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Study of Cohesive Riverbank Erosion Mechanism through Analysis of Flow Fields Near and Inside Eroded Bank

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The Yoshino River cohesive soil sample experiment showed two types of eroded bank; near-water-surface and under-water-surface. Flow field of the near-water-surface eroded bank was examined through physical bank model experiment and numerical analysis. In this paper, the flow fields near and inside of the both eroded banks are investigated. It shows that flow properties of the near-water-surface and under-water-surface eroded bank shapes are different, which signifies two different erosion mechanisms of the bank shapes. The numerical model, which was used to simulate near-water-surface eroded bank flow fields, could not reproduce the flow field of under-water-surface eroded bank because of its confined flow inside the eroded bank. A 2-D numerical model is developed incorporating SIMPLE method for the under-water-surface eroded bank. This model could reproduce the flow fields of successive model eroded banks of near-water-surface and under-water-surface for two different erosion stages.

Key Words: *Erosion mechanism, near-water-surface eroded bank, under-water-surface eroded bank, bank erosion shape, 2-D horizontal flow field*

1. INTRODUCTION

Because of cohesive fine particles, riverbanks may possess a vertical shape. There have been several attempts[1), 2), 3)] in the past to investigate cohesive riverbank erosion mechanism. Erosion process of the vertical cohesive bank has not been studied well yet considering influence from hydraulic properties near bank. As the hydraulic properties near vertical cohesive bank imparts a significant influence on the bank erosion, Fukuoka et al.[2)] did laboratory bank erosion experiment of undisturbed cohesive soil samples collected from the flood channel of the Yoshino River, Shikoku, Japan. During the experiment, loose particles on the cohesive bank eroded from its surface first. With continuation of flow, the erosion expanded in the upstream and downstream direction from the initially eroded locations, and erosion depth became deeper. At some stages of the erosion process, collapse of overhanging banks was observed. The paper revealed two types of eroded bank shapes; one is near-water-surface eroded bank and another is under-water-surface eroded bank. It also showed different erosion process between the two eroded banks. For cohesive riverbank material with large shear resistance, flow hydraulics has a significant influence on its erosion. Therefore, in a companion paper by the authors[4)], similar to the near-water-surface eroded bank shapes at different stage of Yoshino River soil sample erosion experiment; physical model bank shapes were developed to investigate cohesive bank erosion mechanism. It showed that there occurred flow separation area at location of the maximum erosion depth of the near-water-surface eroded bank for larger erosion depth and upstream-eroded surface angle. A 2-D numerical model was developed, which could reproduce the flow fields of different bank shapes of the near-water-surface eroded bank varying in erosion surface angle and erosion depth.

In this paper, we analyze flow fields of successive physical eroded banks of the near-water-surface and under-water-surface, which are similar to the 5 hours and 11.5 hours erosion stage of the Yoshino River soil sample erosion experiment[2)]. It shows that the flow properties of the near-water-surface and under-water-surface eroded bank are different, which signifies different erosion process of the two bank shapes of the Yoshino River soil sample erosion experiment. The 2-D numerical model, which was developed in the previous study[4], could not applied to simulate the present flow fields of the successive eroded banks because of confined flow inside the under-water-surface eroded bank. In this study, a 2-D numerical model is developed using orthogonal curvilinear coordinate and adapting SIMPLE[5] method doing iteration of guess-and-correct operations for the under-water-surface eroded bank. The present model is able to reproduce the measured flow fields of physical model banks experiments, where model banks are based on the 5 hours and equilibrium stage (11.5 hours) of the Yoshino River soil sample erosion.

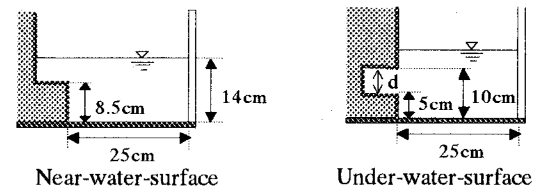


Fig. 1(a) Cross section of 5 hours eroded bank

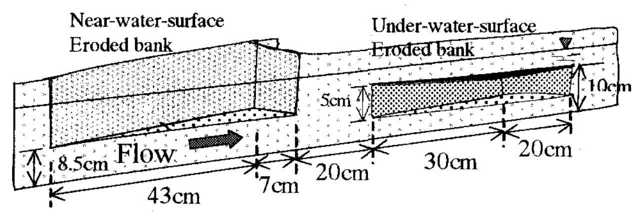


Fig. 1 Side view of 5 hours model eroded bank shapes

2. SUCCESSIVE PHYSICAL BANK MODEL

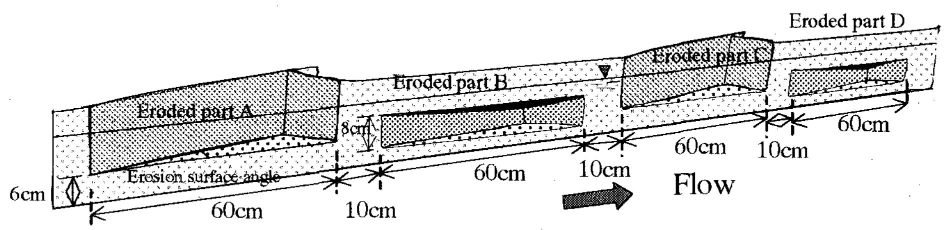


Fig. 2 Side view of 11.5 hours model eroded bank shapes

As the Yoshino River soil sample experiment had two types of bank shape; near-water-surface and under-water-surface, both the bank shapes were reproduced and installed in a straight channel to measure flow fields near and inside the eroded banks. The physical bank models are similar in shape, dimension and location of the initial stage (5 hours of flow duration) and equilibrium stage (11.5 hours of flow duration) of the Yoshino River soil sample erosion. The model bank shape of 5 hours erosion stage possesses the characteristics of initial to developing stage of the soil sample erosion. On the other hand, the model bank shape of 11.5 hours erosion stage is for almost equilibrium soil sample erosion stage. The model banks varied in erosion length, upstream erosion surface angle and height from the channel bed depending on 5 hours or 11.5 hours erosion stage. In the experiment of the 5 hours erosion stage, there were two eroded bank models (**Fig. 1**), where near-water-surface eroded bank was located at 20cm upstream of the under-water-surface eroded bank. For the model bank experiment of 11.5 hours stage, it had successive two sets of model banks (**Fig. 2**), where in each set a near-water-surface eroded bank placed at 10cm upstream of a underwater-surface eroded bank. In the 11.5 hours erosion stage case, the model banks have a spacing of 10cm from one model bank to another. Detail dimensions of the two erosion stage bank models are shown in the **Fig. 1** and **Fig. 2**. For all the cases, the physical model banks were installed along the left bank of a straight channel. The channel was 25cm wide at upstream and downstream of the eroded bank, and provided artificial roughness along the left bank, whereas the channel bed and right-bank of the channel had smooth glass.

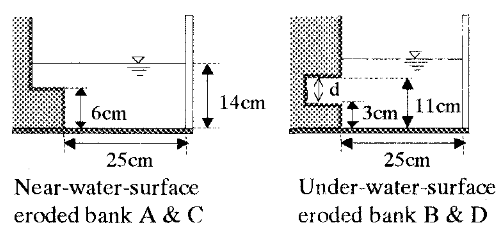


Fig. 2(a) Cross section of 11.5 hours eroded bank

Table 1 Experimental condition

	Upstream erosion surface angle(degrees)		Flow rate (l/s)
	Near-water-Surface	Under-water-surface	
Case 1	5.5	4.5	34.4
Case 2	5.5	4.5	25.5
Case 3	8.5	6.5	34.4
Case 4	8.5	6.5	25.5

2. GOVERNING EQUATIONS

From practical engineering point of view, it is significant to approximate a two-dimensional horizontal flow regime to understand the cohesive riverbank erosion mechanism, as the horizontal flow field is dominant compared to that of vertical. In the previous study, the authors developed a 2-D numerical model, which could reproduce the flow fields of near-water-surface eroded banks of different shape. This model was not able to compute flow fields for the under-water-surface eroded bank because of confined flow inside the eroded bank. In this study, 2-D numerical approach is also attempted to simulate the measured flow fields of the successive eroded model banks of near-water-surface and under-water-surface. The present numerical model incorporates the governing equations of the previous 2-D model[4] for the free surface flow of the near-water-surface eroded bank along with additional equations for confined flow of the under-water-surface eroded bank. In the present model, the free surface flow is computed by the depth integrated continuity equation and momentum equations in curvilinear orthogonal coordinate as described in the previous paper. For the computation of the confined flow inside the under-water-surface eroded bank, governing equations are similar to the previous 2-D numerical model excepting continuity equation. Momentum equations, which are described in the previous study, of the confined flow are modified for the present 2-D model considering constant flow depth inside the under-water-surface eroded bank. The continuity equation of this model is shown below:

$$\frac{\partial}{\partial \xi}\left(\frac{J}{d\xi}u^{\xi}\right)+\frac{\partial}{\partial \eta}\left(\frac{J}{d\eta}u^{\eta}\right)=0 \qquad (1)$$

Here $d\xi^2 = 1/\left(\xi_x^2+\xi_y^2\right)$, $d\eta^2 = 1/\left(\eta_x^2+\eta_y^2\right)$ and Jacobian $J = x_\xi y_\eta - x_\eta y_\xi$.

To solve the governing equations for the under-water-surface eroded bank, the semi-implicit method for pressure linked equations (SIMPLE)[5] algorithm is used. In the pressure-correction approach of the SIMPLE method, iterations of guess-and-correct operations are done to solve the governing equations. At first, a pressure field is assumed, and then the velocity components in ξ direction and η direction are computed using the pressure field. Thereafter, the pressures and velocities are corrected in order to satisfy continuity equation. During computation near interface of free-surface flow and confined flow, the velocity and pressure corrections are assumed zero outside region of the confined flow. This model also uses similar boundary conditions as the last 2-D model. Similar to the previous model, velocity components of this model are computed using staggered grid. Water depth and pressure is evaluated at the center of the grid. It is assumed that eddy viscosity coefficient is proportional to local frictional velocity u_* and water depth h, and bed shear stress is obtained using Manning's roughness coefficient n.

4. COMPUTATION OF FLOW FIELDS

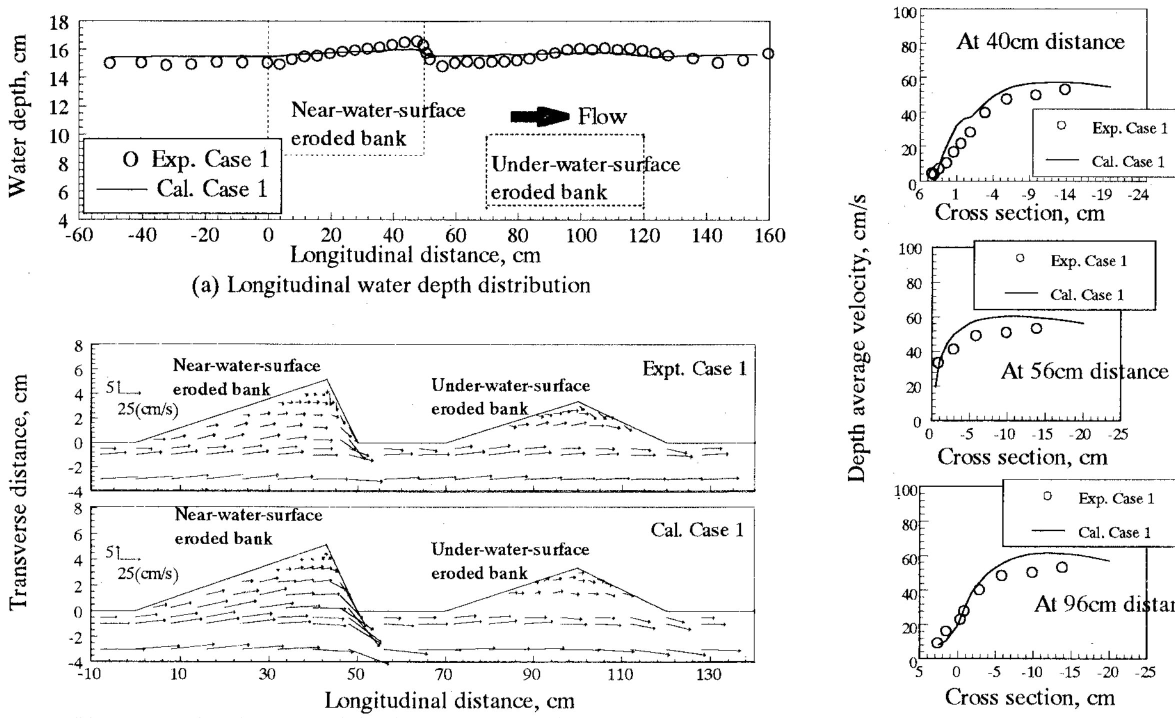
Simulation of flow fields for near-water-surface eroded bank showed good accuracy for smaller erosion surface angle and erosion depth. There was some discrepancy between the computed and the measured results for large erosion surface angle and erosion depth because of three-dimensional flow field near and inside the eroded bank. Even then, the 2-D model reproduced the flow fields with more or less accuracy. In order to understand cohesive riverbank erosion mechanism in the natural river, it is very much significant to approximate two-dimensional flow regime near the cohesive eroded bank considering importance of practical engineering application of numerical simulation in the field. Therefore, the authors further attempt to use two-dimensional approach to reproduce the measured flow fields of the successive eroded bank for the 5 hours and equilibrium erosion stages (11.5 hours).

The present numerical analysis shows that the model could reproduce the flow fields of the successive eroded banks in the channel for both 5 hours and 11.5 hours erosion stages. Among the four cases of the flow fields, Case 1 and Case 2 are for the 5 hours erosion stage, where the former case had larger discharge than the latter case. The measured and computed flow fields of Case 1 and Case 2 are shown in **Fig. 3** and **Fig. 4** respectively. These cases had two successive eroded banks, where near-water-surface bank was placed in upstream of the underwater-surface bank. Results of these cases show that the measured and the computed water levels are close, but the computed longitudinal water depth distribution along 1cm from the left (**Fig. 3(a)** and **Fig. 4(a)**) does not increase sufficiently inside both the eroded banks as in the case of the measured result. **Fig. 3(b)** and **Fig. 4(b)** indicate that the measured and computed velocity vectors are almost similar excepting at the eroded surface downstream of maximum erosion depth of the near-water-surface eroded bank. **Fig. 3(c)** and **Fig. 4(c)** reveal closeness of the measured and the predicted cross-sectional velocity at different cross-section of the channel. It is important to note that both the computed and measured velocity vectors indicate a tendency of reverse flow at location of maximum erosion depth of the near-water-surface eroded bank, whereas there is no reverse flow inside the under-water-surface eroded bank.

Table 2 Condition for numerical computation

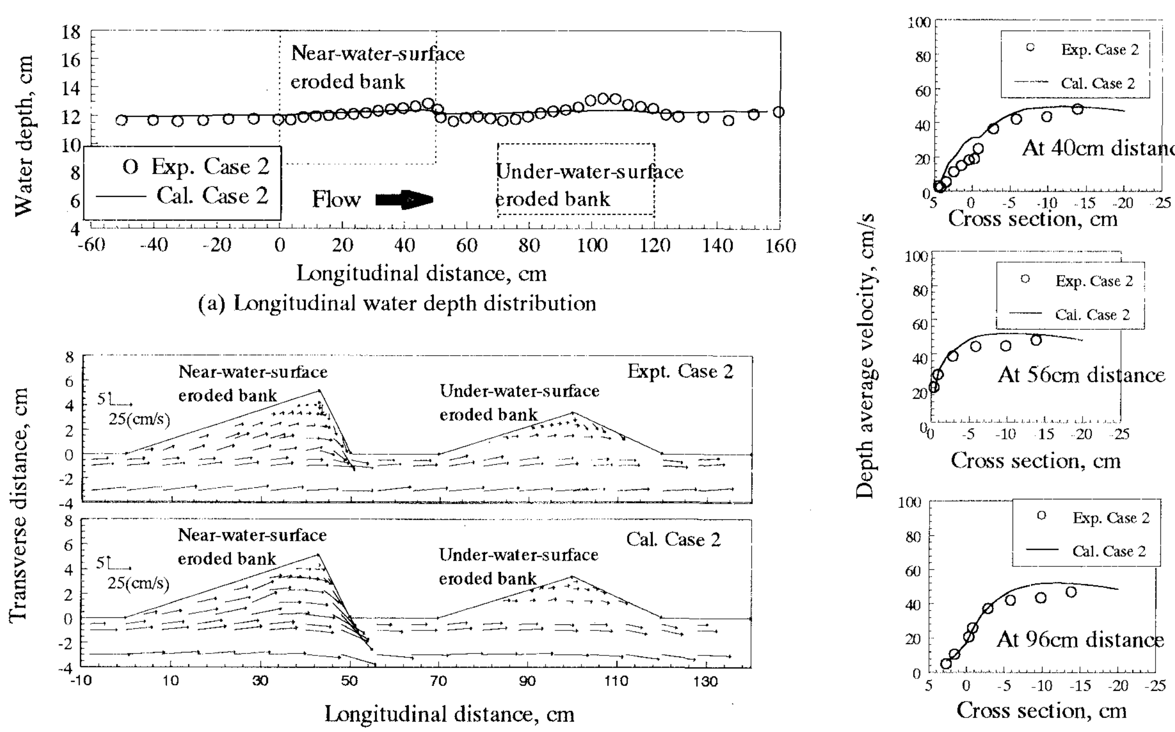
	Erosion Length	Upstream velocity (cm/s)	Upstream water depth (cm)
Case 1	50cm	54.0	14.8
Case 2	50cm	50.2	11.7
Case 3	60cm	97.4	15.6
Case 4	60cm	80.0	12.8

In Case 3 and Case 4, there were four successive model banks A, B, C and D along the left bank of the channel. The flow fields of near-water-surface bank C and under-water-surface bank D were measured, and



(b) Measured and computed depth averaged velocity vector. (c) Depth averaged cross sectional velocity distribution

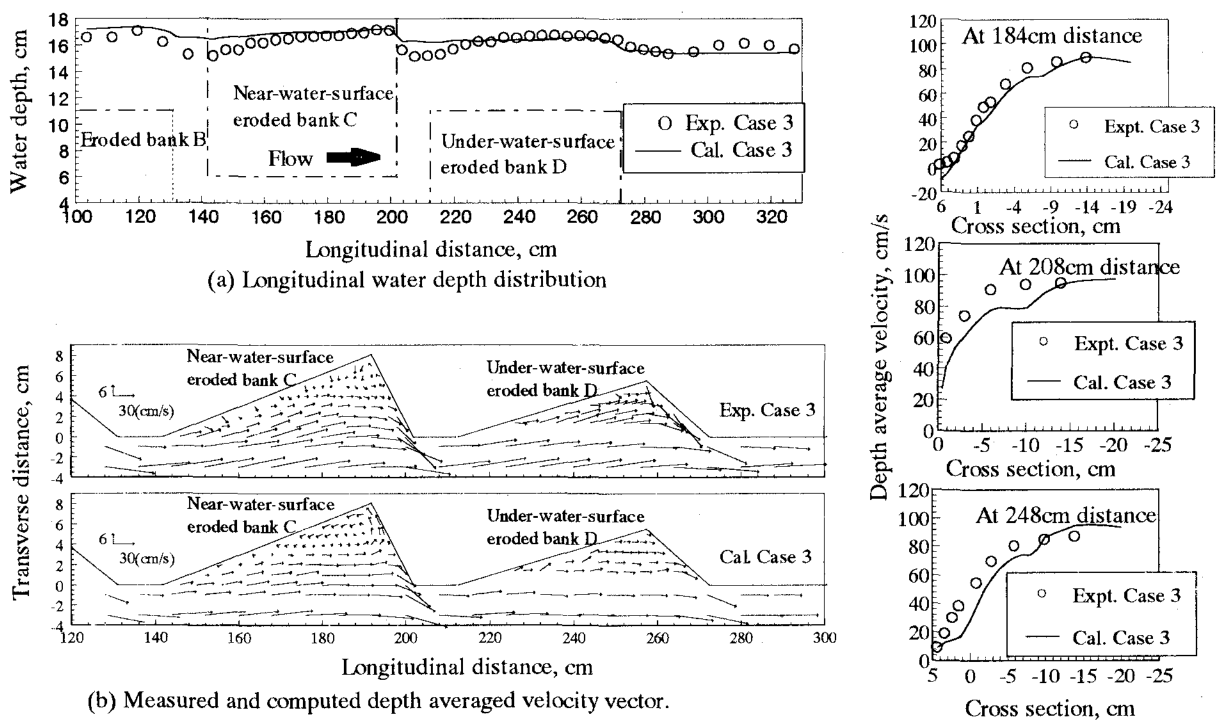
Fig. 3 Computed and measured flow field of Case 1.



(b) Measured and computed depth averaged velocity vector. (c) Depth averaged cross sectional velocity distribution

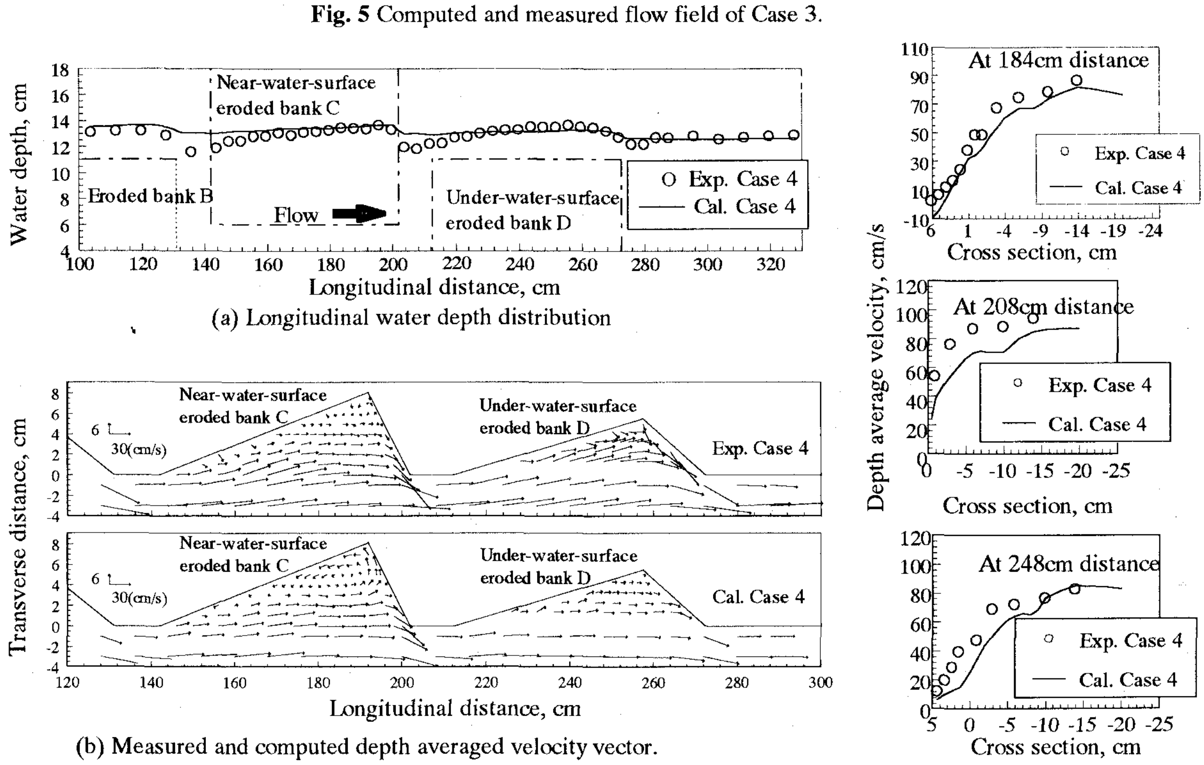
Fig. 4 Computed and measured flow field of Case 2.

the numerical analysis was applied to reproduce those flow fields. **Fig. 5(a)** and **Fig. 6(a)** show longitudinal distribution of water depth along 1cm from the straight left bank of the channel. It can be observed that the model could predict the water level near the eroded banks, but there is some difference between the computed and measured water depth especially at immediate upstream and downstream of each eroded bank. The computed water depth gradually increases inside both the near-water-surface and under-water-surface eroded bank, and it is highest near the locations of maximum erosion depths of each eroded bank. The predicted water depth distribution has deviation from the measured water depth at immediate upstream and downstream of each eroded bank. Computed and measured velocity vectors of 11.5 hours erosion stage of Case 3 and Case 4 are shown in the **Fig. 5(b)** and **Fig. 6(b)**. The 2-D numerical model has good accuracy to predict velocity fields of the main channel and inside the near-water-surface eroded bank, but the computed velocity vectors are smaller than those of the measured inside the under-water-surface eroded bank in both the cases. On the other hand, cross-sectional velocities at 184cm distance (inside near-water-surface eroded bank) show good agreement between the computed and the measured result (**Fig. 5(c)** and **Fig. 6(c)**), but there are some discrepancies at 208cm distance (in between two eroded banks) and at 248cm distance (inside the under-water-surface eroded bank). Because of strong three-dimensional flow mixing near and inside the eroded banks for larger erosion length and erosion angle of



(c) Depth averaged cross sectional velocity distribution

Fig. 5 Computed and measured flow field of Case 3.



(c) Depth averaged cross sectional velocity distribution

Fig. 6 Computed and measured flow field of Case 4.

the equilibrium erosion stage, the 2-dimensional computed results have discrepancies from the measured flow fields. The computed and measured results show flow separation at location of the maximum erosion depth of the near-water-surface eroded bank (**Fig. 5(b)** and **Fig. 6(b)**), whereas there is no flow separation inside the under-water-surface eroded bank of both the computed and measured results.

5. DISCUSSION

Yoshino River soil sample erosion experiment[2] revealed two different erosion processes for the near-water-surface and under-water-surface eroded bank. After initiation of erosion from the locations of comparatively loose soil bank surface, the erosion area near-water-surface expanded in the upstream direction, and created situation for overhanging and collapse of the bank soil. Whereas the under-water-surface initially eroded area expanded in the downstream direction from the initial location of erosion. The authors did succeeding investigations to understand this erosion mechanism. The experimental results of this present study of successive near-water-surface and under-water-surface eroded banks reveal different flow properties of the two bank shapes. It shows that there is flow separation or tendency to have flow separation at the location of maximum erosion depth even during 5 hours erosion stage for the near-water-surface eroded bank. The flow separation area inside this eroded bank became larger for 11.5 hours erosion stage. The flow separation has a strong influence on velocity field in the eroded bank. Due to occurrence of the flow separation in this case, its erosion might expand in the upstream direction. On the other hand, the flow fields of the under-water-surface eroded bank never show reverse flow inside its eroded part at any stage of bank erosion. Experimental results of 5 hours and 11.5 hours erosion stage show that velocity vectors at erosion surface downstream of the maximum erosion depth are larger than those of its erosion surface upstream of the maximum erosion depth. As a result, velocity difference at its downstream erosion surface is larger compared to that of its upstream erosion surface. This larger velocity difference on the downstream erosion surface might cause the erosion of the under-water-surface eroded bank to expand in downstream direction. The longitudinal water depth distribution shows that the water depth increases inside both the near-water-surface and under-water-surface eroded bank. The water depth decreases suddenly in the downstream of the near-water eroded bank, but it decreases gradually in the downstream from the location of maximum erosion depth of the under-water eroded bank. The difference of flow characteristics between the two types of bank shapes becomes prominent for the equilibrium erosion stage. Different flow characteristics of the two types of eroded bank shapes signify their different erosion mechanism. The present 2-D numerical model is applied to simulate the flow fields of the successive eroded banks. Even though, there is some discrepancy between the measured and computed results because of three-dimensional flow regime inside the eroded bank, the numerical model could able to reproduce the flow fields of the both near-water-surface and under-water-surface eroded banks.

In order to reveal riverbank erosion mechanism for a variety of soil and flow conditions, it is necessary to investigate soil resistance against hydrodynamic forces on bank surface, which needs further attention for future study. Once soil resistance against hydrodynamic forces acting on a bank surface become clear, numerical approach might be further applied to estimate natural stream bank erosion process and mechanism.

6. CONCLUSIONS

The cohesive bank erosion of Yoshino River soil sample experiment expanded in the upstream direction for the near-water-surface eroded bank, whereas it progresses in the downstream direction for the under-water-surface eroded bank. The physical bank model experiments of successive eroded banks show different flow properties for the two types of bank shapes. This difference of the flow properties of the two eroded banks might signify their different erosion mechanism. The present numerical model could reproduce the flow fields of the successive near-water-surface and under-water-surface eroded bank. Even though, there is some discrepancy between the measured and the computed results, the model might be use to understand cohesive bank erosion mechanism.

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