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An analytical model for lateral depth-averaged velocity distributions along a meander in curved compound channels

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ABSTRACT

This paper presents an analytical method for modeling the lateral depth-averaged velocity distribution along a half-meander in a curved compound channel. An equation is derived from the momentum equation and the flow continuity equation which contains a velocity term with both streamwise velocity variation and lateral secondary flow variation. A velocity variation parameter is proposed in the main channel and on the floodplain for a series of test sections. To study the validity of these equations experiments were conducted in a large scale meandering compound channel at Sichuan University, China. Based on the experimental data, the generation mechanism of secondary flow in the main channel along half a meander is analyzed. It is shown that the secondary current is enhanced by the centrifugal force and the floodplain flow. Due to the discontinuity of the flow depth and the effect of meandering in the main channel flow, a region divided method is adopted. A new boundary condition is proposed by introducing the angle between the main channel flow and the floodplain flow, and it is shown that this gives better modeling results in cross-over sections. The modeling results indicate that the proposed method, which uses the new boundary condition and includes both the streamwise velocity variation and the lateral secondary flow variation, can model the lateral depth-averaged velocity distributions more accurately. Finally, variations in the velocity term between the main channel and floodplain are discussed and analyzed.

1. Introduction

In a river corridor system, rivers play an important role in the provision of water and habitat to the surrounding fauna and flora. Natural alluvial rivers and streams often exhibit a curved main river and one or two corresponding floodplains. When a flood occurs, the flow depth increases and the floodplains are submerged to convey the extra flow, leading to overbank flow in the meandering compound channel. It is important to note that the flow characteristics in a curved channel are very different to that in a straight one, especially with regard to the generation mechanism of main channel secondary flows. Accordingly, it is necessary to assess the changes of the velocity, secondary flow, bed shear stress and discharge in the meandering compound channels.

To determine sediment transport, channel morphology and bank erosion, the lateral distributions of depth-averaged velocity and bed shear stress are crucial. In recent decades, the three-dimensional flow structure, turbulence characteristics and secondary flows in straight compound channels have been extensively investigated by, amongst others, Knight and Demetriou [14], Pasche and Rouve [25], Knight and Sellin [15], Tominaga et al. [41], Yuen [45], Carling et al. [3] and Yang et al. [43]. Moreover, lateral distribution methods (LDM) for the depth-averaged velocity and bed shear stress, along with the secondary flow and the plan-form vorticity, have been developed by Shiono and Knight [31], Cao et al. [2], Rameshwaran and Shiono [29], Huai et al. [9], Hu et al. [8], Liu et al. [20] and Yang et al. [44]. These researchers showed that the secondary flows affect the predictions of velocity and bed shear stress significantly and ignoring them leads to poor results. Therefore, Ervine et al. [5], Spooner [38] and Huai et al. [10] proposed new secondary flow expressions which were applied at the apex sections in the meandering compound channel with non-mobile bed and mobile bed. However, when the flow depth is discontinuous at the interfaces of main channel and its

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corresponding floodplains the boundary condition must be reconsidered. Knight et al. [16] and Tang and Knight [39] discussed the boundary conditions for the Shiono and Knight Method [31] (hereafter referred as SKM) and discovered that improved results were obtained by using the continuity of depth-averaged shear stress at the interfaces of main channel and floodplain. Furthermore, the turbulent transfer is also an important phenomenon in compound channels and based on mathematical integration, Castanedo et al. [4] identified three different forms of the turbulent diffusion term in the depth-averaged Navier–Stokes equation. Subsequently, these three models and the original SKM were compared by Tang and Knight [40] in both a straight trapezoidal channel and a straight compound channel. Their conclusions show that to obtain good predictions the four models must contain the secondary flow parameter and this affects the results more than the dimensionless eddy viscosity for overbank flows.

For overbank flow in a meandering compound channel with a fixed bed, experimental work [28,32,33] has shown that secondary current cells in the main channel are much stronger than those on the floodplain due to the effect of centrifugal force. For overbank flows in a meandering compound channel, discharge assessment methods have been proposed by various authors [7,19,26,27,34]. Flow characteristics were also discussed in a meandering compound channel with non-mobile bed and three different sinuosities (1.093–1.571) by Shiono and Muto [32], who found that the secondary flow for the inbank and overbank flows originated from different mechanisms. Their experimental results also showed that a strong intensity of secondary current cells existed mainly in the main channel, especially for the overbank flow. Then, experimental research was extended to curved channels with mobile bed and different floodplain vegetation by Ishigaki et al. [11], Lyness et al. [21], Keevil et al. [13], Shiono et al. [35] and Shiono et al. [36,37]. From these studies, some conclusions were obtained: (1) the vegetation on the floodplain reduced the channel conveyance capability significantly; (2) the lateral secondary flow distributions in a meandering channel were quite different between the cases with the non-mobile bed and mobile bed; (3) in the cases with a mobile bed, multiple secondary current cells which cause a series of wavy bedforms occur at deeper flow depth along the meandering main channel when the floodplain roughness increases. These phenomena are usually seen in natural rivers and the conclusions are therefore valuable for engineering projects.

As well as experimental studies, numerical investigations can also give insight into flows in meandering channels. A one-dimensional simulation with vegetation in a curved channel was presented by Martin-Vide et al. [22] and two-dimensional models were described by Shao et al. [30] and Zarrati et al. [46], presenting good modeling results for the velocity distribution, the secondary flow and the flow depth. Morvan et al. [24] and Jing et al. [12] carried out three-dimensional methods to simulate the velocity fields in overbank flow. Further, analytical methods have been proposed by Ervine et al. [6], McGahey et al. [23] and Huai et al. [10], based on the SKM method, to predict the depth-averaged velocity distribution. Although velocity patterns in a meandering compound channel are highly three dimensional, these researchers neglected the streamwise velocity variation to simplify the analytical models which were therefore only applicable at apex sections. Knight et al. [18] pointed out that the modeling capability of SKM is poor in meandering compound channels because of the methodology is derived for steady flows in straight prismatic channels. According to the research described above, it is hard to find a reasonable analytical method to predict the lateral velocity distributions along a meander, and the lack of detailed experimental data also presents difficulties. This forms the motivation for this paper in which a new model is presented along with a series of experiments to demonstrate its derivation and validate its results.

The research presented in this paper explores an analytical method to model the depth-averaged velocity along a meander in a curved compound channel. A governing equation is derived from the streamwise momentum equation and the flow continuity equation. Its velocity term contains the streamwise velocity variation, ignored by Ervine et al. [6], McGahey et al. [23] and Huai et al. [10], and the lateral secondary flow variation. In order to verify this model, two groups of experiments were conducted in a large scale meandering compound channel at Sichuan University in China. The three-dimensional velocities, the flow depth and the Reynolds shear stress were recorded at seven test sections along half a meander. Based on the experimental data, the generation mechanism of secondary flows, including the effects of centrifugal force and floodplain flow, is analyzed and an expression for the velocity variation parameter at the apex and cross-over sections is proposed. Further, the divided method in half a meander is presented by considering the effect of meandering main channel flow. A new boundary condition is proposed by introducing the angle between the main channel and floodplain. Finally, the modeling results of depth-averaged velocity by this method are compared with the experimental data. Each part of the velocity term is discussed and analyzed in the meandering main channel and on the floodplain.

2. Experimental arrangement and apparatus

Two groups of experiments (MN1 and MN2) were conducted in a 35 m long, 4 m wide and 1 m high flume, at State Key Laboratory of Hydraulics and Mountain River Engineering (SKLH), Sichuan University (see Fig. 1). The flow depths of MN1 and MN2 in the main channel are 0.255 m and 0.216 m, respectively. Measurements were carried out for the stage-discharge curve, the Reynolds shear stresses and the three-dimensional velocities. The discharge was measured by a triangular weir installed in front of the flume and the flow depth was measured by an Automatic Ultrasonic

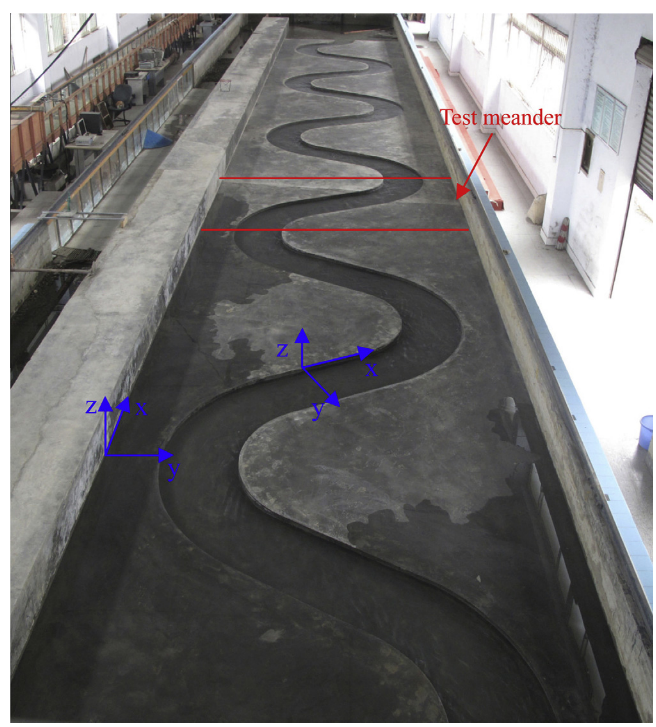

Fig. 1. Photograph of the meandering compound channel in SKLH (the co-ordinate systems in the meandering main channel and on the floodplain are different, except at the apex section).