Journal of Hydrology 556 (2018) 143–153

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Estimation of flow direction in meandering compound channels

Xingnian Liu [a], Qin Zhou [a], Sheng Huang [a], Yakun Guo [b], Chao Liu [a,*]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China
[b] School of Engineering, University of Bradford, BD7 1DP, UK

ARTICLE INFO

Article history:
Received 2 July 2017
Received in revised form 20 September 2017
Accepted 27 October 2017
Available online 16 November 2017
This manuscript was handled by G. Syme, Editor-in-Chief.

Keywords:
Depth-averaged two-dimensional flow direction
Depth-averaged flow angle
Secondary current cell
Meandering compound channel
Overbank flows

ABSTRACT

The flow in the main channel of a meandering compound channel does not occur in the ridge direction because of the effect of the upstream floodplain flows. This study proposes a model for estimating the flow direction in the depth-averaged two-dimensional domain (depth-averaged flow angles) between the entrance and the apex sections. Detailed velocity measurements were performed in the region between the meander entrance section and apex section in a large-scale meandering compound channel. The vertical size of the secondary current cell is highly related to the depth-averaged flow angle; thus, the means of the local flow angles above the secondary current cell and within the cell are separately discussed. The experimental measurements indicate that the mean local flow angle above the cell is equal to the section angle, whereas the mean local flow angle within the cell is equal to zero. The proposed model is validated using published data from five sources. Good agreement is obtained between the predictions and measurements, indicating that the proposed model can accurately estimate the depth-averaged flow direction in the meandering compound channels. Finally, the limitations and application ranges of the model are discussed.

1. Introduction

Natural rivers form meanders due to the sediment transport and bed erosion. Throughout the year, the water in a meandering channel (i.e., the inbank flow) typically flows downstream in the ridge direction. However, when river flood occurs, the floodplains on the two sides of the main river are inundated, forming a meandering compound channel in which the floodplain water and main channel water have different depth-averaged two-dimensional flow directions in the meandering belt, particularly within crossover sections (Shiono et al., 2009; Liu et al., 2014). Numerous previous studies have investigated the complex three-dimensional flow patterns along meanders in meandering channels with overbank flows (e.g., Shiono and Muto, 1998; Lyness et al., 2001; Spooner, 2001; Wormleaton et al., 2004; Shiono et al., 2008, 2009; Liu et al., 2016a) and found that the upstream floodplain flow can significantly affect the main channel flow in crossover sections. For example, the mean velocity in a meandering main channel reaches a maximum at the apex section and a minimum in crossover sections because of the influence of upstream floodplain flows (Liu et al., 2014, 2016a). Floodplain roughness (e.g., vegetation) is an important factor that affects the flow pattern along a meander (Shan et al., 2017). For example, under low-flow conditions, roughened floodplains enhance the conveyance capability of the main channel but reduce the conveyance capability of the entire channel (Shiono et al., 2009; Liu et al., 2016a). These studies provide insights to better understand the evolution of the flow along a meander.

A secondary current cell is a typical flow feature found in a meandering main channel and has been extensively investigated (Sellin et al., 1993; Shiono and Muto, 1998; Wormleaton et al., 2004; Liu et al., 2014, 2016a; Shan et al., 2017). In half of a meander (from one apex section to the next apex section), a secondary current cell initially appears next to the inner corner in the section after the apex section. The cell expands in both the lateral and vertical directions as the section proceeds. The maximum size of the secondary current cell is eventually observed at the next apex section. The cell then rapidly decays after the apex section and disappears before the formation of a new cell (see Fig. 8b in Liu et al., 2016a). A similar development process of secondary current cells was reported based on experimental observations (e.g., Shiono et al., 2008) and numerical simulations (e.g., Jing et al., 2009). In this study, we focus on the flow direction in the depth-averaged two-dimensional region between the entrance section and apex section (e.g., the region between CS5 and CS7 in Fig. 1), where secondary current cells are approximately fully developed. At the meander entrance (CS5), the cell fills the region below the bankfull

* Corresponding author.
E-mail addresses: chaoliu@scu.edu.cn, chaoliu@mit.edu (C. Liu).

https://doi.org/10.1016/j.jhydrol.2017.10.071
0022-1694/

Notation

A	cross-sectional area in an apex section
a	frontal area per unit volume (= md)
B	channel width
b	width of meandering main channel
d_{16}, d_{50}, d_{84}	particle sizes
Dr	relative flow depth (= $(H-h)/H$)
d	stem diameter
H	flow depth in the meandering main channel
h	bankfull level
h_0	height of the secondary current cell
$h_{0(c)}$	distance between the cell bottom ($z=0$) and center ($z=h_{0(c)}$)
h_v	vegetation height
k	dimensionless coefficient ($=\frac{\theta_x}{\theta_{geo}}$)
L_w	wavelength in half of a meander (see Fig. 1)
L_v	valley length in half of a meander (see Fig. 1)
m	vegetation density
N	the number of measurement lines (e.g., $N=13$ in this study, see Fig. 1b)
n_{mc}, n_{fp}	Manning's roughness parameter in the main channel and floodplain, respectively
n_{all}	overall Manning's roughness parameter
Q	total discharge in the meandering compound channel
Q_{mc}	main channel discharge
R	hydraulic radius of the apex section
Re	Reynolds number ($=\frac{QR}{A\nu}$)
Re_d	stem Reynolds number ($=\frac{u_v d}{\nu}$)
r	inner radius
S	valley slope
S_{mc}	slope of the meandering main channel
s	sinuosity of the meandering main channel (= L_w/L_v)
U, V, W	time-averaged velocities in the streamwise, lateral and vertical directions, respectively
u_v	velocity within a vegetated area
x, y, z	streamwise, lateral and vertical coordinates, respectively (see Fig. 1)
θ_a	depth-averaged two-dimensional flow direction ($=\frac{1}{H}\int_0^H \theta(z)dz$)
$\theta_{a(m)}$	lateral mean of θ_a ($=\sum_1^N \theta_a$)
θ_{cell}	local flow angle averaged over the height of the cell (see Eq. (3))
$\theta_{cell(m)}$	the mean value of θ_{cell} in the lateral direction ($=\frac{1}{b}\int_0^b \theta_{cell}dy$)
θ_{upper}	mean local flow angle above the cell (see Eq. (3))
$\theta_{upper(m)}$	mean value of θ_{upper} in the lateral direction ($=\frac{1}{b}\int_0^b \theta_{upper}dy$);
θ_{geo}	the geometrical angle of the region between the entrance section and apex section (see Fig. 1)
θ_x	section angle (see Fig. 1)
$\theta(z)$	local flow angle ($=arctan\frac{V}{U}$)
ν	kinematic viscosity (= 10^{-6} m^2/s)

level because of the suppression effect from upstream floodplain flow. As the section proceeds (i.e., a smaller section angle, θ_x, is formed, as defined in Fig. 1), the effect of upstream floodplain flow on the secondary current cell gradually decreases; thus, the cell further expands in the vertical direction. The secondary current cell occupies the entire main channel in the apex section (CS7) because of the negligible effect of the floodplain flow (see Liu et al., 2014).

The generation mechanisms of secondary flows indicate that the intensities of secondary flows in the meandering main channel are significantly enhanced compared to those in a straight channel due to the contributions of centrifugal forces (Liu et al., 2013, 2014, 2016a). For overbank flows, considering the influence of upstream floodplain flows, the water in the main channel in the region between an entrance section and apex section does not flow downstream in the ridge direction, except in apex sections (e.g., see Fig. 9 in Liu et al., 2014). The depth-averaged two-dimensional flow direction $\theta_a(=\frac{1}{H}\int_0^H \theta(z)dz)$ is defined to quantitatively express this phenomenon, where H is the flow depth and $\theta(z)$ is the local flow angle ($=arctan\frac{V}{U}$, in which U and V are time-averaged velocities in the streamwise and lateral directions, respectively, and z is the vertical position). Previous studies have discussed the planform of θ_a in different situations. The relative flow depth Dr (= $(H-h)/H$ with bankfull level h) is often used in compound channels. For example, Shiono and Muto (1998) reported that in cases with the same Dr (= 0.5), $\theta_a = 26.5°–30°$ in the entrance section ($\theta_x = 60°$), $\theta_a = 17°–19.4°$ in the middle section ($\theta_x = 30°$), and $\theta_a = -9°$ to $-2°$ in the apex section ($\theta_x = 0°$). Their observations indicate that θ_a reaches a maximum in the entrance section because the entrance section has the largest θ_x (= 60°). In contrast, θ_a is close to 0° in the apex section because the apex section has the smallest θ_x (= 0°). Thus, θ_a is associated with the position of the section (i.e., section angle θ_x). In this study, as we focus on the region between the entrance section and apex section, θ_x ranges between 0° and the geometrical angle of the region θ_{geo} (i.e., $\theta_{geo} \geqslant \theta_x \geqslant 0°$). Therefore, θ_{geo} can affect the value of θ_x and the value of θ_a. However, θ_{geo} is initially determined when the curve of the meandering main channel is prescribed. Furthermore, in a given section (i.e., for a given θ_x), θ_a varies with Dr. For example, in the entrance section ($\theta_x = 60°$), Shiono and Muto (1998) reported that $\theta_a = 1°–5°$ (close to 0°) when $Dr = 0$ (the inbank flow), indicating that the water flows downstream in the ridge direction. This behavior occurs because no upstream floodplain flow affects the main channel flow. In contrast, under high-flow conditions, the upstream floodplain flow plunges into the main channel and affects the secondary flows and the flow direction. For example, Liu et al., (2014) found that $\theta_a = 26°–32°$ at $Dr = 0.45$ in the entrance section ($\theta_x = 60°$). Overall, previous studies have suggested that θ_a is related to three factors, namely θ_x, θ_{geo} and Dr.

Several depth-averaged two-dimensional numerical models have been used to determine the planform of the depth-averaged velocity, including the velocity orientation and magnitude (Chen et al., 2015; Harrison et al. 2015; Ding et al., 2017). However, the modeling results of flow direction (orientation) cannot be validated using measured data under high flows because flow measurements during heavy flooding periods are not available. Therefore, a method for estimating the depth-averaged two-dimensional flow direction in a meandering main channel with overbank flows is required. To this end, the goals of this study are to (1) conduct laboratory experiments and measurements in the region between the entrance section and apex section in a meandering compound channel; (2) understand how the vertical profiles of local flow angles are related to secondary current cells; (3) propose a method to estimate the depth-averaged two-dimensional flow direction (i.e., depth-averaged flow angle); (4) validate the proposed model using published experimental data from five sources and (5) discuss the applications and limitations of the model.