

COMPARISONS OF ADVANCED DEPTH-INTEGRATED MODELS WITH TWO AND THREE-DIMENSIONAL MODELS FOR SIMULATING PARTLY EMERGENT RIGID VEGETATION

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1. INTRODUCTION

Vegetation naturally exists in meandering rivers. Vegetation significantly affects the flow structure, reduces the strength of the secondary flow, and moves the position of high-velocity core away from the vegetation (Thorne and Furbish, 1995). The flow velocity in the vegetated area is reduced, while the flow velocity in the main flow is increased. Increased vegetation density leads to increased main flow velocity (Naot et al., 1996). In addition, the presence of vegetation reduces shear stress, indicating that the risk of scour and erosion is reduced (Huai et al., 2012). On the other hand, vegetation also has adverse effects such as reducing discharge capacity and causing rivers to be more prone to flooding. So it is important to understand the flow structure in the vegetated rivers.

A numerical calculation model is a useful tool in analyzing flow structures and supporting river engineering applications. It is well known that three-dimensional calculation (3DC) can capture flow structures in vegetated rivers (Wang et al., 2021). However, 3DC models require long computational time and huge storage, making them difficult to implement in large-scale areas. By contrast, the two-dimensional calculation (2DC) cannot produce the flow structure because it does not consider the effect of secondary flow, which is one of the main features of meandering rivers. Therefore, it is necessary to develop an advanced 2DC model that requires shorter computational time and considers the effects of the secondary flow. This study compared the flow structure between an advanced 2DC model, conventional 2DC model, and 3DC model on meandering vegetated rivers.

2. METHODS

2.1 Numerical calculation models

This study employed an advanced 2DC model developed by (Uchida et al., 2014, 2016) named the bottom velocity calculation (BVC) method. This method is derived from the continuity equation and the Reynold-averaged Navier-Stokes which assumes a thin vortex layer at the bed surface. This study compared different types of calculation of the BVC method: (1) The 2DC model that used the depth-integrated continuity and horizontal momentum equations; (2) The SBVC2 (simplified bottom velocity calculation) method that consists of the depth-integrated horizontal vorticity equation by assuming equilibrium conditions of water surface flow; (3) The SBVC3 method that calculates surface velocity using the horizontal momentum equation on the water surface; (4) The GBVC (general bottom velocity calculation) method is not restricted to shallow water assumptions and calculate the vertical distribution of pressure.

In the BVC method, vegetation is evaluated using the drag force equation. Drag force consists of two components, drag force due to water surface variation and pressure gradient (Uchida et al., 2022). Drag force is used to evaluate the momentum equation, water surface velocity, and vorticity equation. The constant values used in the equation are $C_{D0} = 1.3$, $\beta_{cp} = -0.24$, and $k = 2.1$.

2.2 Experimental conditions

The experiment was conducted in U-shaped channel (Hual et al., 2012), the radius to the center of the channel is 2 m, the width is 1 m, and consisting of 4 m straight inflow and outflow section. The discharge is $0.03 \text{ m}^3/\text{s}$ and the water level at the downstream end is 0.148 m. Vegetation planted on the inner bank with a width of 0.25 m. The vegetation diameter and height are 0.006 m and 0.15 m, respectively. Then, distance between vegetation is 0.05 m. Vegetation planted after 2 m from the inflow and 2 m before the outflow. Velocity measurement were taken at 5 section ($0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ$). The k_s value is 0.0021 m, equivalent to Manning coefficients $n=0.01$, to reproduce the streamwise velocity distribution in the experiment in the free stream region.

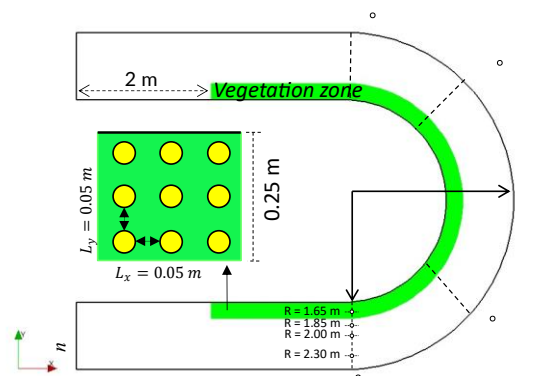


Figure 1. Schematic of experimental channels

Keywords: Depth-integrated model, partly vegetated channel, numerical calculation, secondary flow

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3. RESULTS

Figure 1 compares the streamwise velocity distribution at section 0° and 90° . The streamwise velocity in vegetated areas is I-shaped form and has a smaller value compared to non-vegetated areas. However, velocities in non-vegetated areas tend to increase and has a log law form. Then, it can be seen that the location of high velocity core is away from the vegetated area.

Based on the vertical streamwise velocity profile, before entering the bend (section 0°), there is no significant difference between the streamwise velocity of the BVC model and 2DC model. The model fits the experimental dataset. However, after entering the bend (section 90°), the 2DC model fails to produce the streamwise velocity profile in the experiment dataset. The bottom velocity is underestimated, while the surface velocity is overestimated by 2DC. However, streamwise velocity profile in the bend from the BVC method fits the experimental dataset. BVC model also showed good agreement with the 3DC model. This is because when water enters the bend, the water surface profile increases at the outer bank and decreases on the inner bank due to centrifugal force. The imbalance between centrifugal force and pressure gradient causes the secondary flow. The secondary flow induces momentum transport in the transverse direction from inner to outer bank. Secondary flow is captured well by the BVC method but cannot be captured by the 2DC model, as shown in Figure 1C. The GBVC, SBVC2, and SBVC3 produce the secondary flow that match the experimental dataset and 3DC model (Huai et al., 2012). The flow at the water surface moves towards the outer bank, while the flow at bottom moves to inner bank.

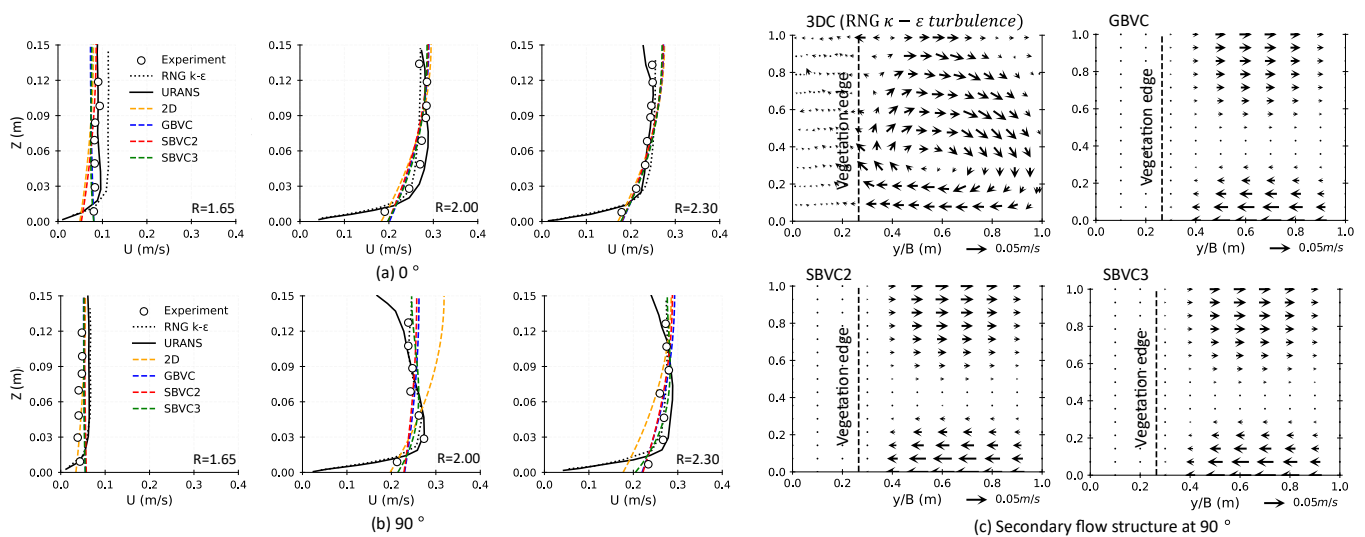


Figure 1. Streamwise velocity profil at section (a) 0° and (b) 90° ; (c) Secondary flow structure at section 90° . The 3DC calculation result is obtained from the RNG $k - \varepsilon$ (Huai et al., 2012) and URANS (Wang et al., 2021)

4. CONCLUSIONS

This study shows the advantages of the BVC method. The BVC method produces streamwise velocity profiles that fits the experimental dataset and also similar with 3DC model. This is because the BVC method can capture the secondary flow phenomenon. In contrast, using the same parameter, the 2DC models show fail to capture the streamwise velocity profile. Bottom velocity values tend to be underestimated, while surface velocity tends to be overestimated. This is also proven that the advanced depth integrated model is very important in river engineering applications for simulating open channel flow.

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