Numerical simulation and 3D flow characteristics for open-channel lateral cavity

Hiroshima University Student Member ○Wenhao Dong
Hiroshima University Regular Member Tatsuhiko Uchida

１． Introduction

Lateral cavities widely exist in natural rivers, ocean shores, and a lot of hydraulic structures, for example, the groyne fields. These cavities have a significant effect on the velocity distribution, sediment transportation, and dispersion of pollutants. Therefore, simulating and understanding the flow characteristics around a cavity area is essential for a wide range of further investigations.

Experiments conducted by Kimura and Hosoda[1)] and Kimura et al.[2)] have given a detailed exploration of fundamental properties in an open channel lateral cavity. Cai[3)] and Mignot et al. [4)] analyzed the evolution of flow patterns experimentally in an open channel lateral cavity with different aspect ratios. While Juez et al.[5)] took multiple cavities as targets and conducted experiments for a wide range of shallowness ratios. However, the effects of the three-dimensional (3D) flow on the horizontal flow field and water surface variations has not yet been investigated. Little is known about how the 3D flow differs from the horizontal two-dimensional (2D) flow structure. Thus, a reliable and efficient computational model that could reproduce the flow pattern around a cavity and capture the 3D flow effect is much needed.

２． Calculation methods and experimental condition

BVC (Bottom Velocity Computation) method is a quasi-3D depth-integrated model. In this model, a set of depth-integrated equations, including depth-integrated momentum and vorticity equations, are used to evaluate the bottom velocity and vertical velocity distribution[6)]. The governing equations are listed in Table 1.

Table 1 Governing equations for the BVC method

Unknown variables	Governing equations	2DC	SBVC	GBVC
h	DI continuity	O	O	O
U_i	DI horizontal momentum	O	O	O
k	DI kinetic turbulence energy	O	O	O
u_{bi}	DI definition equations of horizontal velocity	-	O	O
Ω_i	DI horizontal vorticity	-	O	O
u_{si}	Horizontal momentum equations on water surface	-	O	O
W	Double integrated continuity	-	-	O
dp_b	DI vertical momentum	-	-	O

Note: DI = depth-integrated; SBVC = simplified bottom velocity computation method with shallow water assumption; GBVC = general bottom velocity computation method; h = water depth; U_i = depth-averaged horizontal velocity; k = kinetic energy; u_{bi} = bottom velocity; Ω_i = depth-averaged horizontal vorticity; u_{si} = water surface velocity; W = depth-averaged vertical velocity; dp_b = bottom pressure deviation from the bottom hydrostatic pressure.

In this study, the experimental results of Kimura and Hosoda[1)] were used as a reference to validate the reliability of the BVC model. The basic experimental conditions are shown below:

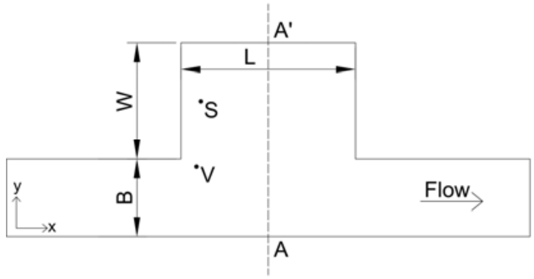

Fig 1. Schematic of open channel cavity in experiments

A lateral cavity with a length of L = 22.5cm is attached to the side wall of the open channel. The cavity extends W = 15 cm from the main channel, and the width of the main channel B = 10cm. For case 1, the streamwise velocity distribution for cross-section A-A' was measured. As for case 2, temporal velocity variations and surface elevation were measured at Point V and Point S, respectively. Other hydraulic parameters are listed in Table 2.

Table 2 Experimental and numerical parameters

Case	Discharge Q (L/s)	Water depth h (cm)	Channel Slope	Mesh size (cm)
1	0.23	1.00	1/1000	BVC: 0.25*0.25
2	0.747	2.02	1/500	3D: 0.25*0.25*0.1

In Case 1, OpenFOAM[7)] was also applied as a 3D computation method for a better comparison among conventional 2D, quasi-3D, and experimental results. As for the roughness condition, all of the methods were set to smooth bed calculations which also correspond to the actual experimental condition. Besides, the time step of the BVC model was set as 0.1s while it was set automatically in OpenFOAM.

３． Results and discussion

All the results presented in Fig. 2 are time-averaged results calculated for 10s after reaching the steady state, it shows the streamwise velocity distribution for cross-section A-A'. The horizontal axis is the distance from the main channel, from 0 to 0.10m is the area of the main channel; while beyond 0.10m is the range within the cavity. The vertical axis is the depth-averaged streamwise velocity. Around the junction of the main channel and the cavity, and near the upper boundary wall of the cavity, there are big differences in the velocity distribution, especially between the 2D model and other models. The simulation results of the BVC models show a great agreement with the experimental results and the 3D model result in this relatively shallow water condition. This also could be the reason why there are little differences between SBVC and GBVC, indicating the shallow water assumption h/L<<1 is reasonable for this condition.

Keywords: Open-channel flow, Lateral cavity, 3D flow effect, Numerical simulation
Contact address: 1-4-1, Kagamiyama, Higashi-Hiroshima, 739-8527, Japan, Tel: +81-80-9790-7074

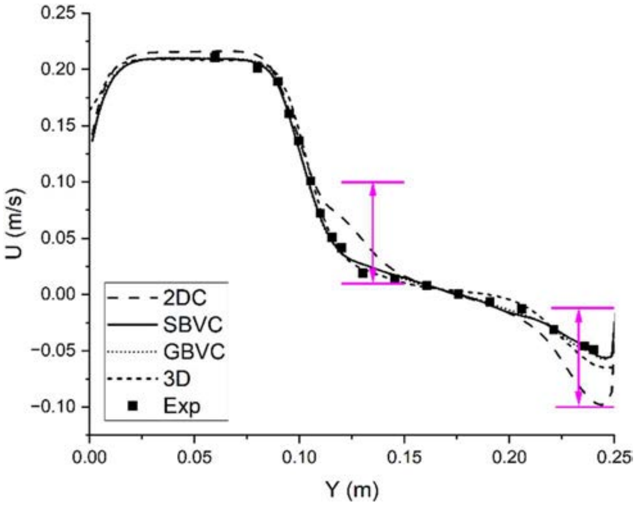

Fig. 2 Streamwise velocity distribution with various methods

By comparing the results of the BVC model with the 2D model, the 3D flow effect can be extracted. That is, the secondary flow contained in the 3D flow, to a certain extent, resists drastic changes in the flow field by transferring momentum outward from the cavity center, increasing the velocity gradient in the junction between the main channel and the cavity and near the upper boundary of the cavity.

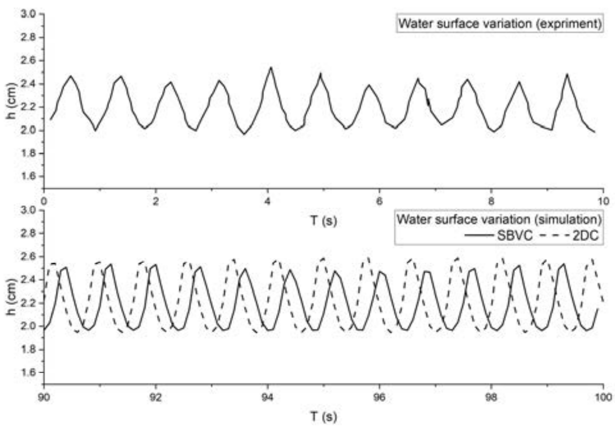

Fig 3. Temporal variation of water surface

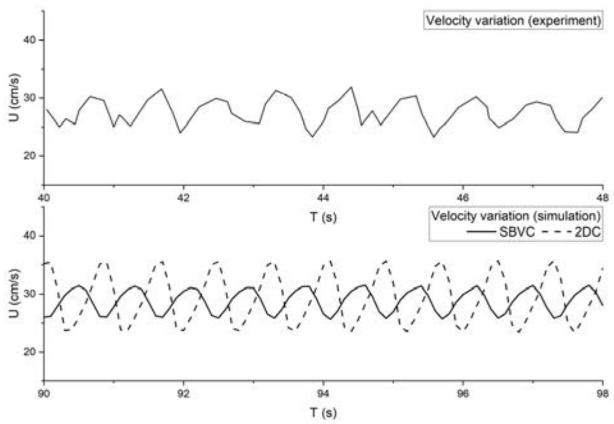

Fig 4. Temporal variation of streamwise velocity

Further analysis of temporal variation in water surface and streamwise velocity are shown in Fig. 3 and Fig. 4, respectively. The horizontal axes are the time elapsed for the experiment or the time after the simulation reaches the steady state. The detailed values of the time period and varied range are shown in Table 3. The simulation results provided by the SBVC model could reproduce the oscillation characteristics for both time period and oscillation amplitude while the 2D model overestimated the amplifications and underestimated time periods.

Table 3 Temporal variation characteristics

Case	Time Period	Varied Range
h (exp)	0.85s	1.97cm-2.54cm
h (BVC)	0.82s	1.97cm-2.54cm
h (2DC)	0.80s	1.95cm-2.59cm
U (exp)	0.85s	0.23m/s-0.32m/s
U (BVC)	0.82s	0.25m/s-0.31m/s
U (2DC)	0.80s	0.23m/s-0.36m/s

4. Conclusion

This study set out to explore the flow characteristics around an open-channel lateral cavity including the velocity distribution and the temporal variation of water surface and velocity. By using a quasi-3D model called the Bottom Velocity Computation method together with OpenFOAM and experimental investigation, the three-dimensional effect was captured and the BVC model had also been proven to be reliable and efficient for open-channel cavity flows.

The presence of secondary flow in 3D flows can lead to velocities near the cavity boundaries much slower than the prediction of the 2D model. In other words, the 3D flow effect increases the resistance within the cavity which can be explained by the momentum exchange due to the secondary flow. The 3D flow also decreases the temporal variation ranges of velocity and wave height and increases the time periods slightly.

A limitation of this study is that the reference experiments were conducted under quite shallow water conditions, with h/L equal to 0.04. And this could potentially lead to insignificant differences among various methods. Further studies regarding the role of relative water depth and aspect ratios would be worthwhile.

References

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