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Accurate Estimation of Discharge Hydrograph in a Compound Meandering Channel Using a Two-Dimensional Numerical Model

ACCURATE ESTIMATION OF DISCHARGE HYDROGRAPH IN A COMPOUND MEANDERING CHANNEL USING A TWO-DIMENSIONAL NUMERICAL MODEL

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ABSTRACT

An accurate estimation of flood discharge hydrographs has been one of the most important issues in River Engineering. This paper explores a numerical estimation method of discharge hydrograph at arbitrary cross sections by using 2-d shallow water equations and water level hydrographs measured at gauging stations. The numerical method adopts CIP-CLS2 scheme for convective terms in the shallow water equations. It is applied to an experiment on unsteady flow in a compound meandering channel. The comparison between the experiment and the numerical simulation reveals that the propagation speed of flood peak can be used to estimate the flow resistance in the channel and thereby the present method can reproduce the discharge hydrograph with high accuracy.

Keywords: flood discharge hydrograph, water level hydrograph, 2-d numerical simulation, compound meandering channel, CIP-CLS2 scheme

1. INTRODUCTION

A compound channel, consisting of main channel and floodplains, is a representative shape of large rivers in Japan. It is known that the attenuation of peak discharge and the deformation of discharge hydrograph in meandering compound channels are significantly affected by river channel shape and floodplain roughness, which is necessary to be clarified for river improvement plans.

Fukuoka et al. (2004) paid special attention to the accuracy of and accessibility to water level hydrographs and proposed a methodology to estimate flood discharge hydrograph with a 2-D numerical method coupled with water level hydrographs along the river reach and at the upstream and downstream boundaries. They demonstrated that their approach can give better estimation of discharge hydrograph at an arbitrary cross section when the floodplain roughness and the permeability of vegetation are well predicted, which is realized in their method to reproduce the discharge hydrograph observed at a station.

Recently Uchida and Kawahara (2006) developed a 2-D numerical model for unsteady shallow flows on the Cartesian coordinate system with the CIP-CLS2 scheme originally proposed by Nakamura et al. (2001). Uchida and Kawahara demonstrated that their numerical model works very well for complex flows even with coarse grids.

In this study, following Fukuoka et al. (2004), we develop an estimation method for discharge hydrograph using water level hydrographs at gauging stations. Our method,

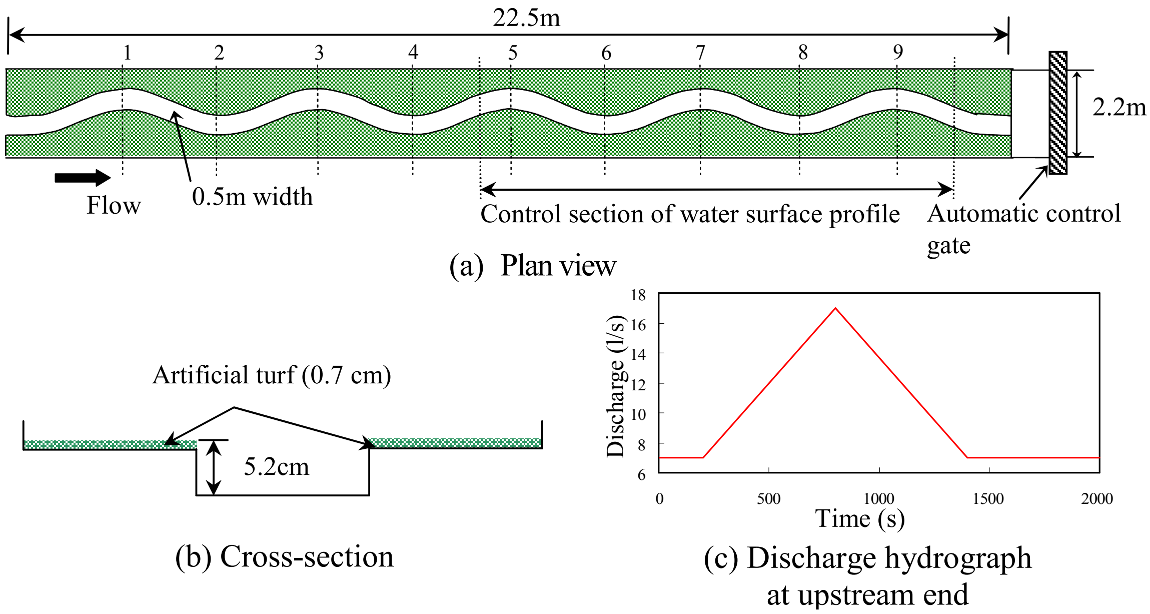


Figure 1 Experimental setup and condition.

however, differs from that of Fukuoka et al. in two points. First, our method does not use any observed discharge hydrograph but uses the propagation speed of flood peak to estimate the flow resistance in the river reach. Second, it also uses the 2-D numerical model by Uchida-Kawahara (2006). This paper consists of three parts; 1) the description of the experiment on unsteady flow in a compound meandering channel (Morishita et al., 2006), which is used to validate our method, 2) the explanation of our numerical model and 3) the application of our model to the experiment to show that the floodplain roughness can be well estimated from the observed propagation speed of the flood peak and that thereby discharge hydrograph can be calculated accurately.

2. EXPERIMENTAL SETUP AND CONDITIONS

Figure 1 shows the compound meandering channel used in this study. The channel has 22.5 m in length, and its slope is fixed at 1/1,000. It has a smooth main channel and adjacent roughened floodplains. The height of the floodplains is 5.2cm including the artificial turf on the floodplains. The roughness coefficients of the main channel and the floodplains are n_{mc}=0.010 and n_{fp}=0.021, respectively. It has five waves of meandering reaches with a sinuosity of 1.10.

We repeatedly generate the discharge hydrograph of an isosceles triangle to measure the time variation in water level at nine cross-sections shown in Figure 1. Three velocity components are measured by two-component electromagnetic current meters in the reach between sections 6 and 7. The gate at the downstream end is automatically controlled to maintain a constant water surface slope in the measuring reach throughout the flood.

3. NUMERICAL MODEL

Uchida and Kawahara (2006) developed a 2-D numerical simulation model to simulate inundation flows in urban areas which have complex structures and boundary conditions. They demonstrated that the model can give more accurate results than conventional methods even with relatively coarse numerical grids on Cartesian coordinate system.

The governing equations of two-dimensional unsteady flows in a compound

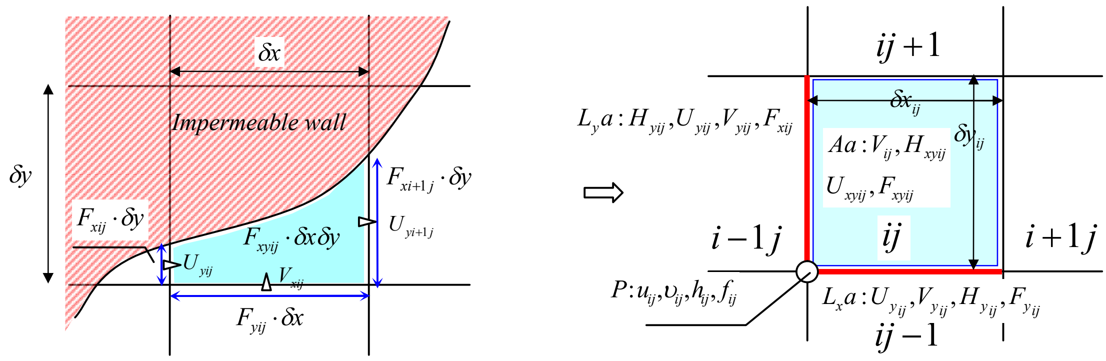


Figure 2 Computational grids with impermeable walls and the arrangement of main variables on the volume *ij*.

meandering channel are described by the following shallow water equations

$$\frac{\partial fh}{\partial t} + \frac{\partial u_j \cdot fh}{\partial x_j} = 0 \tag{1}$$

$$\frac{1}{fh}\left(\frac{\partial fu_i h}{\partial t} + \frac{\partial u_j \cdot fu_i h}{\partial x_j}\right) = -g\frac{\partial \zeta}{\partial x_i} - \frac{\tau_{0i}}{h} + \frac{\partial \tau_{ij} h}{h \partial x_j} \tag{2}$$

where subscripts i,j follow the summation convention, indicating $1 = x$ and $2 = y$, respectively; h = water depth; u_i = velocity in the x_i direction; f= occupancy ratio of fluid; g = acceleration due to gravity; ζ = water surface elevation (h+z); z = ground elevation; τ_{0i}=bed shear stress ; and τ_{ij}= horizontal shear stress tensor due to diffusion and dispersion. In this study, bed shear stress is expressed by the Manning equation. The Reynolds stresses are represented by an eddy-viscosity model.

Figure 2 shows a computational grid consisting of permeable and impermeable areas together with the arrangement of main variables in the grid. All the variables in the governing equations are set at the same location. Each control volume *ij* has three kinds of variables, i.e., the value at the intersection of the grid (Point Value (*P*), denoted by lower-case characters), the averaged value along the side of the grid (Line-averaged Value ($L_x a$, $L_y a$), upper-cased with subscript of *x* or *y*) and the averaged value over the grid (Area-averaged Value (*Aa*), shown with capital letters with subscript of *xy*). The staggered grid systems usually require the interpolation of the variables in many numerical schemes including the original CIP scheme whereas in the present scheme no interpolation is necessary. Many types of boundary conditions can be taken into account by using the three kinds of valuables. In the original CIP scheme for the shallow water equations, the advection terms are transformed from conservative form into non-conservative form to eliminate water depth *h* in the advection terms with the help of the Continuity equation (1). In the present scheme, time variation of the depth-integrated momentums and water depths are computed directly by CIP-CSL2 (Nakamura et al., 2001) without the transformation of the advection terms.

The grid size used in the study is 10 cm×5 cm and the time step is 0.005 sec. The water levels are changed in the imaginary ponds set at the upstream and downstream ends in such a way that the observed water levels are reproduced at the upstream and downstream ends of the calculation domain.

4. NUMERICAL RESULTS AND DISCUSSIONS

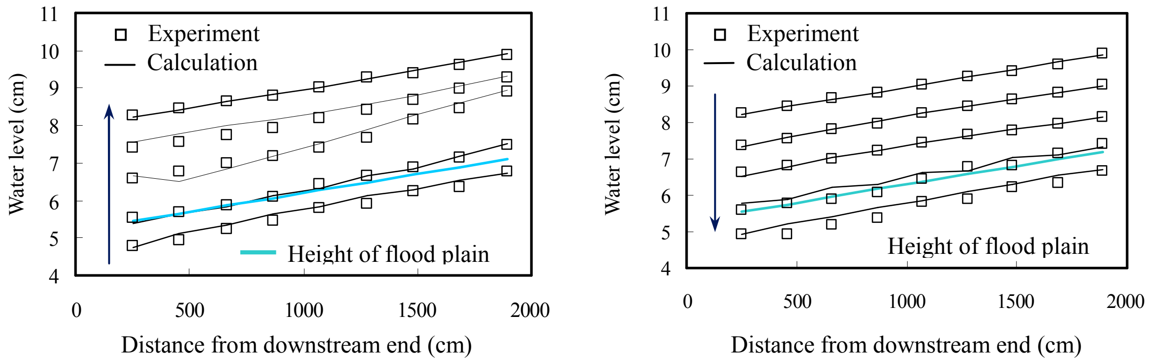


Figure 3 Time change in longitudinal profile of water level.
(Left : Rising stage, Right : Falling stage)

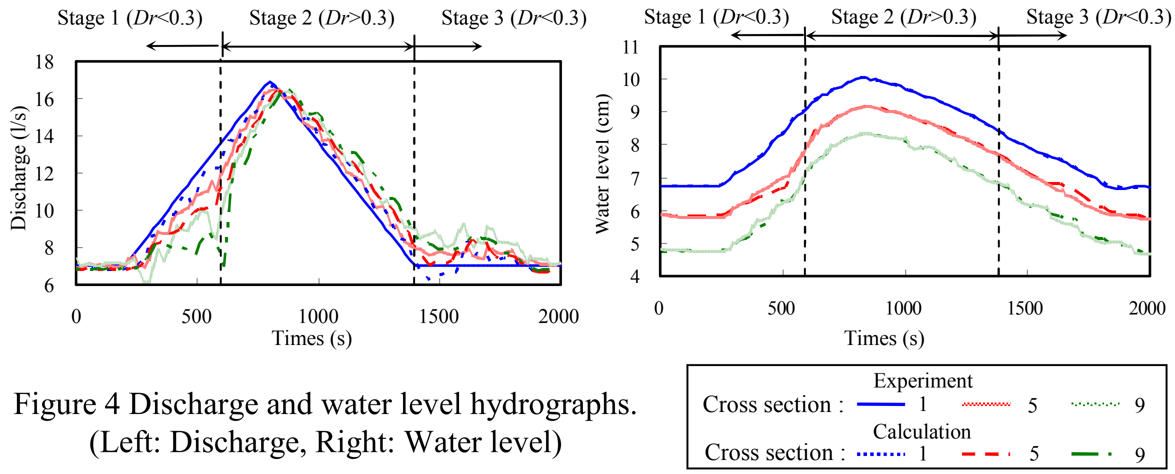


Figure 4 Discharge and water level hydrographs.
(Left: Discharge, Right: Water level)

Comparison with experimental results

Figure 3 shows the experimental and computational results of the longitudinal water level profiles in rising and falling stages with the floodplain roughness of 0.021. We divide the flood hydrograph into three parts, which are Stage 1, Stage 2, and Stage 3, based on the relative depth Dr (defined as the ratio of depth over the flood plains to that in the main channel). Main emphasis is placed on the numerical results in Stage 2 where the effects of the flow interaction between main channel and floodplains are strong and the effect of the artificial turf over the floodplains is significant.

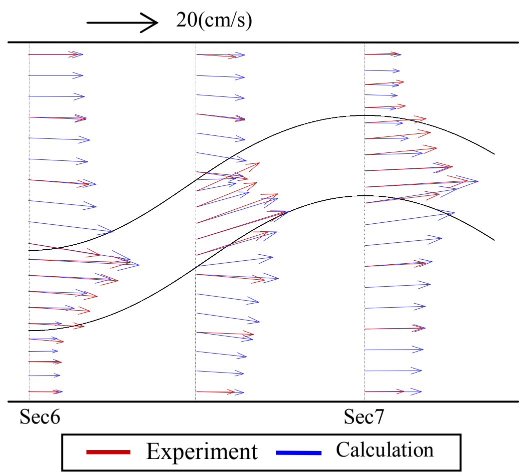


Figure 5 Comparison of depth-averaged velocity.

Figure 4 also compares the calculated results and the observed ones of discharge and water level hydrographs in cross-sections 1, 5, and 9. The computational results agree fairly well with the experimental ones, particularly in Stage 2.

Figure 5 depicts the depth averaged velocity distributions at t=880 sec near the peak of the flood. The calculated velocity vectors show good agreement with the measured ones except near the interface between main channel and floodplains where the flow field become highly three-dimensional.

Estimation of floodplain roughness

We carry out numerical calculations for nine cases to estimate the effects of the flood plain roughness on the longitudinal water level profiles, the water level and the discharge hydrographs. Table 1 summarizes the nine cases where the floodplain roughness n_{fp} are consistently changed around 0.021 in Run 5, because it leads to the best agreement with the measured data.

Figure 6 shows the longitudinal profiles of water levels in rising and falling stages for two values of n_{fp}. In Figure 6 it is confirmed that the longitudinal water level profiles are not much affected by the different value of n_{fp} since the water levels at boundaries are the same in all cases.

Figures 7 demonstrate the discharge and the water level hydrographs in cross section 5 for several values of n_{fp}. It is clear that the discharge in cross-section 5 changes significantly according to the value of n_{fp}, particularly in Stage 2 near the flood peak. Meanwhile, the water level hardly changes irrespective of the change in floodplain roughness.

We scrutinize the sensitivity of the discharge and the water level to n_{fp}. Figure 8 shows the relations between the relative errors in discharge and water level and the relative error of n_{fp}. The computational result in Run 5 is treated as the reference and the deviations from it in the other cases are regarded as errors.

Table 1 Computational conditions

	Floodplain roughness n_{fp}	Change compared with Run 5 (%)
Run 1	0.010	-52.4
Run 2	0.017	-19.0
Run 3	0.019	-9.5
Run 4	0.020	-4.8
Run 5	0.021	0.0
Run 6	0.022	4.8
Run 7	0.023	9.5
Run 8	0.025	19.0
Run 9	0.030	42.9

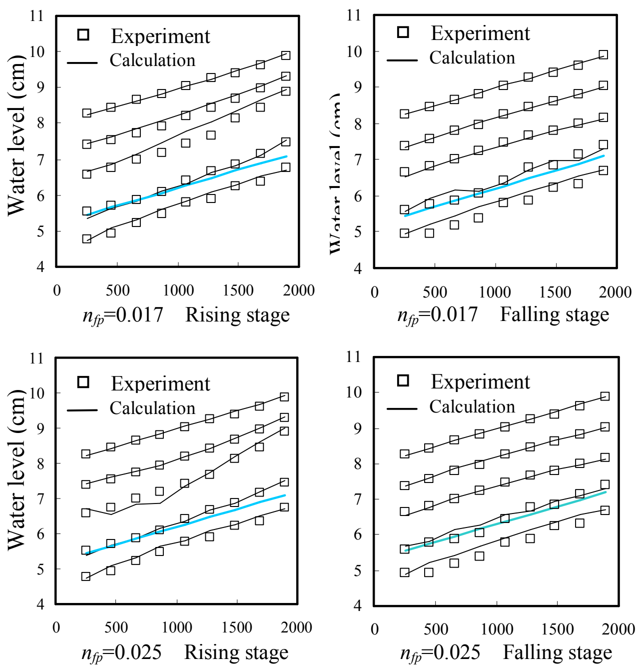
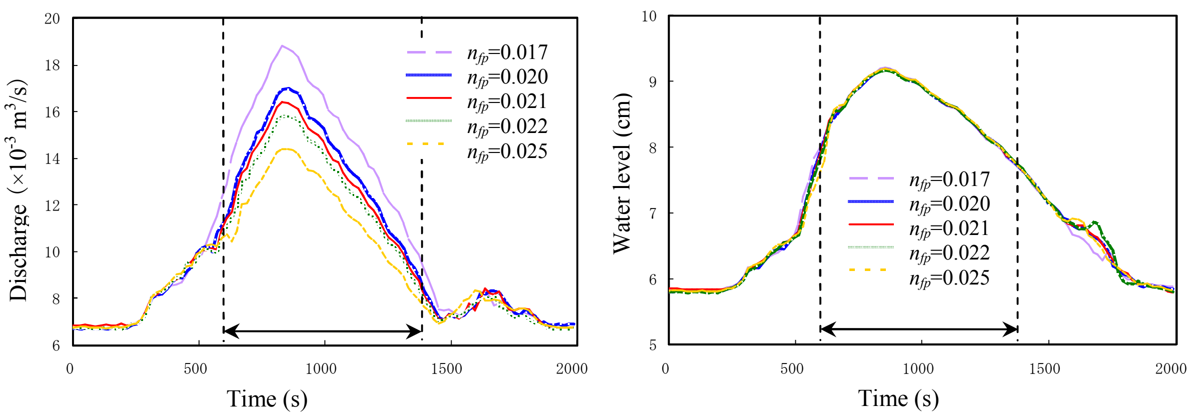


Figure 6 Time change in longitudinal water level profiles.



(a) Discharge hydrograph (b) Water level hydrograph

Figure 7 Effects of floodplain roughness on discharge and water level hydrographs.

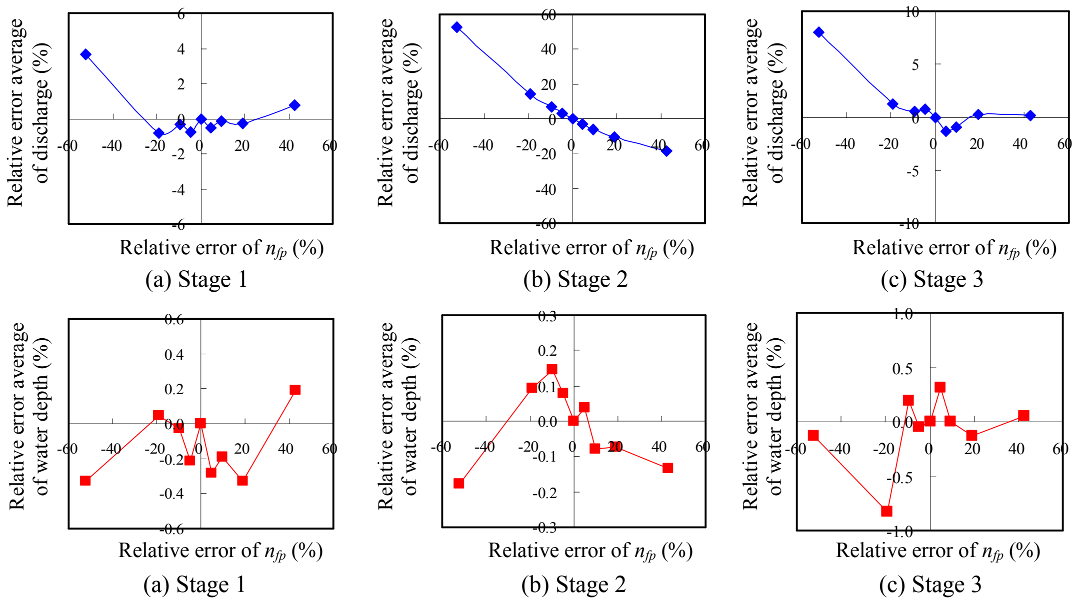


Figure 8 Relation between the error in discharge/water level and the error in n_{fp}.

The relative error of discharge increases linearly from -10% to 20% in Stage 2 when the error of n_{fp} varies from 20% to -20% in Stage 2. Contrarily the sensitivity of the water level to n_{fp} is much smaller than that of discharge. This means that even if the calculated water level shows good agreement with the measured one with accuracy of less than 1%, the accuracy of discharge is not high. For this reason, the information on observed discharge at a cross-section is important to estimate the discharge hydrograph with high degree of accuracy, which is the basic concept of Fukuoka et al. (2004).

Figure 9 shows the relationship between the occurrence time of peak water level and the location, where the distance and the time are non-dimensionalized by the distance between Sections 1 and 9 and by the time difference of the peak water level at Sections 1 and 9, respectively. We can obtain this relationship from water level hydrographs at multiple points along the channel and we do not need measured discharge data. Hence it can be said that if we can determine the floodplain roughness through the tuning of the occurrence time of water level, we can calculate the discharge hydrograph with enough accuracy. Naturally the flood discharge data taken at some water depth, not at its peak, are useful to estimate the magnitude of floodplain roughness.

5. CONCLUSIONS

We have developed a numerical estimation method of discharge hydrograph at arbitrary cross sections by using 2-d shallow water equations and water level hydrographs measured at multiple locations. The numerical method adopting CIP-CLS2 scheme is applied to an unsteady flow in a compound meandering channel. The comparison between the calculated results and observed ones reveals that the propagation speed of flood peak

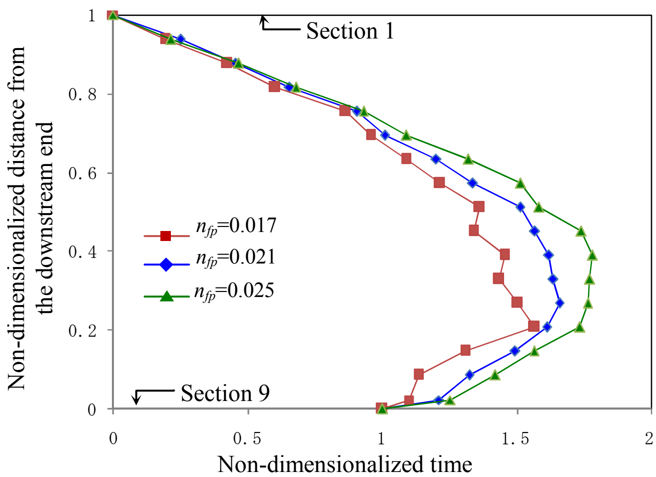


Figure 9 Relation between the time of water level peak and the floodplain roughness.

can be used to estimate the floodplain roughness and thereby the present method can reproduce the discharge hydrograph with high accuracy. The observed data of discharge are useful to determine the floodplain roughness but are not always necessary with the present method.

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