

STUDY ON THE TIME-AVERAGED THREE-DIMENSIONAL FLOW STRUCTURE IN A COMPOUND MEANDERING CHANNEL

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ABSTRACT

In Japan's rivers with compound cross-sections and meandering main channels, it is known that during floods, the flow on the flood channel mixes with the flow in the main channel. The degree of this mixing significantly alters the secondary flow driven by centrifugal force, which dominated in the main channel. Analysis of such flood flows has become practically feasible through quasi-three-dimensional analysis (Q3D-FEBS), which vertical velocity distributions as cubic functions considers both the flow's non-hydrostatic pressure distribution and shear stress distribution by expressing. However, this analysis method still leaves issues regarding the reliability of the flow's non-hydrostatic pressure distribution and shear stress distribution.

Based on the premise that the relationship between the meandering alignment, discharge, and riverbed shape is crucial in compound meandering channels, experiments were conducted in a compound meandering channel with a mobile bed. In this study, three-dimensional numerical simulations using LES were performed for these experimental results. The study investigates the time-averaged three-dimensional flow structure in the compound meandering channel, particularly the changes in the secondary flow distribution and pressure distribution both within cross-sections and along the longitudinal varying channel profile.

It also indicates that a future research topic is how this three-dimensional flow structure changes depending on the relative magnitudes of the meandering alignment, discharge, and riverbed shape of the main channel.

Keywords: *Mobile-bed compound meandering flow; Meandering of the main channel; Three-dimensional structure of secondary flow; Non-hydrostatic pressure distribution*

1. Introduction

In compound meandering rivers with a compound cross-section consisting of a meandering main channel and a flood channel, during periods when floodwater flows within the main channel, the secondary flow of first kind arises due to the flow's centrifugal force, creating a simple meandering flow where the outer bank is subject to scouring. During floods when water covers the flood channel, Fukuoka et al. demonstrated that complex secondary flows occur within the channel, influenced by the degree of meandering in the main channel, the width of the flood channel, and the flood channel water depth (Fukuoka et al., 2005). Fukuoka (2005) conducted experiments in a compound channel, which has a cross section with a meandering main channel which flat uniform and rectangular shape. Through experiments and analysis, they demonstrated that when the relative depth D_r (flood channel water depth/main channel water depth) exceeds approximately 0.3, the mixing between flow in the main channel and flow on the flood channel generates a secondary flow distribution rotating in the opposite direction to the centrifugal secondary flow. Specifically, the flood channel flow entering the main channel drops near the maximum velocity line where the main channel flow and flood channel flow concentrate. The flood channel flow entering the main channel flows downstream in a gentle spiral along the secondary flow. After passing the meander apex, it discharges onto the flood channel area on the outer bank side. This transformed the secondary flow induced by centrifugal force into a secondary flow rotating in the opposite direction (Ikeda et al., 2009). However, while Fukuoka (2005)'s experiments with a flat, fixed bed are significant for fundamental research on secondary flows in compound meandering channels, if the main channel bed were a mobile bed, scouring and deposition at the bed would occur, rendering it no longer flat. This would likely alter the flow structure. Experiments on compound meandering flows in flat-bed channels, where the riverbed cannot change, should be considered phenomena occurring under quite special

conditions. Ignacio et al. (2018) analyzed compound meandering channels using Large-eddy Simulation (LES), showing secondary flow structures and shear stress distributions, and examined their impact on sedimentation/erosion risk and meander formation. However, their main channel bed was also flat, making their study insufficient for examining the three-dimensional nature of compound meandering channel flow.

The flow structure in compound meandering rivers is influenced by the scale and arrangement of sandbars formed on the main channel bed due to the mixing between main channel flow and flood channel flows as water levels rise. Focusing on this point requires further investigation.

Regarding compound meandering flow in rivers, quasi-three-dimensional flood flow analysis considering non-hydrostatic pressure distribution has been conducted (Takemura et al., 2019), enabling prediction with considerable practical accuracy. However, these analyses assume a cubic expression for the vertical velocity distribution and use the resulting shear stress and non-hydrostatic pressure distributions. It remains unclear whether this approach fully reproduces the hydraulic phenomena of compound meandering flows.

In this study, we perform three-dimensional numerical simulations (Fukuoka et al., 2014) of a compound meandering channel with a fixed longitudinal and cross-sectional bed profile, based on the results of a mobile bed experiment conducted in this channel, to clarify the three-dimensional structure of the secondary flows and non-hydrostatic pressure distribution.

2. Experimental conditions

As shown in Fig. 1, the steady flow was supplied to a channel with a length of 21.9 m, a main channel width of 0.8 m, a main channel meander wavelength of 6 m, sinuosity of 1.04, and a bed slope of 1/1000. The riverbed profile was fixed in the equilibrium shape reached after 20 hours of flow, starting from an initial flat bed, based on steady-flow mobile bed experiments (Okada et al., 2003, Fukuoka et al. 2005). The coordinate axes were defined as follows: the x-axis in the flow direction, the y-axis in the cross-sectional direction, and the z-axis vertically upward. Two experimental cases were conducted: Case 1 involved simple meandering channel flow, and Case 2 involved compound meandering channel flow. The upstream end was fed a discharge of $Q = 0.0106 \text{ m}^3/\text{s}$ for Case 1 and $Q = 0.03 \text{ m}^3/\text{s}$ for Case 2. For time averaging, data measured every 1/250 second for 130

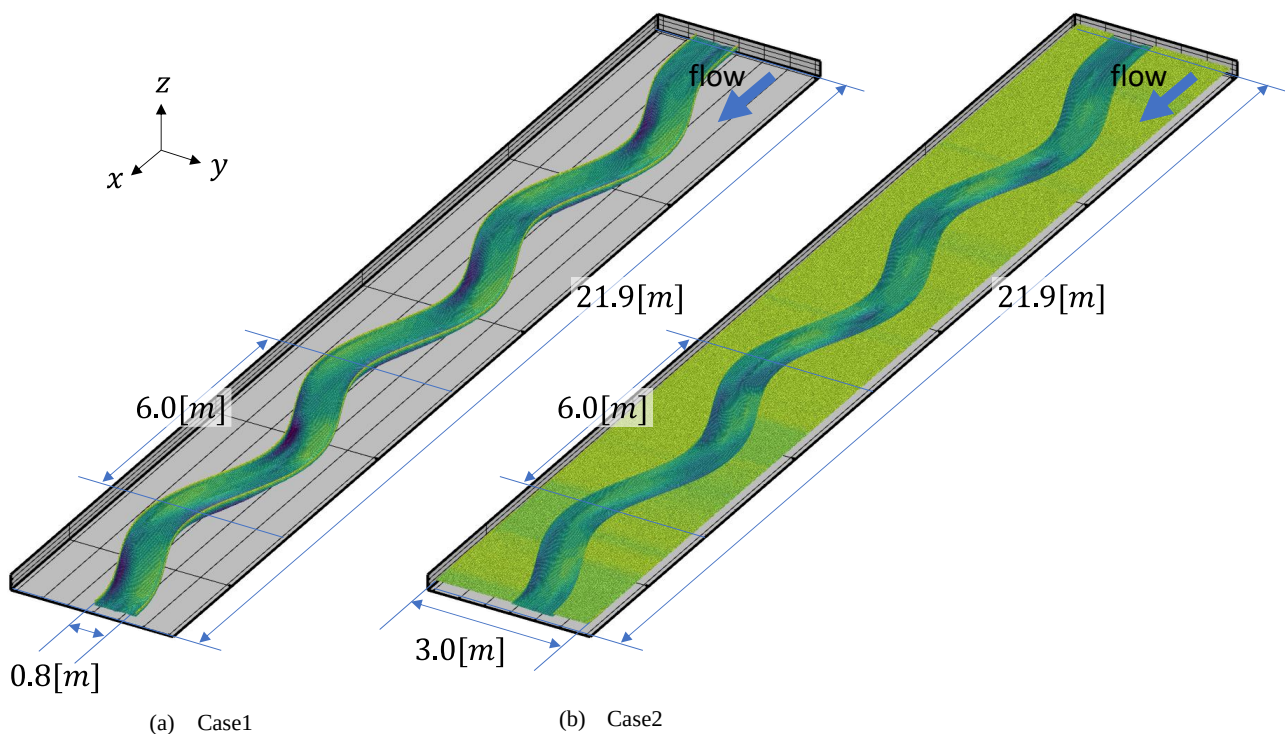


Fig. 1. Numerical movable-bed channel and the coordinate system

seconds after the flow field had sufficiently developed was used to calculate the time-averaged quantities. Table 1 shows the experimental condition.

Table 1. Experimental conditions

	Case1	Case2	
Discharge	0.0106	0.03	m ³ /s
Relative depth	0.0	0.4	-

3. Numerical method

This analysis employs the Arbitrary Particle Multiphase (APM) method (Fukuoka et al., 2014). For the flow analysis, turbulence larger than the computational grid is solved directly, while smaller turbulence is modeled using LES, which is capable of capturing the instantaneous structure of the flow. The governing equations are shown below.

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{Du_i}{Dt} = g_i - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \{2(\nu + \nu_{SGS})S_{ij}\} \quad (2)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3)$$

$$\nu_{SGS} = (C_s \Delta)^2 \sqrt{2S_{ij}S_{ij}} \quad (4)$$

where u_i = i-directional component of mass-averaged velocity; P = sum of isotropic components of SGS stress; g_i = i-directional component of gravitational acceleration; ρ = volume-averaged density; ν = kinematic viscosity; ν_{SGS} = SGS turbulent viscosity; S_{ij} = strain rate tensor; C_s = Smagorinsky constant (=0.173); Δ = computational grid width.

Furthermore, the side walls and riverbed are composed of particles, and the boundaries are solved using a one-fluid model. The basic equations for the one-fluid model are shown below.

$$\rho = \alpha_s \rho_s + (1 - \alpha_s) \rho_f \quad (5)$$

$$u_i = \frac{\alpha_s \rho_s u_{s,i} + (1 - \alpha_s) \rho_f u_{f,i}}{\rho} \quad (6)$$

where α_s = volume fraction of solid phase; ρ_s = density of the solid phase; ρ_f = density of liquid phase; $u_{s,i}$ = velocity of solid phase; $u_{f,i}$ = velocity of liquid phase.

This accounts for the complex channel boundaries. The free surface is evaluated using the Volume of Fluid (VOF) method. Table 2 shows the analysis parameters.

Table 2. Simulations parameters

computational grid width (dx, dy)	0.005	m
computational grid width (dz)	0.002	m
Ratio of computed lattice width to subcell width	6	-
Time step for the fluid simulation	1.0×10^{-3}	s
Density of water	1000	kg/m ³
Smagorinsky constant	0.173	-

4. Results and discussions

4.1. Three-Dimensional Structure of Flow

The section extending from 12.8 m to 18.8 m upstream of the upstream end is chosen for the investigation to minimize the effects at both the upstream and downstream ends. Figure. 2 shows the longitudinal distribution of observed water levels, analyzed water levels, and the average main channel bed elevation for Cases 1 and

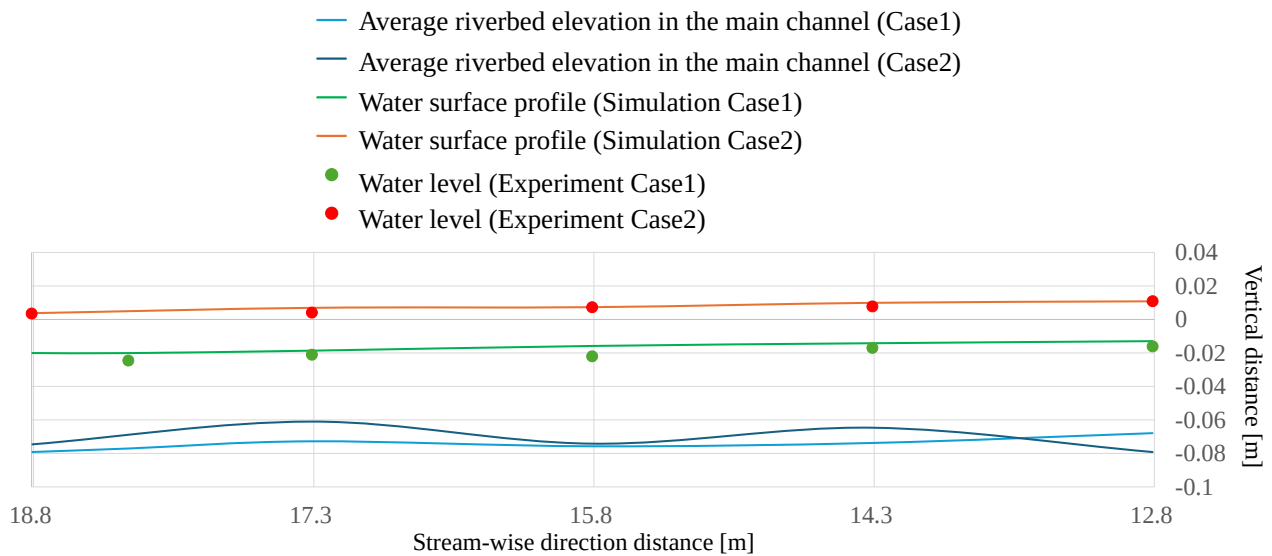


Fig. 2. Longitudinal distributions of water level and its bed

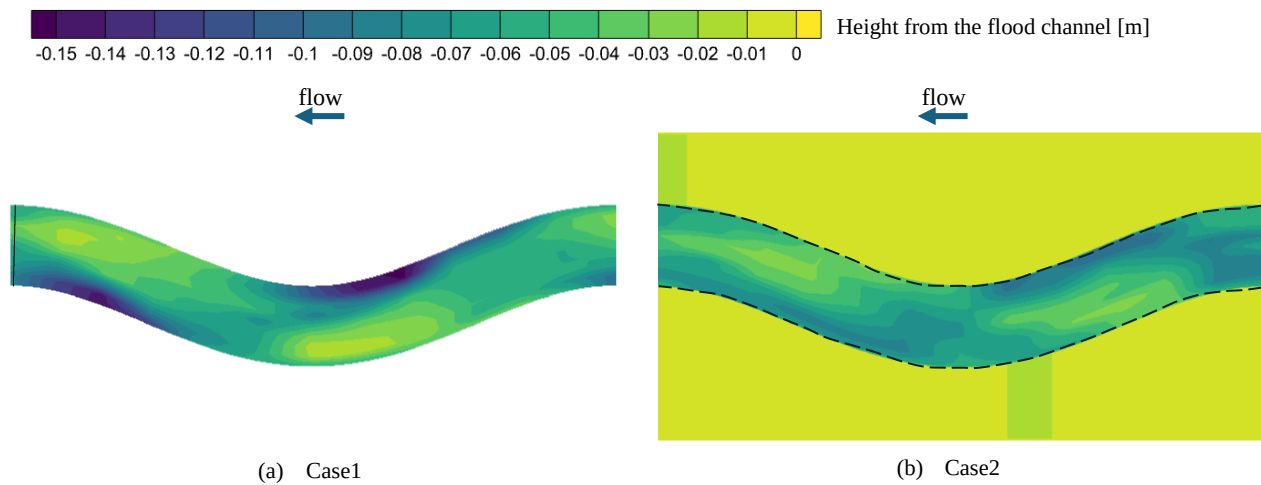


Fig. 3. Bed variation contours

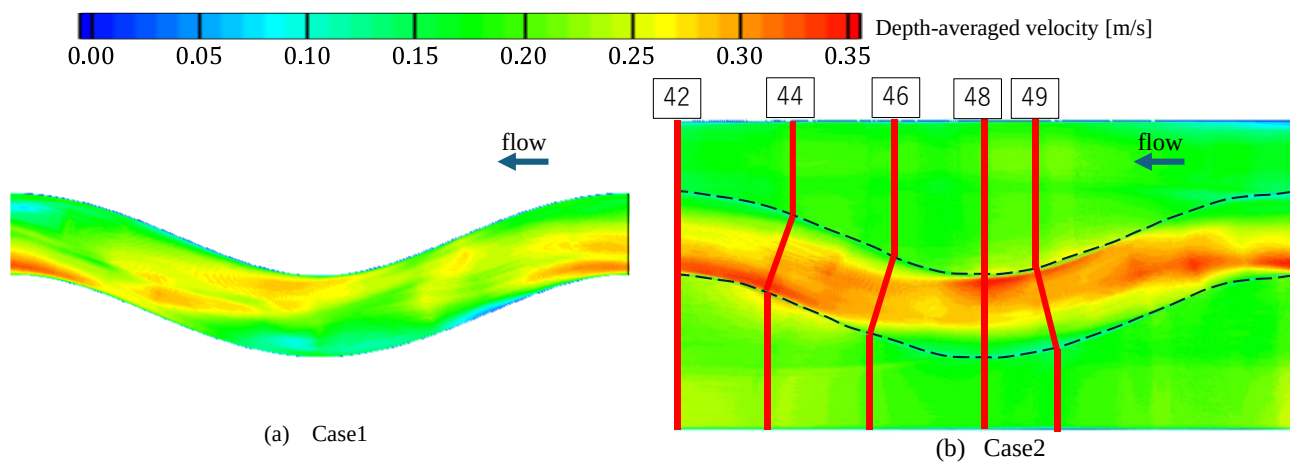


Fig. 4. Plan distribution of the depth-averaged velocity

2. In both cases, the analyzed water levels match the observed water levels, indicating that the analysis results generally reproduce the actual phenomena.

Figures. 3-4 show the plan distribution of the riverbed elevation (relative to the high-water plain elevation) and the depth-averaged velocity. In Case 1, the inner bank side is scoured, and the location of the maximum flow velocity corresponds to the scouring position on the riverbed. Furthermore, in Case 2, the slow flow velocity from the flood channel enters the main channel, exhibiting the characteristic of compound meandering flow (Fukuoka, 2005), where the main flow shifts toward the inner bank.

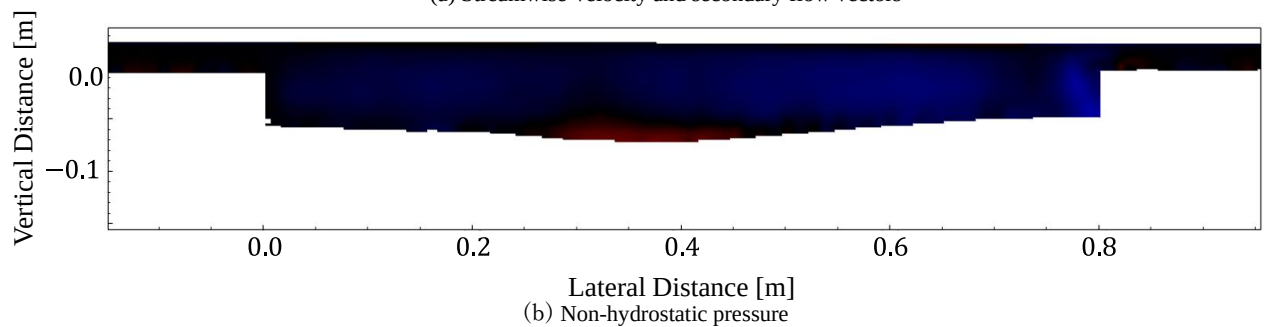
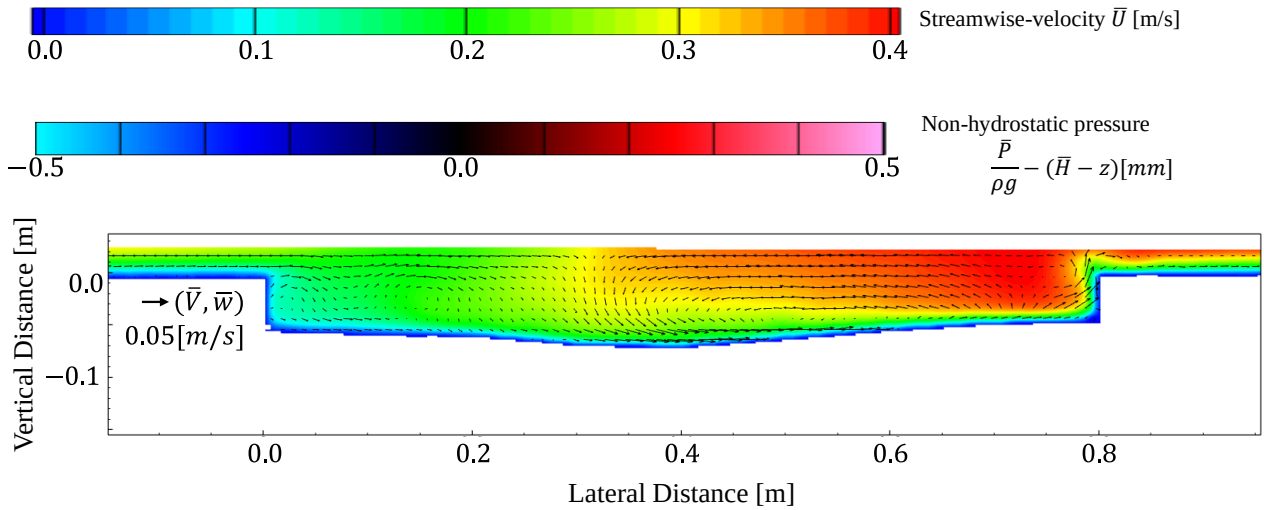


Fig. 5. Cross-sectional distribution at the meander crest (Section 48) of the compound meandering (Case 2)

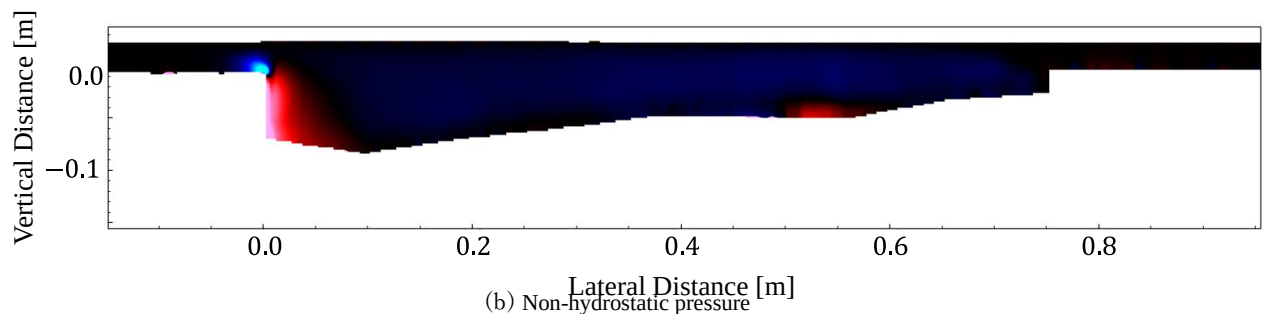
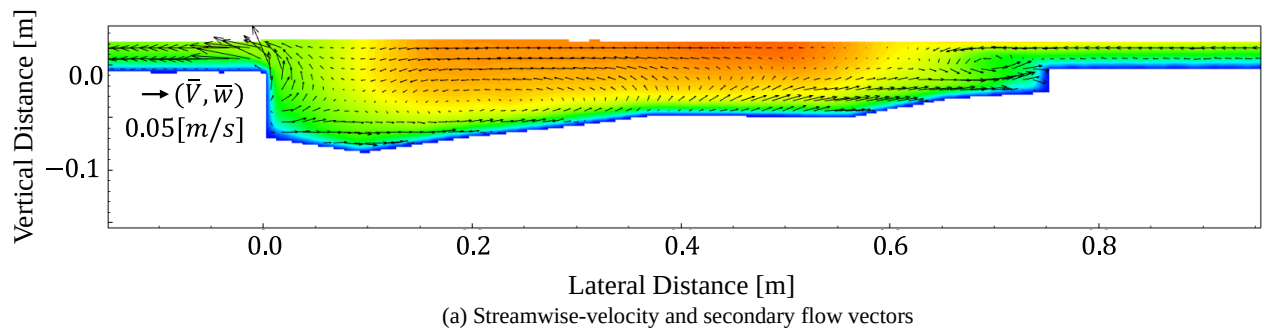


Fig. 6. Cross-sectional distribution near the meander inflection point (Section 46) in the compound meandering flow (Case 2)

Figures. 5-8 show the cross-sectional distributions of the stream-wise velocity, secondary flow vectors, and the non-hydrostatic pressure at Sections 48, 46, 44, and 42, respectively, for the compound meandering flow (Case 2). The cross-section locations are shown in Fig. 4. Furthermore, the mainstream direction of the main channel was calculated from its average flow velocity. The velocity along this direction was defined as the stream wise velocity U , and the velocity in the perpendicular direction was defined as the transverse velocity V . From the center of the main channel at Section 48, which is the convex meander crest on the left side, toward the right bank, a counterclockwise secondary flow caused by centrifugal force occurs. Meanwhile, on the left bank side of the main channel, flow from the flood channel enters, causing a small clockwise secondary flow due to convection mixing. Furthermore, at the center of the secondary flow caused by centrifugal force on the right bank side, a small negative non-hydrostatic pressure is generated. At the slightly downstream Section 46, two counterclockwise secondary flows of differing magnitudes occur on the left and right bank sides of the main channel. The secondary flow on the left bank is due to centrifugal force, while the secondary

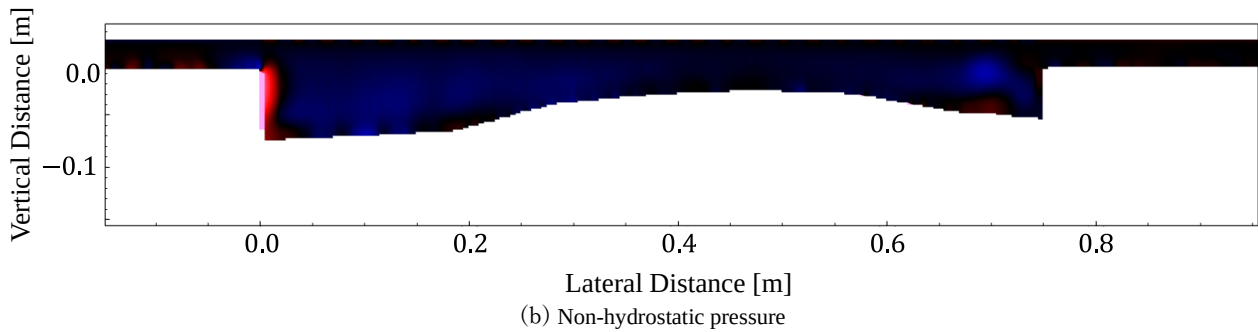
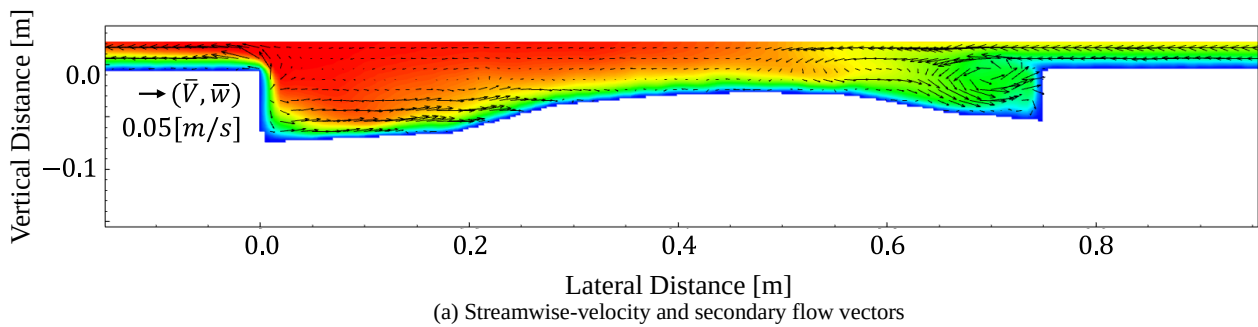


Fig. 7. Cross-sectional distribution near the meander inflection point (Section 44) in the compound meandering flow (Case 2)

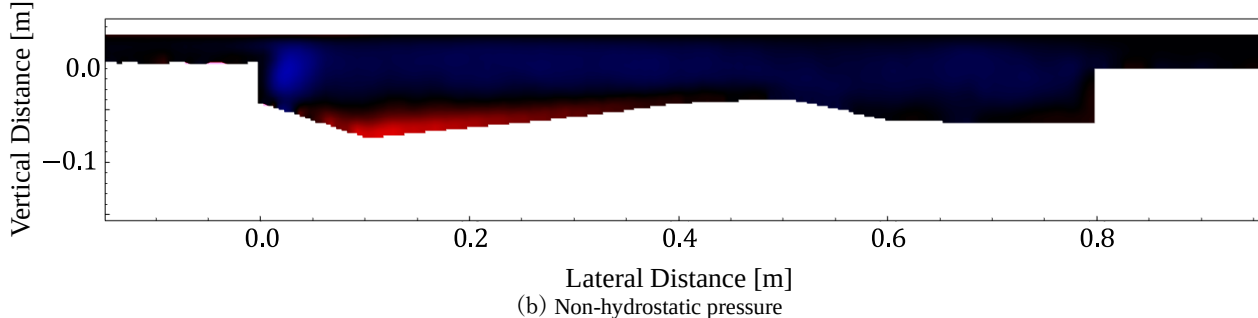
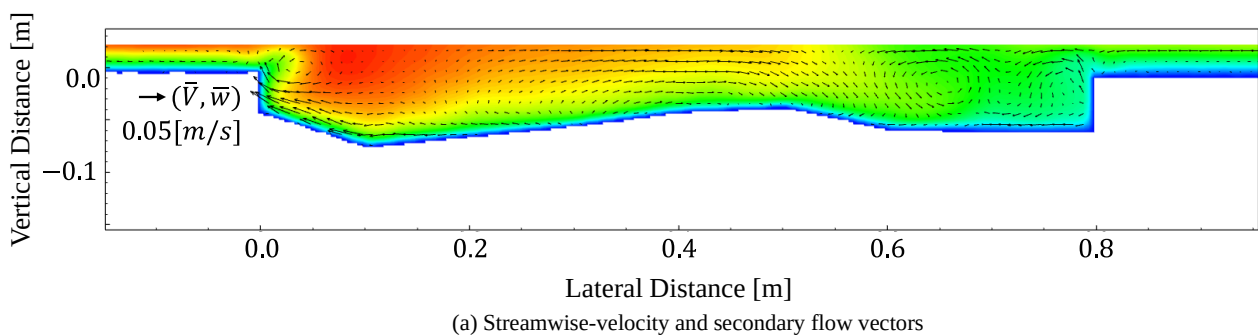


Fig. 8. Cross-sectional distribution at the meander crest (Section 42) of the compound meandering (Case 2)

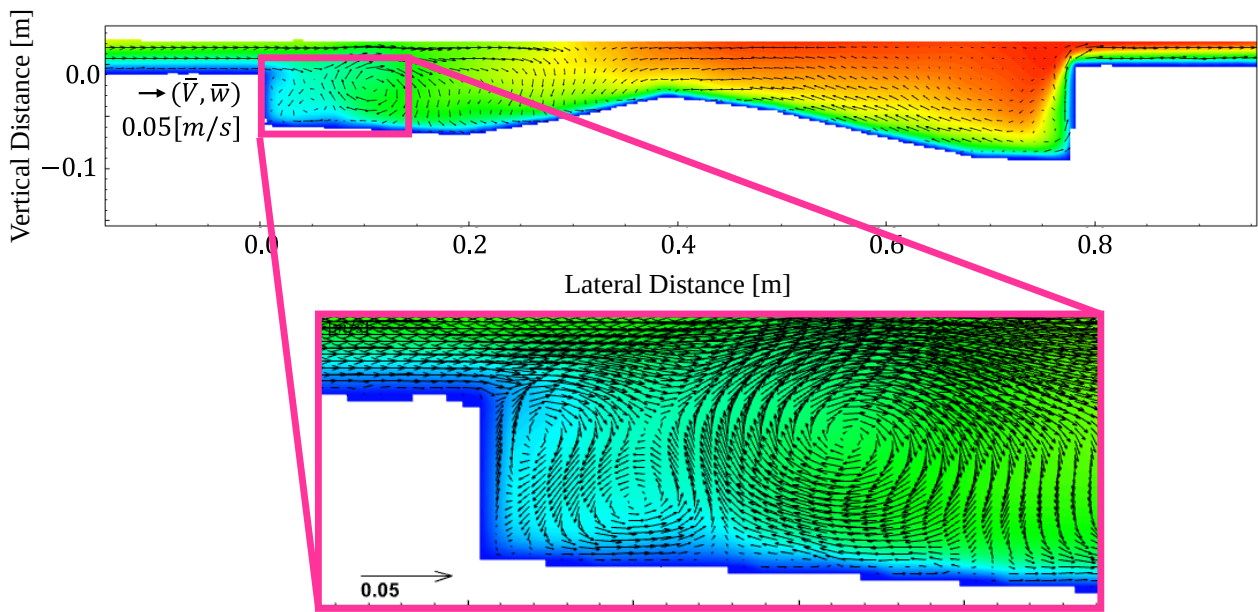


Fig. 9. Cross-sectional distribution of the mainstream velocity and secondary flow vector at cross-section 49 in the compound meandering flow (Case 2)

flow on the right bank is due to convection mixing. Further downstream at Section 44, the secondary flow structure is almost identical to that at Section 46. However, the right bank is more deeply excavated, making the secondary flow on the right bank distinctly visible. Additionally, at Sections 46 and 42, pressure increases because the main flow collides with the left bank of the main channel. At Section 42, which is the convex meander crest on the right side, unlike Section 48 (the convex meander crest on the left side), a counterclockwise vortex caused by centrifugal force forms on the right bank, while a clockwise vortex due to convection mixing forms on the left bank. Furthermore, at the center of the secondary flow caused by centrifugal force, similar to Section 48, a small negative hydrostatic pressure is generated. Additionally, the secondary flow caused by centrifugal force occurs in a manner that erodes the bed surface on the left bank side, generating a positive hydrostatic pressure component. Thus, in the compound meandering channel studied here, secondary flows caused by centrifugal force and convection mixing coexist due to the mixing between main channel meandering flow and flood channel flow, forming a complex yet relatively cyclic three-dimensional structure.

4.2. Connection to Real River Problems

Figure 9 shows the cross-sectional distribution of the main flow velocity and secondary flow vectors at Section 49 in Case 2. Slow-velocity flow enters the main channel from the left bank flood channel, generating secondary flows due to convection mixing. Furthermore, adjacent to this, a counter-flow secondary flow occurs in correspondence. In actual rivers, these secondary flows are thought to scour the banks of the main channel. However, quasi-three-dimensional analysis methods for flood flows, such as Q3D-FEBs (Takemura et al., 2019), commonly used in rivers, struggle to reproduce such secondary flows. Therefore, when analyzing sediment transport near the banks using quasi-three-dimensional analysis methods, improving the accuracy of the analysis, including the occurrence of such secondary flows, is considered essential. However, directly applying this analysis method to rivers is currently difficult. The immediate goal is to investigate the generation of various secondary flows caused by the mixing of meandering flow in the main channel and flow in the flood channel, considering their relationship with the meandering alignment of the main channel, discharge, and bed changes. The immediate goal is to enable the quasi-three-dimensional analysis method to reproduce these results to some extent, making it applicable to actual rivers.

5. Conclusions

In this study, we conducted mobile bed experiments and corresponding numerical simulations on turbulent flow in meandering main channels. The following results were obtained regarding the three-dimensional structure of the meandering flow:

- ① In compound meandering channels, the meandering alignment of the main channel, discharge, and riverbed shape interact to generate secondary flows within the cross-section. These secondary flows arise from centrifugal forces and convection mixing. The longitudinal variation in these interactions creates a complex three-dimensional flow field.
- ② In compound meandering flow, how the secondary flow due to centrifugal force and the secondary flow due to convection coexist within the cross-section, what kind of three-dimensional flow structure they possess, and how this structure changes depending on the relative magnitude relationship among the three components remain future research topics.
- ③ Utilizing the results obtained in this study for the quasi-three-dimensional flood flow analysis method used in compound meandering rivers is also a future task.

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