

STUDY ON THE STRUCTURE OF SECONDARY FLOW IN A COMPOUND MEANDERING CHANNEL WITH LONGITUDINAL VARIATIONS IN PLANFORM AND CROSS SECTION, BASED ON THE CHANNEL EXPERIMENT AND QUASI-THREE-DIMENSIONAL ANALYSIS (Q3D-FEBS)

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ABSTRACT

From the 1990s to the early 2000s, many studies on compound meandering channel flow have primarily focused on experimental research, at various scales, using compound meandering channels with levee alignments in a straight configuration. Although these research results were considered advanced at the time, the progress in analytical techniques and the development of highly accurate analysis methods today have made it possible to conduct quantitative investigations of compound meandering channel flow. In a compound meandering channel, the degree of flow mixing between flood channel and main channel varies greatly in the longitudinal direction, depending on the phase difference between the levee alignment and main channel, as well as the flood water level. Correspondingly, the characteristics of bed variation also change spatiotemporally, and the relationship between the two becomes complex. Therefore, in order to elucidate the phenomena in a compound meandering channel, it is essential to investigate not only the characteristics of the flow but also those of bed variation in an integrated and quantitative manner. For this reason, it is essential first to clarify the flow structure described above.

In this study, a mobile bed experiment was conducted using a large-scale compound meandering channel with planform that varies longitudinally. The bed in equilibrium formed in this experiment was then fixed, and a quasi-three-dimensional non-hydrostatic flood flow analysis (Q3D-FEBS) was performed for this channel. Through this approach, the structure of secondary flow in a compound meandering channel with longitudinal variations in planform and cross section was examined analytically and compared with the experimental results. This study demonstrated, through both experiments and analysis, that the compound meandering channel flow consists of the coexistence of secondary flow caused by centrifugal force in the meandering channel and secondary flow generated by convective mixing between the flood channel and the main channel. It was shown that this coexistence of the secondary flow varies with changes in planform and cross section, resulting in a complex three-dimensional flow structure.

Keywords: *compound meandering channel flow; secondary flow; flow structure; quasi-three-dimensional analysis; convective mechanism; convective mixing of flow*

1. Introduction

Research on compound meandering channel flow has been conducted primarily through experimental studies by many researchers. Many compound meandering channels used in experiments to date have had straight levee alignments, and their main channels have been constructed by combining circular-arc channels and straight channels. (Willetts et al., 1993, Sellin et al., 1993, Shiono et al., 1998, Shiono et al., 2009a, Shiono et al., 2009b). However, the main channel of a natural river meanders in more variation patterns. These experimental studies have clarified the following points regarding compound meandering channel flow.

- (1) In a compound meandering channel, the degree of flow mixing between the flood channel and the main channel varies substantially in the streamwise direction, depending on the phase difference between the levee alignment and the main channel alignment, as well as the flood water level.

- (2) Because the characteristics of bed variation vary spatiotemporally in response to spatiotemporal variations in the secondary flow structure, the relationship between the flow and bed variation becomes complex.

Advancement of understanding of hydraulic phenomena in compound meandering channels requires an integrated and quantitative examination of the characteristics of both the flow and bed variation, rather than of the flow alone. During the period spanning the 1990s through the early 2000s, these findings from experimental studies were advanced; however, quantitative examination has faced challenges. Owing to recent technological advances and the development of accurate analytical methods, it has now become possible to examine the compound meandering channel flow quantitatively. On the other hand, the mechanisms governing bed variation in compound meandering channels, whose planform and cross section vary in the longitudinal direction, are complex. For this reason, simultaneously examining the flow and bed variation remains challenging. Therefore, it is fundamental first to clarify the structure of the compound meandering channel flow.

In this study, we first conducted a mobile bed experiment using a large-scale compound channel whose planform varies longitudinally (Okada et al., 2003, Fukuoka et al., 2005). Subsequently, the equilibrium bed formed in this experiment was used in the topographic condition of the fixed-bed, and non-hydrostatic quasi-three-dimensional flood-flow analysis (Q3D-FEBS) (Takemura et al. 2019) was performed for this condition. This approach enabled an analytical investigation of the structure of secondary flow in a compound meandering channel characterized by longitudinal variations in planform and cross section, and the results were compared with the experimental results. On this basis, the utility and limitations of Q3D-FEBS relative to three-dimensional analysis are examined.

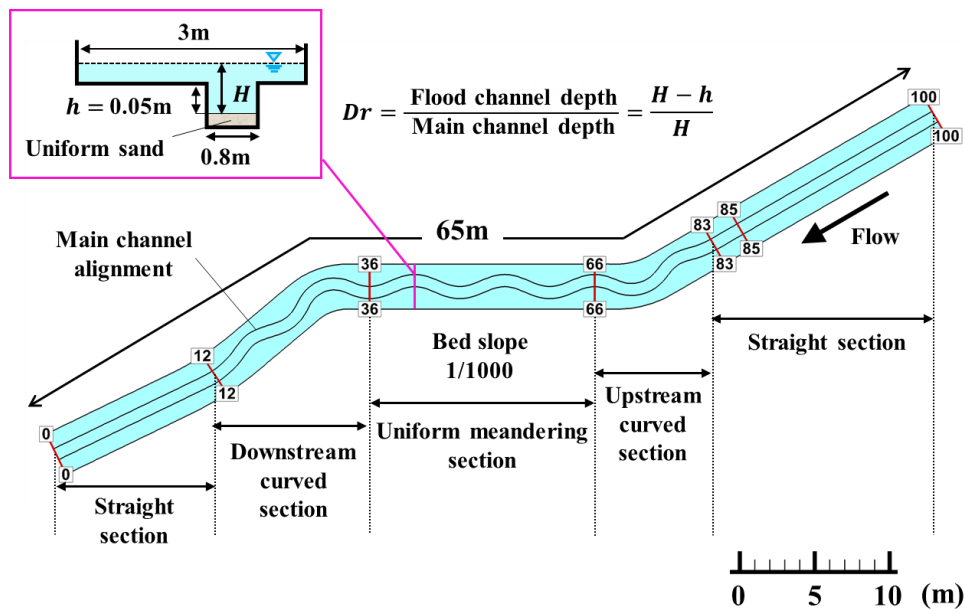


Fig.1 The planform of the experimental channel and a representative initial cross section

Table.1 Experimental condition

Relative depth Dr	Flow form	Bed mobility	Discharge (m^3/s)	Total width (m)	Main channel width (m)	Sinuosity	Bed slope	Sediment size (mm)	Relative density
0.40	Compound meandering channel flow	Mobile	0.3	3	0.8	1.04	1/1000	0.8	2.59

2. Overview of the experiments used for the analysis and the analysis conditions

2.1. Experimental overview

Figure 1 shows the planform of the experimental channel and a representative initial cross section of it. The experimental channel has a total length of 65 m, a channel width of 3 m, and a main channel width of 0.8 m. The channel consists of upstream and downstream straight sections, and a midstream uniform meandering section, which are connected by curved sections. The cross section of the main channel is rectangular, and the main channel in the uniform meandering section meanders along a sine-generated curve. Artificial turf was laid on the flood channel so that its roughness would be greater than that of the main channel. In the main

channel, uniform sand (with a relative density of 2.59 and a sediment size of 0.8 mm) was evenly placed as a flat bed so that the bed slope would be 1/1000 and the initial flood channel elevation would be 0.05 m. The sand in the upstream straight section (15 m) of the channel was regarded as the sediment supply section, and no sediment feeding was conducted from the upstream end. In the uniform meandering section, a stable flow field in meandering sections is established. Table 1 shows the experimental conditions. In this study, experiments were conducted under compound meandering channel flow conditions in which water also flows over the flood channel. Starting from a flat bed condition, the flow was run for 20 h until an equilibrium bed was achieved. After an equilibrium state was reached, the water level was measured longitudinally along the centerline of the main channel. The water level was measured using a point gauge. In addition, the bed topography of the main channel was measured at intervals of 0.5 m in the streamwise direction and 0.1 m in the transverse direction. The bed elevation was measured with an ultrasonic bed-topography measuring device. The elevation was calculated from the time required for the ultrasonic wave emitted from the tip of the detection probe to be reflected at the bed surface and return.

2.2. Analysis conditions

The Quasi-3D model considering Flow Equations on Boundary Surfaces (Q3D-FEBS) was used as the analysis method (Takemura et al., 2019). In this analysis method, the vertical distribution of the horizontal velocity is assumed to follow a three-order polynomial given in Eq. (1).

$$u_i = \Delta u_i(12\eta^3 - 12\eta^2 + 1) + \delta u_i(-4\eta^3 + 3\eta^2) + U_i \quad (1)$$

Where, $i = 1, 2$ ($x_1 = x, x_2 = y$), u_i : velocity in i direction, U_i : depth-averaged velocity in i direction, $\eta = (z_s - z)/h$, z_s : water surface elevation, h : water depth, u_{si} : water surface velocity in i direction, u_{bi} : bottom surface velocity in i direction, $\Delta u_i = u_{si} - U_i$, $\delta u_i = u_{si} - u_{bi}$. In addition, by solving the depth-integrated continuity equation (Eq. (2)), the depth-integrated momentum equation in the i direction (Eq. (3)), the momentum equation on the water surface (Eq. (4)), and the momentum equation on the bottom surface (Eq. (5)) in an integrated manner, the flow structure in a compound meandering channel is analyzed in a three-dimensional framework.

$$\frac{\partial h}{\partial t} + \frac{\partial U_i h}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial U_i h}{\partial t} + \frac{\partial U_j U_i h}{\partial x_j} = -gh \frac{\partial z_s}{\partial x_i} - \frac{1}{\rho} \frac{\partial h \bar{p}'}{\partial x_i} - \frac{p'_b}{\rho} \frac{\partial z_b}{\partial x_i} - \frac{\partial h \bar{u}'_i \bar{u}'_j}{\partial x_j} + \frac{\partial}{\partial x_j} \bar{v}_t h \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + \hat{S} \frac{\bar{v}_t}{h} \frac{\partial u_i}{\partial \eta} \Big|_b \quad (3)$$

$$\frac{\partial u_{si}}{\partial t} + u_{sj} \frac{\partial u_{si}}{\partial x_j} = -g \frac{\partial z_s}{\partial x_i} - \frac{1}{\rho h} \frac{\partial p'}{\partial \eta} \Big|_s \frac{\partial z_s}{\partial x_i} + \hat{S} \frac{\bar{v}_t}{h^2} \frac{\partial^2 u_i}{\partial \eta^2} \Big|_s \quad (4)$$

$$\frac{\partial u_{bi}}{\partial t} + u_{bj} \frac{\partial u_{bi}}{\partial x_j} = -g \frac{\partial z_s}{\partial x_i} - \frac{1}{\rho} \frac{\partial p'_b}{\partial x_i} - \frac{1}{\rho h} \frac{\partial p'}{\partial \eta} \Big|_b \frac{\partial z_b}{\partial x_i} + \frac{\partial}{\partial x_j} \bar{v}_t \left(\frac{\partial u_{bi}}{\partial x_j} + \frac{\partial u_{bj}}{\partial x_i} \right) + \frac{\hat{S}}{\rho} \frac{\hat{\tau}_{bi} - \hat{\tau}_{oi}}{\delta z_b} \quad (5)$$

Where, t : time, ρ : density of water, $u'_i = u_i - U_i$, g : gravitational acceleration, p' : non-hydrostatic pressure, p'_b : non-hydrostatic pressure on bottom surface, $\bar{v}_t$: eddy viscosity, $\hat{S} = \sqrt{1 + (\partial z_b / \partial x_i)^2}$, $\tilde{S} = \sqrt{1 + (\partial z_s / \partial x_i)^2}$, $\hat{\tau}_{bi}$: bottom shear stress in i direction, $\hat{\tau}_{oi}$: bed shear stress in i direction, $\delta z_b = c_{zb} h$, $c_{zb} = 0.03$. Overbar "—" represents a depth-averaged value.

In this analysis method, by assuming the vertical distribution of flow velocity with Eq. (1), the momentum-transport term associated with the vertical distribution of horizontal velocity can be evaluated as the fourth term on the right-hand side of Eq. (3). As a result, in addition to the convection term shown as the second term on the left-hand side of Eqs. (3)–(5), the convective effect arising from changes in the vertical distribution of horizontal velocity can be assessed. The equilibrium bed obtained after 20 h of flow run was used as a fixed-bed topographic condition. This allowed the flow structure that formed this bed to be investigated. A boundary-fitted grid was used for the computational grid, with spacings of 0.25 m in the streamwise direction and 0.05 m in the transverse direction. In addition, because the present analysis method is a quasi-three-dimensional model, the main channel bank is treated as the bed surface within its framework. Accordingly, since the main channel bank becomes stepwise, the grid spacing at the main channel bank was set to 0.01 m in the transverse direction to reproduce the topography near the boundary between the flood channel and the main channel as realistically as possible.

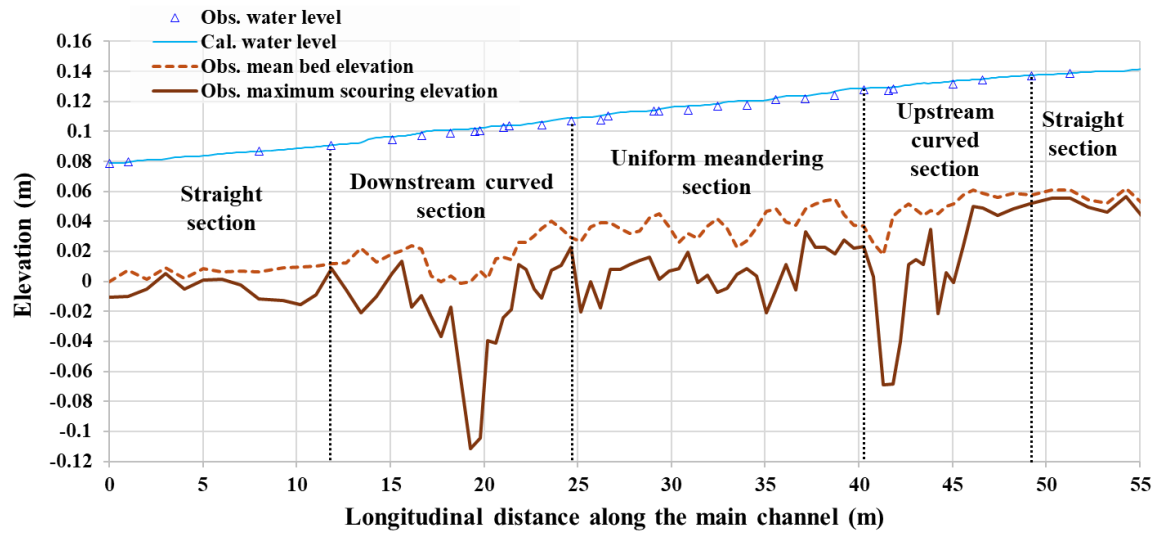


Fig.2 Comparison of observed and computed longitudinal distributions of water level, and the longitudinal profiles of the cross-sectionally mean bed elevation in the main channel and the maximum scouring elevation after a 20-hour flow run.

Table.2 Analysis condition

Relative depth	Discharge (m^3/s)		Error(%)	Bed condition	Manning's $n(\text{m}^{-1/3} \cdot \text{s})$	
Dr	Observed	Computed			Main channel	Flood channel
0.40	0.03	0.0299	0.3	20h later	0.014	0.021

Computed water surface vector: — 0.4 [m/s]

Observed water surface vector: — 0.4 [m/s]

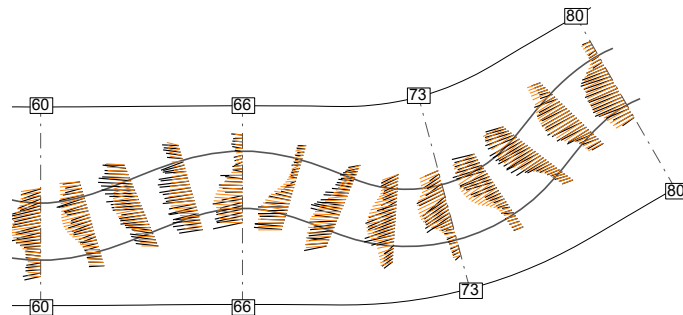


Fig.3 Comparison of the observed water-surface velocity and the computed water-surface velocity

3. Structure of compound meandering channel flow with longitudinal variation in planform and cross section

3.1. Comparison of observed and computed longitudinal distributions of water level and for water-surface velocity

Figure 2 compares the observed and computed longitudinal distributions of water level and shows longitudinal profiles of mean bed elevation and maximum scouring elevation in the main channel at 20 h after the start of flow. Table 2 presents the analysis conditions. When the listed roughness coefficients are used, the computed longitudinal distribution of water level reproduces the observed longitudinal distribution of water level well. In addition, the error between the experimental discharge and the computed discharge is 0.3%. Figure 3 shows a comparison between the water-surface velocity measured using a float and the computed water-surface velocity. The computed water-surface velocity shown in orange generally reproduces the measured water-surface velocity shown in black. Because the observed longitudinal distribution of water level, experimental discharge, and velocity distribution are generally reproduced, this analysis method is regarded as a numerical model capable of appropriately reproducing meandering flow over a stable riverbed, and the following investigations are conducted.

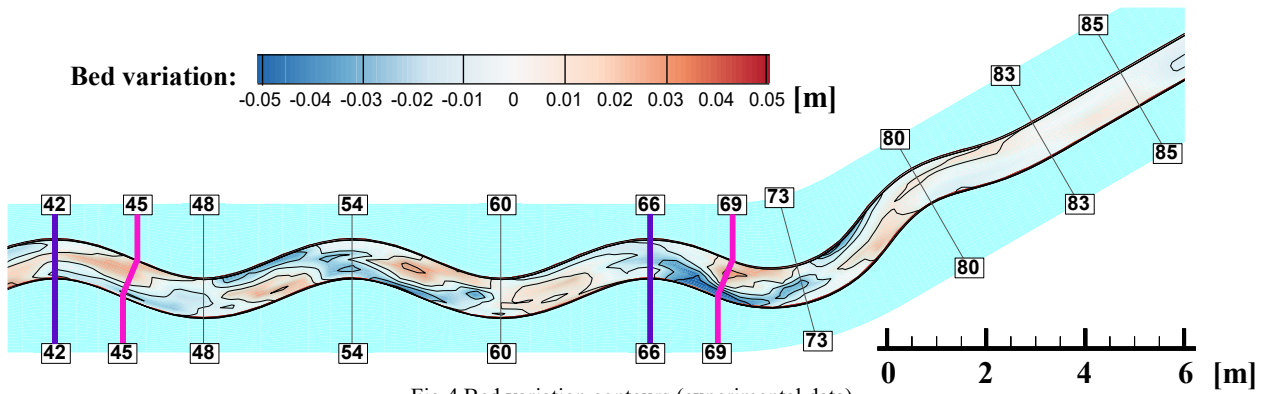


Fig.4 Bed variation contours (experimental data)

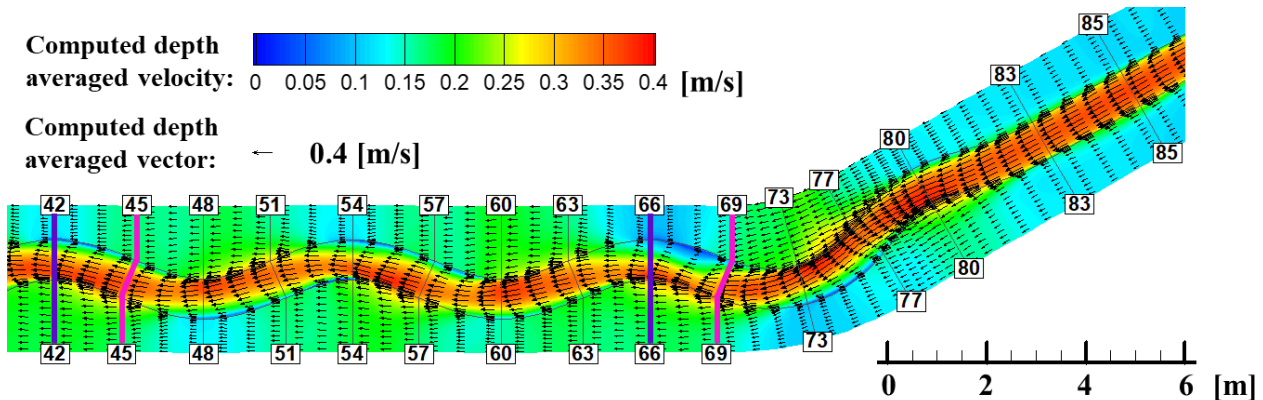


Fig.5 The plan distribution of the computed depth-averaged velocity

3.2. Structure of compound meandering channel flow

Figure 4 shows bed variation contours (experimental data). In the upstream curved section, fast flow from the straight section concentrates toward Section 69, which corresponds to the water-impingement zone, resulting in a large contrast between scour and deposition. In contrast, in the uniform meandering section, the contrast between scour and deposition is small, and a sandbar forms closer to the center of the channel. Figure 5 shows the plan distribution of the computed depth-averaged velocity. Focusing on the velocity in the main channel, the velocity in the compound meandering section is lower than that in the upstream compound straight section. This is attributed to the meandering in the main channel, where the longitudinal momentum exchange between the main channel and the flood channel increases relative to that of the compound straight section, thereby flow resistance within the compound channel increases. Consequently, the streamwise flow tends to shift toward the inner bank.

Figure 6 shows analytical results of streamwise velocity contours and secondary flow vectors for each cross section. In the upstream curved section, fast flow in the main channel entering from the straight compound section is discharged longitudinally from Section 80 onto the right-bank flood channel, accelerating the flood channel flow. Because the accelerated flow re-enters the main channel longitudinally from Section 73 (Fig. 5), at Section 69 the centrifugal secondary flow develops strongly within the main channel, and a large volume of flow also discharges from the right-bank flood channel. This effect extends downstream; at Section 66, a secondary flow opposite to the centrifugal secondary flow is formed across the entire cross section. In the uniform meandering section, flow mixing between the flood channel and the main channel occurs symmetrically and periodically at both banks, and the outflow and inflow occur simultaneously within the meander transition reach (Fig. 5). At Section 45, flow enters from the right-bank flood channel, but the inflow volume is smaller than that at Section 69 in the upstream curved section. In addition, the streamwise flow follows the deep scour zone along the left bank, and the centrifugal force field is maintained because the difference between the water-surface velocity and the near-bed velocity becomes large. Therefore, in the left-bank side of Section 45, a centrifugal secondary flow is formed. Under this influence, at Section 42, a secondary flow induced by convective mixing from the right-bank flood channel develops, and from the left bank to the channel center a flow tending toward a transition of the centrifugal secondary flow develops with the meander transition.

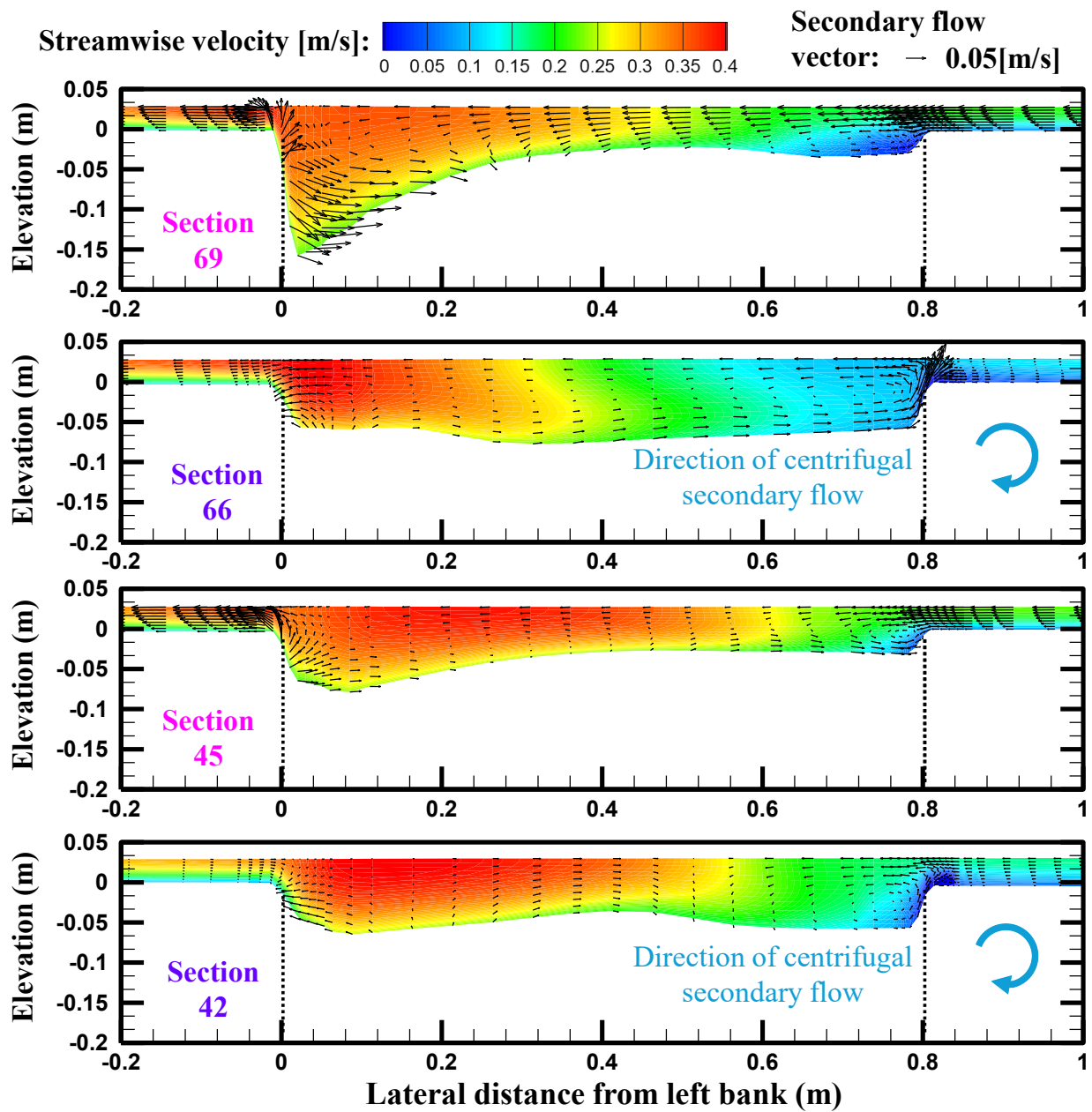


Fig.6 Streamwise velocity contours and secondary flow vectors for each cross section

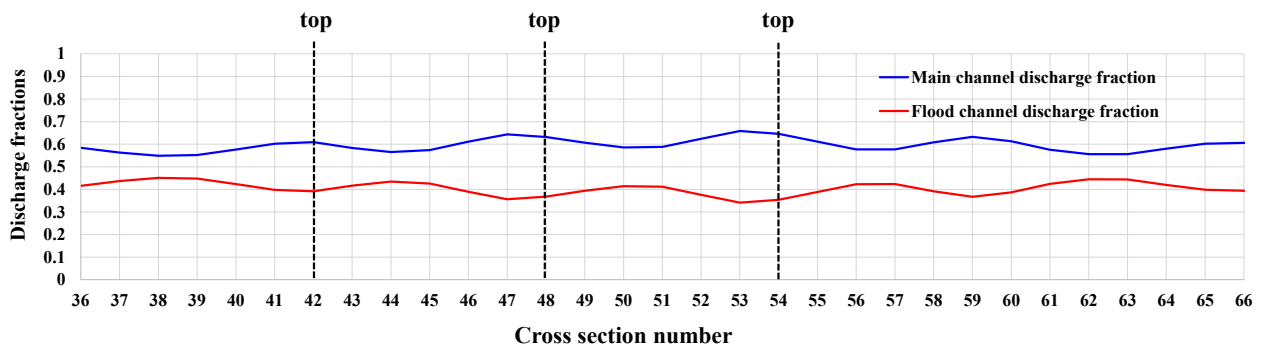


Fig.7 The longitudinal variation in the discharge fractions of the main channel and the flood channel within the uniform meandering section

Figure 7 shows the longitudinal variation in the discharge fractions of the main channel and the flood channel within the uniform meandering section, obtained from the analysis results. In the meander transition reach, the discharge fractions vary longitudinally due to outflow from the main channel to the flood channel and inflow from the flood channel to the main channel. From this, it is evident that the convection mechanism of the time-averaged flow changes longitudinally as the meandering alignment transitions. In the present experimental

channel, despite the narrow main channel width and the small difference in elevation between the flood channel and the main channel, as much as 60% of the discharge flows through the main channel on average. This suggests that, even in compound meandering channel flow, the centrifugal force field is maintained because a large proportion of the discharge flows through the main channel. For these reasons, in compound meandering channel flow, longitudinal changes in the phase relationship between the levee alignment and the main channel alignment lead to large variations in the degree of momentum exchange between the flood channel and the main channel. Depending on this degree of momentum exchange, the flow structure differs in both the longitudinal and transverse directions. Furthermore, within the main channel, the streamwise flow follows the scour zone because the riverbed is not flat and has cross sections that vary longitudinally.

Consequently, an increased velocity difference between the water surface and the bed surface maintains the centrifugal force field. That is, the flow structure in compound meandering channel flow is characterized by the formation of a secondary flow opposite to the centrifugal secondary flow; however, these two types of secondary flows coexist depending on the degree of mixing. The coexistence state of the two secondary flows varies with the outflow and inflow discharges induced by the phase difference between the levee alignment and the main channel alignment, as well as with longitudinal and transverse variations in bed topography. As a result, the convection mechanism of the time-averaged flow varies in both the longitudinal and transverse directions, and compound meandering channel flow exhibits a complex three-dimensional flow structure that differs from place to place.

4. The utility and limitations of quasi-three-dimensional analysis relative to three-dimensional analysis

In the present study, flow analysis was performed with accuracy using the quasi-three-dimensional analysis method (Q3D-FEBS). Meanwhile, in recent years, advances in analysis techniques have enabled studies based on three-dimensional analysis using Large-Eddy Simulation (LES) to be conducted (Ignacio et al., 2018). However, in natural rivers, the analysis domain is extensive and exhibits complex planform and cross section; moreover, coupling with bed variation analysis is required. Therefore, the practical application of three-dimensional analysis to natural rivers is not straightforward. In contrast, Q3D-FEBS is useful in that transformation into a boundary-fitted grid is readily achieved, coupling with bed variation analysis can be performed, and analysis over long distances is possible (Tabata et al., 2021).

At the same time, to enable three-dimensional analysis while keeping the computational cost low, Q3D-FEBS adopts the following assumptions.

- a) The vertical distribution of velocity is approximated by a three-order function (Eq. (1)), and the momentum-transport term associated with the vertical distribution of velocity is incorporated using a depth-averaged value (the fourth term on the right-hand side of Eq. (3)).
- b) Reynolds stresses are accounted for using an eddy-viscosity model.
- c) When evaluating the bed shear stress $\hat{\tau}_{0i}$, the no-slip condition is not used; instead, the vertical distribution of velocity under uniform flow (Engelund 1974) is assumed.

Because convective mixing is dominant in compound meandering channel flow, the velocity distribution varies in both the longitudinal and transverse directions. Therefore, since the convection term takes large values and varies spatiotemporally, it is necessary to verify, in the actual flow field, whether the vertical distribution of velocity assumed in (a) is satisfied. Furthermore, given that the shear stress used to evaluate sediment transport relies on the assumptions in (b) and (c), issues remain regarding how the velocity is evaluated in the vicinity of the bed surface. This is an essential issue in coupling with bed variation analysis and must be addressed appropriately to improve the accuracy of fluid force evaluation acting on sediment. Accordingly, it is necessary to examine the validity of these assumptions using the results of three-dimensional analysis, in order to improve the accuracy of flow analysis and bed variation analysis within a practical use.

5. Conclusion

The conclusions obtained in the present study are summarized below.

- (1) In a compound meandering channel, the flow structure features the coexistence of the centrifugal secondary flow and a secondary flow generated by convective mixing associated with the compound cross section. Because the coexistence state of these secondary flows varies with longitudinal changes in planform and cross sections, a complex three-dimensional flow structure develops in both the longitudinal and transverse directions.

- (2) Q3D-FEBS enables accurate flow analysis and can be coupled with bed variation analysis; however, it relies on assumptions such as the assumed vertical distribution of velocity and the treatment of velocity in the vicinity of the bed surface. Accordingly, it is necessary to assess the validity of these assumptions using three-dimensional analysis and to improve, in a practical manner, the accuracy of flow analysis and bed variation analysis.

References

- Engelund, F. (1974) Flow and bed topography in channel bends, *Journal of the Hydraulics division, ASCE*, Vol.100, No.11, pp.1631-1648
- Fukuoka, S., Shibata, T., Tamura, H., Tabata, K. & Yamagata, K. (2005) Study on sediment discharge distributions in a compound channel with different plan forms, *Annual Journal of Hydraulic Engineering*, Vol.49(2), pp.1027-1032
- Ignacio J. M., E., Manuel G., V., Muto, Y., Shiono, K., Palau, S., G. (2018) A numerical study of the complex flow structure in a compound meandering channel, *Advances in Water Resources*, Vol.116, pp.95-116
- Okada, S., Julio M., J., Fukuoka, S., Tamura, H. & Shigematsu, R. (2003) Flow and bed topography in a compound channel consisting of different plan shapes, *Annual Journal of Hydraulic Engineering*, Vol.47, pp.655-660
- Sellin, R.H.J., Irvine, D.A., Willetts, B.B. (1993) Behaviour of meandering two-stage channels, *Proceedings of the Institution of Civil Engineers: Water, Maritime and Energy*, Vol 101, 99-111.
- Shiono, K., Chan, T. L., Spooner, J., Rameshwaran, P., & Chandler, J.J. (2009a) The effect of floodplain roughness on flow structures, bedforms and sediment transport rates in meandering channels with overbank flows: Part I, *Journal of Hydraulic Research*, 47(1), 5-19.
- Shiono, K., Chan, T. L., Spooner, J., Rameshwaran, P., & Chandler, J.J. (2009b) The effect of floodplain roughness on flow structures, bedforms and sediment transport rates in meandering channels with overbank flows: Part II, *Journal of Hydraulic Research*, 47(1), 20-28.
- Shiono, K., Muto, (1998) Complex flow mechanisms in compound meandering channel flow overbank flow, *J. Fluid Mechanic*. 376, 221-261.
- Tabata, K., Gotoh, T., Takemura, Y., Sakou, K. and Fukuoka, S. (2021) Flood damage analysis for urban district and mountainous narrow area by integrating analysis of flood flow and inundation under the 2020 kumagawa heavy rain, *Advances in River Engineering*, Vol.27, pp. 597-602
- Takemura, Y. & Fukuoka, S. (2019) Analysis of the flow in undular and hydraulic jump stilling basins using non-hydrostatic quasi-three dimensional model considering flow equations on boundary surfaces, *Journal of Japan Society of Civil Engineers, Ser. B1(Hydraulic Engineering)*, Vol.75, No.1, pp.61-80
- Willetts, B.B., Hardwick, R.I. (1993) Stage dependency for overbank flow in meandering channels, *Proceedings of the Institution of Civil Engineers: Water, Maritime and Energy*, Vol. 101. 45-54.