothly over the cross section. This result showed that the present method can reflect more rationally the simulated results over the whole cross section as compared to a nudging scheme, i.e. one of general methods used for data assimilations. For Case 2, although differences appeared at a few points between the interpolated results using the present method and the simulated data, the results using the present method gave better agreement with the simulated velocities than those obtained using the simple interpolation method. This fact demonstrates that the present method has a higher performance for the spatial interpolation of the velocities at discrete points across the cross section.



(a) Case 1

(b) Case 2 (circles and squares depict the data used and not used in the spatial interpolation, respectively)

Figure 4 Lateral distributions of the interpolated velocities using both methods.

To confirm the dynamic balance for fluid motion for Case 1, Fig. 5 represents the lateral distribution for each term of Eq. (4). In the figure, the first, second, third and fourth terms in Eq. (4) are referred to herein as the water-elevation gradient, horizontal diffusion, bottom friction and F_a, respectively. The terms for the water-elevation gradient and bottom friction are positive and negative over the whole cross section, respectively, while the additional term F_a has positive and negative values over the cross section. It should be noted that the distribution of F_a in the spanwise direction varied smoothly, as shown for the velocities depicted in Fig. 4. Figure 6 indicates a comparison of the lateral distribution of F_a for Cases 1 and 2. The squares and circles show the simulation data used in the spatial interpolation for the Cases 1 and 2, respectively. Although at about $y = 10$ m the value of F_a for Case 2 was less than that for Case 1, both the results are in acceptable agreement. This result means that the solution of the additional term does not change appreciably, even

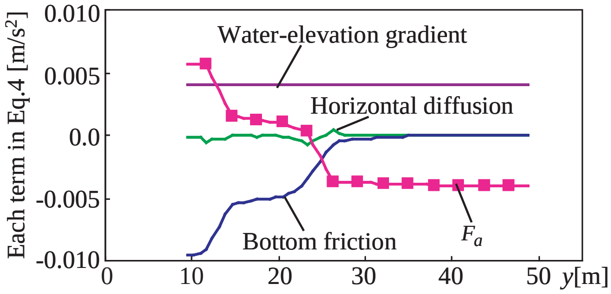


Figure 5 Dynamic balance for fluid motion for Case 1.

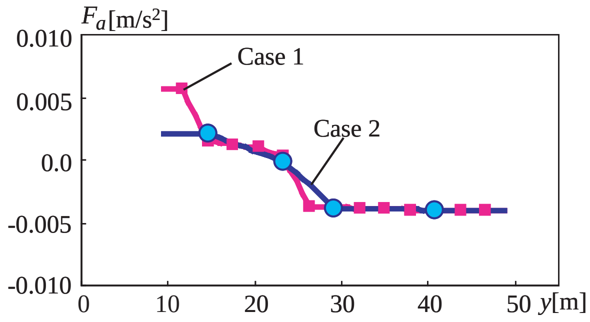


Figure 6 Comparison of the lateral distribution of F_a for Cases 1 and 2.

though the number of the simulated velocities used in the spatial interpolation was small.

4 Conclusions

To evaluate accurately river velocities and discharges from observed data, a new method has been developed in the present study for data assimilation, in which observed results for velocities have been appropriately incorporated into a river-flow computation. In the present method, a new additional term has been introduced into the depth-averaged momentum equation to reflect smoothly the influence of the observed data in the numerical simulations over the whole cross section. To confirm the fundamental performance of the present method, the present method is applied to the spatial interpolation of the velocities across the cross section using simulation data for the river-flow computations. The results indicate that the interpolated velocities using the present method give better agreement with the simulation data than those obtained using the simple interpolation method, and thereby demonstrating that the present method provides a higher level of accuracy for the spatial interpolation of velocities over a cross section.

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