論 文 の 要 旨

題　目　Numerical Simulation Methods for Flow Resistance and Sediment Transport Dynamics in Curved and Meandering Rivers

（湾曲・蛇行河川における流下抵抗と土砂輸送力学の数値解析法）

氏　名　Fikry Purwa Lugina

Flooding can be caused by more than just heavy rainfall; it can happen when the volume rate of flood water surpasses the river's capacity. Sediment transport dynamics trigger rivers' shape to change, it can be riverbed's elevation and/or river narrowing, and it will promote the decreased river capacity. When river capacity decreases, its response to flow rate/discharge becomes more prone to flooding.

Flow resistance plays a crucial role in governing the behavior of water in streams and rivers, significantly impacting flow hydraulics. It directly influences the ability of a channel to carry water by affecting the velocity of the flow and, consequently, the depth of the water. Additionally, flow resistance has a direct influence on the distribution of shear stress along the channel boundary, which, in turn, affects the extent and pattern of erosion on the channel bed and banks.

Numerical models, validated through experiments or observational datasets, prove to be cost-effective tools. While a three-dimensional (3D) numerical model is preferable for capturing complex flow patterns in meandering rivers, many such models are susceptible to numerical instability and demand substantial computational resources. Consequently, hydraulic engineers often favor simpler two-dimensional (2D) depth-averaged or one-dimensional (1D) cross-section-averaged models for practical applications. However, these models lack the capability to depict the vertical flow distribution of streamwise and transverse velocity characteristic of meandering river flows.

This study: (1) investigated flow resistance and sediment transport dynamics in meandering rivers to get a comprehensive understanding of decreased river capacity mechanisms; (2) developed a numerical model with both efficient calculation time and high accuracy. The work was divided into three parts: developing numerical models, investigating flow resistance, and investigating sediment dynamics.

In the first part, a high momentum transfer near the wall was found by incorporating shallow water assumption for flow dynamics investigation in curved open channels. In a channel bend, the momentum transfer is attributed to the vertical velocity distribution in transverse direction. The vertical velocity distribution is frequently disregarded by a two-dimensional model, leading to inaccuracies in the main velocity distribution. The evaluation of the dispersion term becomes increasingly crucial for calculating momentum transfer attributed to the vertical velocity distribution, surpassing the importance of the advection term. In simpler terms, an incorrect discretization of the dispersion term can lead to unphysical solutions similar to those arising from the advection term, considering that the dispersion term originates from the advection term.

This study developed a numerical discretization method of an upwind scheme for dispersion terms to overcome unphysical phenomena with the shallow water assumption. The proposed method was then applied to a quasi-three-dimensional numerical, so-called bottom velocity calculation (BVC), method to investigate its applicability in reproducing flow structures. . The BVC method evaluates velocity on the bed coupled with depth-integrated continuity and horizontal momentum equations with additional equations of depth-integrated horizontal vorticity equations, momentum equations of the water surface, double integrated continuity equation over depth, and depth-integrated vertical momentum equation for non-hydrostatic pressure distribution. There are several types of BVC models employed in this study: (1) 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. (2) 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.

The effectivity of the proposed method was then compared to a conventional two-dimensional model and a fully three-dimensional model into sharply and mildly curved channels dataset. The proposed method effectively mitigated the occurrence of excessively high velocities near the wall. It demonstrated the capability to accurately replicate both the experimental water levels and velocity profiles within the channel bend using the experimental dataset. Furthermore, it exhibited strong agreement with the results obtained from a fully three-dimensional model. While the conventional two-dimensional model cannot predict well the water surface profile in curved channel because of the inability to consider the increase in flow resistance due to secondary flow. In addition, even with modified roughness coefficients to reproduce the increased channel resistance, the conventional two-dimensional model underestimated the water surface elevation along the outer bank.

After confirming the applicability of the method with the discretization scheme in dispersion terms, the models were then extended to be applied to the bed profile case. The BVC models results show a variation, at some cross-section there is a good agreement between BVC models, experimental dataset, and the three-dimensional model, but at some cross-section not. For overall qualitative results, BVC models are rather good compared to experimental dataset and the three-dimensional model.

For the second part, this study investigated the flow resistance resulting from shear forces in meandering channels, by integrating laboratory experiments with numerical models featuring uniform width and rectangular cross-sections. The study specifically concentrates on distortion resistance and skin resistance, while excluding the consideration of spill resistance and form drag effects. The study has two primary objectives. Firstly, to examine the impact of channel shape, aspect ratios, and bed roughness on flow resistance through laboratory experiments. In this study, a combination of factors was explored to gain a more comprehensive understanding of flow resistance. Secondly, the study aims to validate the effectiveness of the BVC method in simulating the impact of different factors on flow resistance and to investigate flow resistance in channels with different sinuosity.

Laboratory experiments and numerical model simulation were conducted to explore diverse factors influencing flow resistance. To analyze the impact of channel shape on flow resistance, experiments were conducted on both straight and meandering channels. To assess the influence of aspect ratio on flow resistance, four cases with varying aspect ratios (ranging from 2.6 to 7.0) were examined. The effect of bed roughness on flow resistance was investigated by implementing two bed conditions: a smooth concrete bed and a rough gravel bed with a particle size of 5-10 mm. The investigation into different sinuosities was carried out after validating the numerical method with experimental data.

The meandering channels exhibit higher friction factors compared to straight channels, indicating a greater resistance in meandering channels. This increase in friction factor can be attributed to the additional transverse bed shear stress component and the advective momentum transport in the vertical direction caused by secondary flow, these factors increase the velocity near the bed and increase bed shear stress. The friction factor for smooth bed conditions decreases gradually with increasing the aspect ratio due to the decreasing in the side wall shear stress. On the other hand, in the case of rough bed conditions, the friction factor tends to rise as aspect ratio increases. This is attributed to the increase in relative roughness height as the aspect ratio increases with decreasing water depth. The larger the relative roughness height, the more dominant role bed roughness plays in determining flow resistance compared to distortion resistance.

The BVC models were in good agreement to replicate both water surface elevation and flow resistance caused by secondary flow. Meanwhile, the 2D model cannot predict well the water surface elevation and flow resistance because of the inability to consider the increase in flow resistance due to secondary flow. As for velocity distribution validation, laboratory experiment and numerical model experiment were combined. Velocity distribution close to the channel bed was measured using an Acoustic Doppler Velocimeter (ADV) (SonTek 16-MHz MicroADV), while a 3D model was applied to describe velocity close to the water surface.

Once the model validation was confirmed to be in good agreement with the experimental results, the next step involved using the models to estimate the impact of channel sinuosity on flow resistance. The numerical investigation demonstrated that as sinuosity increased, flow resistance also increased until reaching a sinuosity value of 1.75. However, beyond this point, flow resistance started to decrease. This phenomenon can be attributed to the strengthening of secondary flow, whereby a smaller curvature ratio value resulted in a more pronounced secondary flow. The numerical investigation revealed that even the 2D model can capture the increase in flow resistance caused by the distortion effect arising from the distribution of depth-averaged velocity.

And the final part, we discussed sediment transport dynamics in curved and meandering channels with sediment supply condition. Application of quasi-3D models for sediment transport analysis is still limited to simple cases, in which curved open channel and without sediment supply condition. In spite of this, the consideration of more complex channel shapes and conditions is critical, e.g., sediment-flood disasters in Japan as a result of heavy precipitation in 2018. Therefore, this research aims to investigate the applicability of quasi-3D models to predict bed deformation in meandering channel with excessive sediment supply. The models of the BVC method were validated with three different cases, strongly curved channel, mild slope meandering channel, and steep slope meandering channel. The result showed that three-dimensional flow structures have a significant role in distributing sediment in curved and meandering channels. The numerical investigation confirmed that the BVC models' results are in good agreement with experiment dataset in terms of predicting the location of scouring and deposition, however they failed to represent the magnitude of scouring and deposition.