

Three-dimensional flow structures modelling based on a depth-integrated method in a sharply curved open channel over topography

Fikry Purwa Lugina^{1*}, *Tatsuhiko Uchida*¹, and *Koen Blanckaert*²

¹Graduate School of Advanced Science and Engineering, Hiroshima University, 1-4-1 Kagamiyama, Highashi-Hiroshima City, Hiroshima 739-8527, Japan

²Institute of Hydrology and Water Resources Management, Vienna University of Technology, Karlsplatz 13/222, A-1040 Vienna, Austria

Abstract. In this study, we introduce the bottom velocity calculation (BVC) technique, a depth-integrated approach for modeling three-dimensional flow systems in the two-dimensional (2D) river management model framework. The method has been expanded to a general coordinate system and its applicability to flow in bends and meanders for the applications to rivers. The method was validated to a laboratory experiment conducted in a sharply curved channel over topography. The pattern of water surface elevation and vertical velocity distribution can be replicated by the BVC method's models, which also show strong qualitative agreement with the experimental dataset and 3D model. The benefit of using the BVC technique instead of the 2D model is verified; the 2D model is unable to replicate the profile since it does not take into account three-dimensional flow structures. As seen above, the BVC method is helpful in evaluating the river environment because it can account for the complicated material transports caused by three-dimensional flows in the meandering sections of the river channel.

1 Introduction

The complex interplay between fluid dynamics and geomorphology in natural river systems has long captivated the attention of hydraulic engineers and geomorphologist. Curved and meandering rivers exhibit distinct hydraulic behaviours driven by the interaction of centrifugal force and water surface elevation [1]. The bed topography profile of the rivers, including point bars and pools, further influence flow dynamics [2,3].

In recent years, advancements in measurement techniques, such as high-resolution remote sensing, acoustic Doppler profilers, and numerical modeling approaches, have provided unprecedented opportunities to delve deeper into the dynamics of flow structures in non-planar rivers [1-4]. These interdisciplinary efforts have shed light on the intricate interactions between flow processes and channel morphology, paving the way for more holistic approaches to river management and restoration.

*Corresponding author: fikrypl@hiroshima-u.ac.jp

The complexities inherent in three-dimensional (3D) flow structures in rivers demand sophisticated modeling approaches capable of capturing complex interactions between fluid dynamics and channel geometry. Previous studies [4] used three-dimensional models to capture the interaction between flow and sediment dynamics in a detailed experiment dataset conducted by Blanckaert [2]. On the other hand, depth-integrated models have been improved based on the two-dimensional model to overcome a huge computational cost required for a 3D model calculation [5].

The bottom velocity calculation (BVC) [6,7] method employed in this study and has been validated with several experiment dataset, such as flow dynamics in mildly and sharply curved channel [8] and flow resistance in a meandering channel [9], and it showed a good agreement with experimental dataset. Expanding upon previous studies, this research explores the effectiveness of the BVC method in capturing three-dimensional flow structures, particularly focusing on its performance in channels featuring complex bed topography.

While past investigations have addressed the influence of secondary flow on flow dynamics [8,9], the impact of bed topography on horizontal flow structures remains underexplored. This study presents a validation of the BVC method through laboratory experiments conducted in sharply curved channels with varying bed topographies. Furthermore, this study aims to elucidate the role of bed topography in shaping secondary flow patterns within sharply curved channels.

2 Methods

2.1 Experiment dataset

An experimental dataset comprising bed and water surface topography was used to test the models' ability to mimic flow characteristics across topography [2] (Figure 1). A 5 m outflow portion, a 193° curved segment, and a 9 m input section made comprised the experimental setup's flume. The sand had an average diameter of around 2.0 mm. The discharge was 0.089 m³/s, and the water depth was 0.141 m. The flume width was $b=1.3$ m, and the Reynolds number was 68,000.

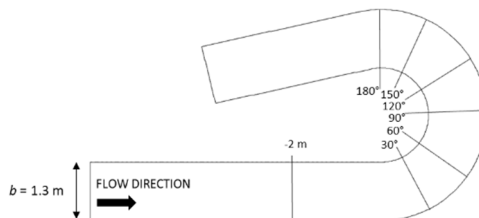


Fig. 1. Configuration of channel by Blanckaert [2].

2.2 Numerical calculation method

The general bottom velocity calculation (GBVC) and simplified bottom velocity calculation (SBVC) models are two prominent variations of the BVC method that are intended to characterize flow dynamics [6, 7]. Assuming shallow water conditions, the SBVC model uses hydrostatic pressure distribution to simplify computations: SBVC3 considers horizontal momentum equations at water surface, SBVC2 model assumes that water surface flow is in

equilibrium. The GBVC model, on the other hand, provides a more thorough method that goes beyond shallow water assumptions by accounting for vertical velocity changes and non-hydrostatic pressure distributions. See Table 1 for governing equations. In this paper, the zero-equation turbulence model is applied assuming the local equilibrium condition for the turbulent kinetic energy transport equation [4].

The curvilinear coordinate system has a complete governing equation that can be found in [9] with the curved square grid of $d\xi = d\eta = 0.05$ m. The downstream boundary condition was determined by using the weir heights, while the upstream boundary condition was provided by the experimental discharge. The equivalent roughness value was 10 mm.

Table 1. Numerical models employed in this study.

Numerical models		Unknown variable	Governing equation
GBVC3	SBVC2	2D	h DI continuity equations
			U_i DI horizontal momentum equations
		u_{bi} Bottom velocity equations	
		Ω_i DI vorticity equations	
		u_{si} Momentum equation for water surface	
		dp_b DI vertical momentum equation	
		W Double integral of continuity equations	

Note: DI = depth-integrated

3 Results and discussion

Figure 2 shows a longitudinal comparison of the water level elevation's cross-sectional average. The 2D model understates the results, while the BVC models can properly represent the water level slope in cross-sectional average form despite the complexity of the bed topography profile. Figure 3 provides a closer view of the profile in a channel cross-section. The model with a higher water surface at the outer bank can replicate the superelevation of the water surface. The intricate bed topographical structure explains why all of the models understate the experimental dataset results during the beginning of curvature, when the most scouring and deposition occurs.

Underestimation of the model findings indicates that bed topography might encourage extremely complex flow configurations [2] that are hard for the models to depict. However, the superelevation of the water surface caused by the diminishing 3D flow structures once the flow approaches the bend exit (180°) may be replicated by the BVC models.

Because GBVC3 results more closely resemble the experiment dataset than SBVC3, it is advantageous to include non-hydrostatic assumptions. SBVC2 overestimates the outcome because there is no horizontal momentum at the water's surface. The 2D model underestimates the transverse water surface gradient because it does not take secondary flow's increased vertical momentum transfer into account.

The vertical velocity comparison for streamwise and transverse directions is displayed in Figures 4 and 5, respectively. The distance between the water's bed and surface is shown by the vertical axis. The vertical velocity profiles at the left, center, and right banks are shown

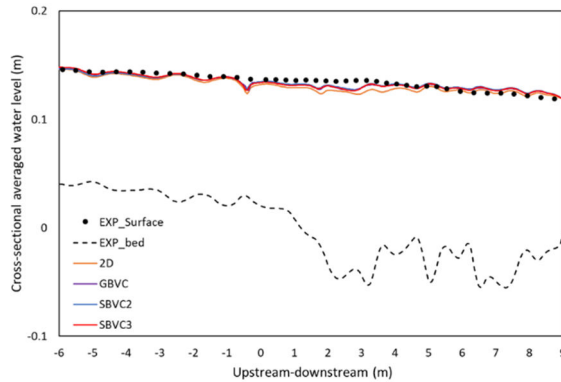


Fig. 2. Cross-sectional average of the longitudinal comparison of water levels.

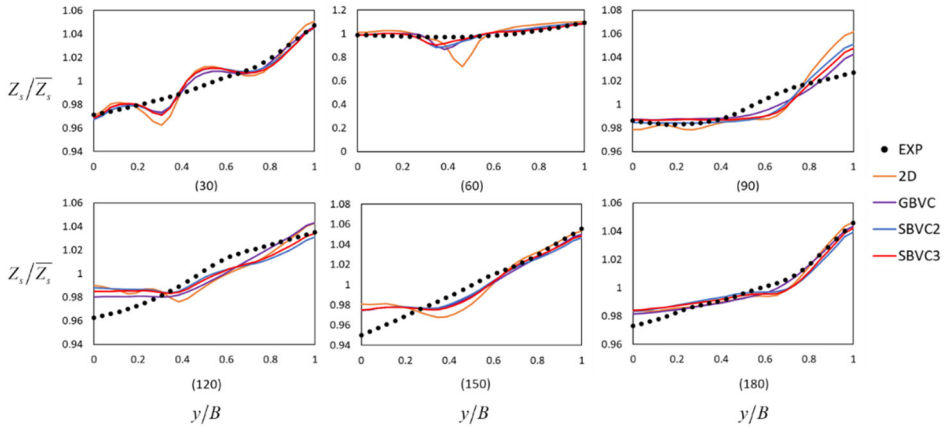


Fig. 3. Water level cross-sectional comparison between experimental data and numerical model output. \bar{Z}_s is the water level's cross-sectional average.

on the horizontal axis. Comparisons were made at 30°, 60°, 120°, and 180°. Data for the cross-sections at 60° and 120° along the left bank are unavailable due to the heavy deposits. The vertical velocity result was compared with the BVC model using a large-eddy simulation (LES) [3].

There might be slight discrepancies between the experimental dataset and the LES model because the presence of small-scale dunes may be the cause of the slight variations between the LES model and the experimental dataset; the finer details of the dunes were not resolved by the spatial resolution of the model [3]. The outcomes of the BVC models vary; for certain cross-sections, the experimental dataset, the BVC models, and the LES model agree well, but not for others. Overall qualitative results show that BVC models outperform experimental datasets and LES models.

Figure 4 generally illustrates how the bottom velocity of GBVC3 accelerates relative to SBVC3 and SBVC2 due to the non-hydrostatic pressure assumptions that explain the vertical velocity distribution. Because SBVC2 assumes a quadratic polynomial distribution for vertical velocity and ignores the horizontal momentum equations at the water's surface, it tends to follow a linear velocity distribution profile that is similar to a 2D model.

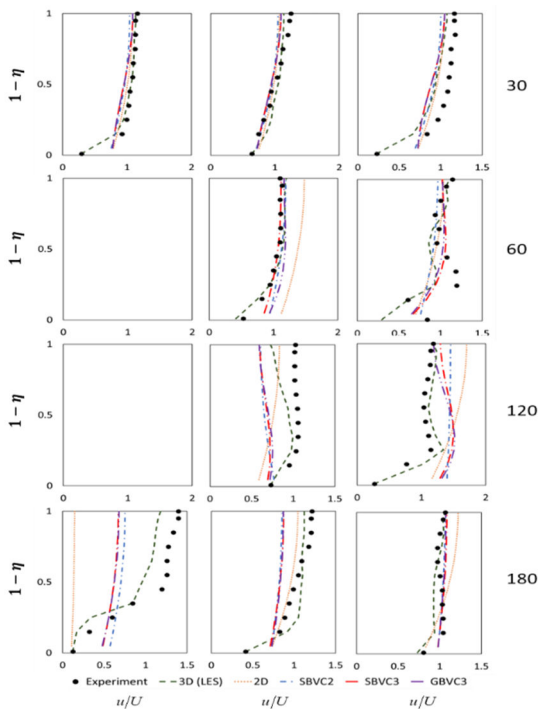


Fig. 4. Comparison of the numerical model findings with the experimental dataset's vertical velocity distribution in streamwise direction.

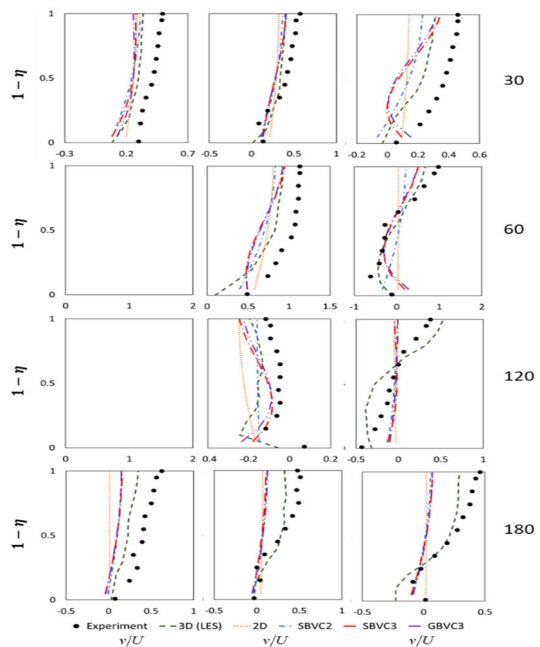


Fig. 5. Comparison of the numerical model findings with the experimental dataset's vertical velocity distribution in transverse direction.

To examine how topographic profile shapes vertical velocity distribution, Figure 6 compares the vertical velocity in the streamwise and transverse directions on the flatbed case between the 2D and GBVC models. The streamwise component shows that 2D model produces smaller velocity on the bed than the GBVC model for the flatbed case since the 2D model does not consider vertical momentum exchange with the secondary flow that induces an acceleration on the bottom velocity. The 2D model also shows that the transverse vertical velocity distribution of the model tends to have zero transverse velocity component on the flatbed case. However, the profile shown by the 2D model in the topographic profile case (Figure 5) shows a non-zero profile indicating that the topographic profile can induce the increasing of bottom shear stress that is independent from the one that induced by secondary flow. The effect of bed profile in increasing bottom shear stress can be confirmed by the profile shown by the GBVC model, the bottom velocity acceleration induced by the vertical velocity distribution can be seen in Figure 6 for flatbed case and it is amplified by the bed profile that can be seen in Figures 4 and 5.

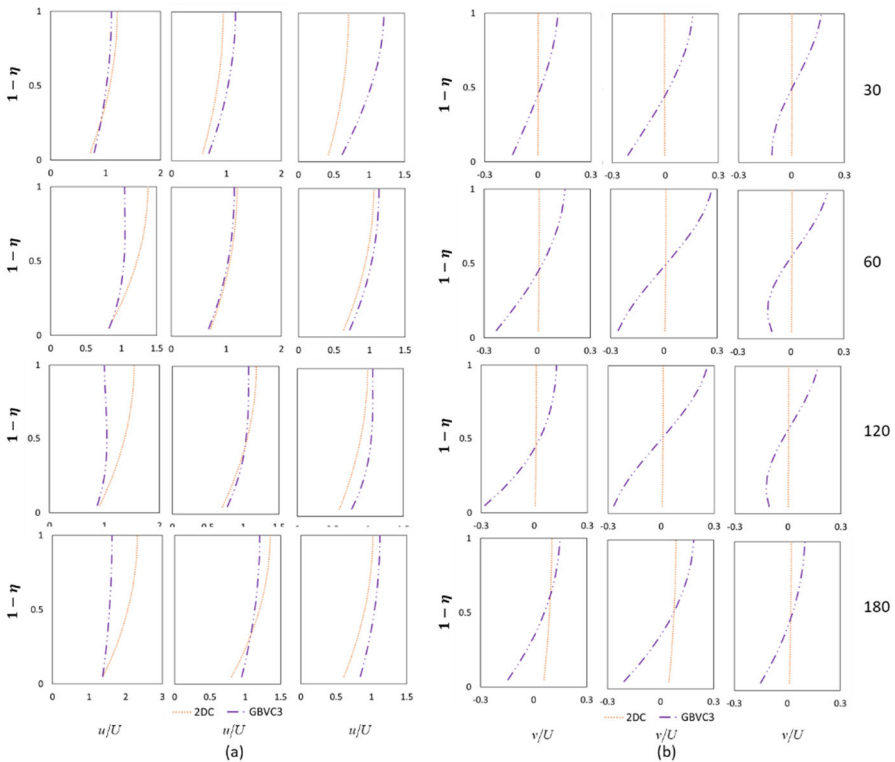


Fig. 6. Comparison of the 2D and GBVC models' vertical velocity distribution on the flatbed case in (a) streamwise and (b) transverse directions.

4 Conclusion

This study examined the degree to which the flow patterns in the curved channel across topography were accurately reproduced by the BVC approach. In addition to having strong qualitative agreement with the 3D model and experimental dataset, the models created using the BVC technique are able to replicate the pattern of vertical velocity distribution and water surface elevation. The superiority of the BVC technique over the 2D model has been shown;

the latter is unable to replicate the profile due to its disregard for three-dimensional flow structures.

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