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Sensitivity of free bar morphology in rivers to secondary flow modeling: Linear stability analysis and numerical simulation

Toshiki Iwasaki[a,b,*], Yasuyuki Shimizu[c], Ichiro Kimura[d]

[a] Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, 205 N, Mathews Avenue, Urbana, IL 61801, USA
[b] U.S. Geological Survey, Geomorphology and Sediment Transport Laboratory, Golden, Colorado, USA
[c] Laboratory of Hydraulic Research, Graduate School of Engineering, Hokkaido University, N13, W8, Kita-ku, Sapporo 060-8628, Japan
[d] Laboratory of Hydraulic Research, Graduate School of Engineering, Hokkaido University, N13, W8, Kita-ku, Sapporo 060-8628, Japan

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ABSTRACT

A number of numerical models have been proposed to understand and simulate fluvial river morphodynamics; however, it is somewhat unclear whether all the models are able to consistently simulate flow-bed instability phenomena. This study investigates the sensitivity of free bar morphology in rivers to secondary flow models used in depth-averaged models using linear stability analyses and numerical simulations. Both the linear analyses and numerical simulations suggest that under certain hydraulic conditions, an equilibrium-type secondary flow model, which has been widely used in river morphodynamic models, fails to generate a finite wavelength and bar mode, allowing the inception of bars of infinitely short scale and infinitely high mode. Using a nonequilibrium-type secondary flow model avoids the unphysical formation of these incipient free bars, and gives better solutions regarding finite amplitude bars. Since free bars are essential, intrinsic river morphological features, the findings of this study can be applied to a wide range of river morphodynamic calculations.

1. Introduction

Free bars in rivers are essential, intrinsic morphological features because they are caused by a boundary instability phenomenon between turbulent open channel flow and the river bed surface (Tubino et al., 1999). This depositional pattern affects flow and sediment transport in rivers, and thereby river morphology, and generates habitat structures for many aquatic species. Understanding and predicting the dynamics of free bars is a central and classic issue from scientific and engineering points of view (Seminara, 2010).

The basic properties of free bars have been investigated through a number of well-controlled experiments in straight channels (e.g., Ikeda, 1984; Fujita and Muramoto, 1985; Garcia and Ninõ, 1993; Lanzoni, 2000). To obtain physically based explanations of the boundary instability phenomenon, theoretical studies have been conducted, namely, linear stability analyses (Callander, 1969; Parker, 1976; Fredsøe, 1978; Kuroki and Kishi, 1984a) and nonlinear stability analyses (Colombini et al., 1987; Schielen et al., 1993; Pornprommin and Izumi, 2011). These theoretical investigations have revealed that horizontal two-dimensional (2D) approaches, which combine a shallow water flow model and an equilibrium bedload transport model with transverse slope effects, can explain the formation of free bars with finite wavelengths and waveheights. The morphodynamic models have been extended to investigations of free bar morphologies that are affected by planimetric channel shapes, for instance, those of weakly meandering channels (Tubino and Seminara, 1990), those with spatial width variation (Wu and Yeh, 2005), and those with a combination of curvature and width variations (Luchi et al., 2010; Zolezzi et al., 2012).

Since linear stability analyses show that system equations of 2D morphodynamic models have intrinsic bar instability, we have been able to numerically simulate the formation and development of free bars by discretizing the governing equations, thanks to recent progress in computational technologies and numerical techniques (e.g., Shimizu and Itakura, 1989; Nelson, 1990; Defina, 2003; Federici and Seminara, 2003; Crosato et al., 2012; Siviglia et al., 2013). These numerical models are potential tools for investigating the complex physical processes that relate to free bars, for instance, the co-evolution of a bar and a meandering channel (Nagata et al., 2000; Darby et al., 2002; Jang and Shimizu, 2005a; Duan and Julien, 2005; Asahi et al., 2013), free bar development with graded sediment (Takebayashi and Egashira, 2004), the formation of braided channels and mid-channel bars (Nicholas et al., 2013; Schuurman et al., 2013), and the effect of vegetation on river

* Corresponding author. Tel.: +12074024623.
E-mail address: tiwasaki@illinois.edu (T. Iwasaki).

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morphology (Jang and Shimizu, 2007; Crosato and Saleh, 2011; Li and Millar, 2011; Bertoldi et al., 2014; Iwasaki et al., 2016).

To further elucidate river morphodynamic processes, several sub-models have been incorporated into the basic depth-averaged morphodynamic models. For instance, with respect to three-dimensional (3D) flow structures, because curvature-driven secondary flow plays an important role in finite-amplitude bars (Nelson, 1990) and must be taken into account to simulate the bed evolution in curved open channels (e.g., Engelund, 1974), the effects of secondary flow have been incorporated into sediment transport models (Struiksma et al., 1985) and hydrodynamic models (Kalkwijk and de Vriend, 1980; Johannesson and Parker, 1989; Lanzoni, 2000). Although recent increases in computational power permit the use of 3D hydrodynamic models to simulate free bar formation (Schuurman and Kleinhans, 2015), advanced 2D morphodynamic models that include the effects of 3D flow structures might be necessary for practical use. However, despite the large number of applications for these advanced models, it is rather unclear how the sub-models, which are used to improve the numerical results, might affect the calculation of free bar instability. In other words, incorporating the sub-models into numerical models could accidentally enhance/depress the characteristics of free bars in simulations, leading to a misunderstanding of the numerical results. Because free bars are morphological features inherent to river systems, the governing equations used in the morphodynamic models should be able to explain the formation of free bars consistently. Using a linear stability analysis could reveal what type of instability features may be included in the governing equations. However, theoretical and numerical studies have generally been conducted separately. A comprehensive study that combines both types would contribute to a better understanding of the performance and consistency of morphodynamic models.

This paper focuses on modeling curvature-driven secondary flow for the simulation of free bar dynamics. Curvature-driven secondary flow, a spiral flow in the vertical direction, is caused by an imbalance between centrifugal force and pressure induced by the streamline curvature. This is addressed in order to understand the bed evolution of curved open channels. Because the flow field in curved open channels is forced by the channel curvature, secondary flow is a key element in controlling flow and sediment transport and, therefore, in determining the bed topography, i.e., local scouring at the outer bank region and point bars in the inner bank region. As such, we have to incorporate this effect into the morphodynamic model in order to reproduce the bed geometry typical of curved/meandering rivers. Several models of secondary flow have been proposed: an equilibrium-type model that is derived from the steady and equilibrium flow field in a constant curvature channel (e.g., Engelund, 1974), a non-equilibrium model that describes the development of secondary flow in a curvature-varying channel such as a meandering river (e.g., Johannesson and Parker, 1989), and a model that can handle an interaction between main flow and secondary flow (e.g., Zolezzi and Seminara, 2001; Blanckaert and de Vriend, 2003).

Analogous to the case of curved channels, finite amplitude alternate bars are able to generate meandering flow in straight channels as well. The streamline curvatures associated with bar morphology may also drive a curvature-driven secondary flow (i.e. topographically induced) rather than the planform channel configuration. This bar-induced secondary flow plays a crucial role in bar dynamics at the nonlinear level (Hasegawa, 1983; Fukuoka and Yamasaka, 1984; Nelson, 1990). To incorporate this effect into the numerical models, the secondary flow model derived for curved channels has been extended to the streamline curvature of the depth-averaged flow field instead of channel curvature. This means that even at the linear level, in which free bars are not significant, secondary flow might have some impact on the morphodynamic processes. However, it is somewhat questionable whether secondary flow can influence the initial development of bars, because bar height at the linear level might be insufficient for secondary flow to develop. Since linear stability analyses regarding the formation of free bars have often not considered secondary flow effects, it is unclear whether the use of secondary flow modeling affects the results of free bar linear development. Although Kuroki and Kishi (Kuroki and Kishi, 1984b), Tubino et al. (Tubino et al., 1999), and Lanzoni (Lanzoni, 2000) conducted linear stability analyses of free bars with a secondary flow model, their discussion is limited to the case of alternate bars; there is no discussion about the case of multiple bars. Moreover, for the numerical models, there was no thorough investigation of how differences in secondary flow modeling might affect the results of linear and nonlinear bar dynamics.

In this study, we investigate how the modeling of secondary flow affects free bar dynamics in a straight channel by comparing numerical simulations and linear stability analyses. The base model used here consists of a 2D shallow water flow model and an equilibrium bedload transport model with local slope effect in the streamwise and transverse directions. We consider the effect of secondary flow in only the bedload transport direction, neglecting its effect on the flow structures themselves. We test three different treatments regarding the effect of secondary flow: (1) a model with no secondary flow effect, (2) an equilibrium-type model derived in a constant curved channel (e.g., Engelund, 1974), and (3) an non-equilibrium-type model that considers the development of secondary flow (e.g., Johannesson and Parker, 1989). Linear stability analyses on equations for the above systems reveal the effect of secondary flow modeling on the linear development of free bars. In addition to linear analyses, we conduct numerical simulations by solving three types of system equations directly in order to discuss the effect of secondary flow modeling on nonlinear bar dynamics. We also compare the numerical simulation results with experimental data to understand how the model performs at the nonlinear level. This investigation attempts to validate the numerical model from both theoretical and experimental points of view. Finally, we discuss the applicability of the secondary flow model to the simulation of free bars in the case of a depth-averaged model. This study may also reveal model performance, providing useful insights regarding the use of different types of numerical models to simulate river morphodynamics.

2. Methods

2.1. Numerical modeling

2.1.1. Governing equations

The present study adopts an unsteady, fully nonlinear depth-averaged 2D shallow water flow equation in a Cartesian coordinate system to simulate the flow field, as follows:

$$\frac{\partial \tilde{h}}{\partial \tilde{t}} + \frac{\partial \tilde{u}\tilde{h}}{\partial \tilde{x}} + \frac{\partial \tilde{v}\tilde{h}}{\partial \tilde{y}} = 0, \tag{1}$$

$$\frac{\partial \tilde{u}}{\partial \tilde{t}} + \tilde{u}\frac{\partial \tilde{u}}{\partial \tilde{x}} + \tilde{v}\frac{\partial \tilde{u}}{\partial \tilde{y}} = -g\frac{\partial \tilde{h}}{\partial \tilde{x}} - g\frac{\partial \tilde{\eta}}{\partial \tilde{x}} - C_f\frac{\tilde{u}\sqrt{\tilde{u}^2+\tilde{v}^2}}{\tilde{h}}, \tag{2}$$

$$\frac{\partial \tilde{v}}{\partial \tilde{t}} + \tilde{u}\frac{\partial \tilde{v}}{\partial \tilde{x}} + \tilde{v}\frac{\partial \tilde{v}}{\partial \tilde{y}} = -g\frac{\partial \tilde{h}}{\partial \tilde{y}} - g\frac{\partial \tilde{\eta}}{\partial \tilde{y}} - C_f\frac{\tilde{v}\sqrt{\tilde{u}^2+\tilde{v}^2}}{\tilde{h}}, \tag{3}$$

where $\tilde{t}$ is the time; $\tilde{x}$ and $\tilde{y}$ are the Cartesian coordinates; $\tilde{u}$ and $\tilde{v}$ are the depth-averaged flow velocities in the $\tilde{x}$ and $\tilde{y}$ directions, respectively; $\tilde{h}$ is the water depth; $\tilde{\eta}$ is the bed elevation; and g is the gravitational acceleration. C_f is the drag coefficient of bed friction, which is herein obtained using Manning's roughness law, as follows:

$$C_f = \frac{g{n_m}^2}{\tilde{h}^{1/3}}, \tag{4}$$