COMPARISONS OF ADVANCED DEPTH-INTEGRATED MODELS WITH TWO AND THREE-DIMENSIONAL MODELS FOR BEND FLOWS

Hiroshima University Student Member ○Fikry Purwa Lugina
Hiroshima University Regular Member Tatsuhiko Uchida

1. INTRODUCTION

A numerical calculation model becomes one of the most cost-effective ways to study flow structures in rivers over field observation and physical measurement. Hydraulic engineers have often employed two-dimensional calculation (2DC) models in practical use due to their simplicity in application, even though flow structures in rivers are fully three-dimensional. A 2DC model cannot consider the vertical flow distribution of streamwise and spanwise velocity that characterizes the flow within channel bends. The vertical velocity distributions are not uniform at the channel bend due to the secondary flow generation that arises from the imbalance between the transverse water surface gradient and the centrifugal force. As a result, water flows outward at the surface but inward near the riverbed, leading to erosion along the outer bank and deposition at the inner bank.

Secondary flows induce an increase in near-bed velocity, which leads to an increase in flow resistance (Nikora et al., 2012). A better understanding of flow resistance is crucial for determining the discharge capacity of rivers and the distribution of shear stress around the boundary. A three-dimensional calculation (3DC) model effectively captures complicated flow structures with satisfactory accuracy (Yan et al., 2020). However, it requires a considerable amount of computation time to be applied to practical engineering problems because of the additional calculation grid in the vertical direction and the iterative calculation cost of the pressure equation compared with a 2DC model. Hence, there is a need to develop an advanced 2DC model that can solve the issue of long computation time and lack of computational detail in determining flow structures in rivers. This study compared the advantage of an advanced 2DC model with a conventional 2DC and 3DC model for water surface profiles in curved open channels, including increasing flow resistance.

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. The BVC method is an integrated multiscale simulation of flows in rivers that can evaluate vertical and bottom velocity distributions by introducing depth-averaged horizontal vorticity and horizontal momentum equations on a water surface. Several types of calculation models were compared in this study to analyze the advantages of the BVC method: (1) A non-hydrostatic 3DC model, NaysCUBE; the solver is available in the public domain in the iRIC river software package (Kimura, 2020); (2) The 2DC model that consists of depth-integrated continuity and horizontal momentum equations; (3) The SBVC (simplified bottom velocity calculation) method with shallow water assumption that employs hydrostatic pressure distribution and neglects the variation in vertical velocity. The SBVC2 model assumes the equilibrium condition of water surface flow, while SBVC3 calculates the momentum equations for water surface flows. (4) The GBVC3 (general bottom velocity calculation) model is not restricted to the shallow water assumption and calculates the non-hydrostatic pressure distribution and variation in vertical velocity.

2.2 Experimental conditions

Two sets of experimental data of a sharply curved open channel (Rozovskii, 1957) and a mildly curved channel (de Vriend, 1979) were used to validate the models. Table 1 summarizes the channel geometries and hydraulic conditions for each case. The experimental discharge gives the upstream boundary condition. The experimental water depth gives the downstream water depth; the k_s values are 0.0073 m, equivalent to Manning coefficient n=0.024 and 0.0005 m, equivalent to Manning coefficient n=0.011 for the sharply and mildly curved channels, respectively.

Table 1. Experimental conditions for flow measurements

	Q (m^3/s)	h_0 (m)	B (m)	θ	R_c (m)	R_c/b	S
Sharply curved channel	0.0123	0.051	0.8	180°	0.8	1.0	0.0
Mildly curved channel	0.18	0.189	1.7	180°	4.25	2.5	0.0

3. RESULTS

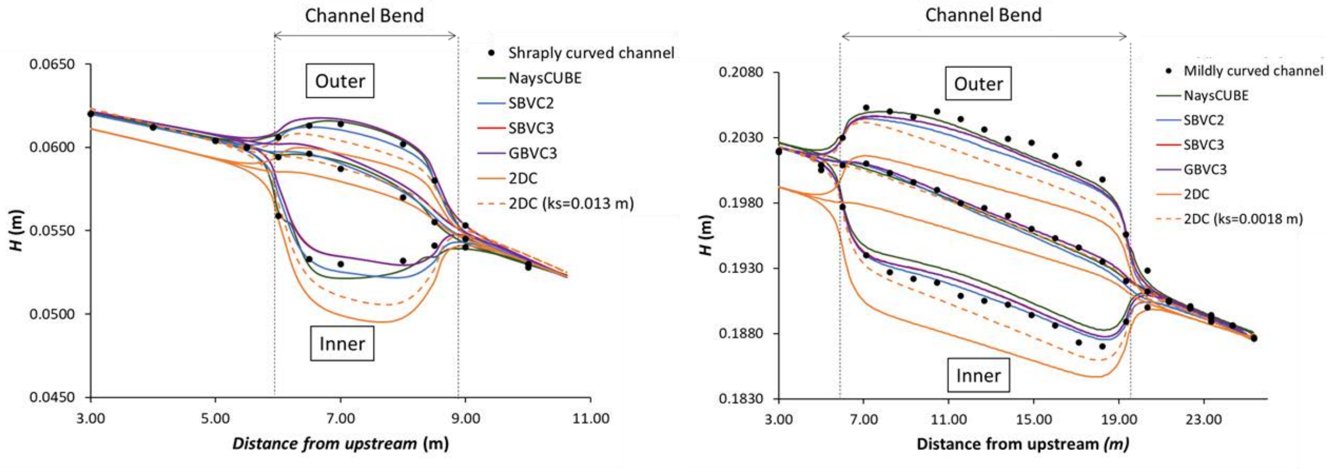
Figure 1 compares the water surface profiles along the outer and inner banks for the sharply and mildly curved channels, respectively. The water surface profile is uniform in the upstream section of the bend. Once the flow enters the curved part, the water surface profile increases at the outer wall and decreases at the inner wall owing to the centrifugal force effect. After leaving the bend, the water surface profile becomes uniform again.

Keywords: Curved open channel, depth-integrated model, flow resistance, numerical model, secondary flow

Contact address: 1-4-1 Kagamiyama, Higashi-Hiroshima City, Hiroshima, 739-8527, Japan, Tel: 080-4339-5924

The models of the BVC method can reproduce the effect of secondary flow on the increase in channel resistance presented in the water surface profile with the experimental datasets and are in good agreement with the NaysCUBE model. 2DC can produce a transverse water surface in the channel bend; however, it underestimates the longitudinal surface gradient. To fit the experimental results of the bend, the 2DC requires a coarser k_s value than the physical value obtained from the experimental water surface and velocity profiles because it is unable to consider the increase in vertical momentum transfer due to secondary flow. The orange dashed line shows the 2DC results with modified *ks* to reproduce the channel resistance, where the k_s values are increased to 0.013 m and 0.0018 m for the sharply curved channels, respectively.

However, even with the increased roughness coefficient, the 2DC failed to reproduce the water surface profile in the channel bends. In particular, it is essential to note that 2DC underestimates the water surface superelevation along the outer bank. This problem is due to not considering momentum transport with the secondary flow in the outer bank direction. The velocity along the outer bank is small at 2DC, and the centrifugal force is underestimated. While SBVC2 depends on underestimating the super-elevated water surface along the bank, it is demonstrated that SBVC3 and GBVC3 can reproduce the experimental water levels along the outer banks with the same accuracy as the full three-dimensional model.



(a) (b)

Figure 1. Water surface profile comparison: (a) sharply curved channel, (b) mildly curved channel.

4. CONCLUSIONS

This study presented the advantage of the BVC method over the 2DC model by comparing experimental datasets and 3DC results for sharply and mildly curved channels. The models of the BVC method were in good agreement with experimental data sets and NaysCUBE, in which a fully three-dimensional model in reproducing water surface elevation in the channels. The 2DC model cannot significantly improve the water surface elevation because of the inability to consider the increase in flow resistance due to secondary flow. The best-fit water surface profile could not be reproduced using the equivalent roughness value obtained directly from the velocity distribution. In addition, even with modified roughness coefficients, the 2DC model underestimated the water surface elevation along the outer bank. This study shows that using the advanced depth-integrated model in practical engineering for simulating open channel flows is essential because: (1) the conventional 2DC model underestimates the water surface elevation, and it can be harmful to societies; (2) the advanced depth-integrated model has smaller computational resources compared to NaysCUBE, a fully three-dimensional model.

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