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CFD MODELING VEGETATED CHANNEL FLOWS: A STATE-OF-THE-ART REVIEW

SUNG-UK CHOI[1] and WONJUN YANG[2]

[1] Associate Professor, School of Civil and Environmental Engineering,
Yonsei University, Seoul, Korea
(Tel: 82-2-2123-2797, Fax: 82-2-364-5300, e-mail: schoi@yonsei.ac.kr)
[2]Ph.D. Student, School of Civil and Environmental Engineering, Yonsei University, Seoul, Korea
(Tel: 82-2-2123-2797, Fax: 82-2-364-5300, e-mail: pulip@yonsei.ac.kr)

Abstract: This paper presents the state of the art of the CFD applications to vegetated open-channel flows. First, important aspects of the physics of vegetated flows found through the laboratory experiments are briefly reviewed. Then, previous CFD applications to one-dimensional vertical structure, partly-vegetated flows, compound open-channel flows with floodplain vegetation, and fully three-dimensional numerical simulations are reviewed. Finally, topics for further researches such as relationship between the resistance and flexural rigidity, additional drag due to foliages, and melting the experience of CFD with the depth-averaged modeling, are suggested.

Keywords: Vegetation, Open-channel flows, CFD, Turbulence, Vegetated channel flows

1. INTRODUCTION

Environmental concerns about the restoration of urban streams and wetlands increase recently. In restoring the disturbed water environments, vegetation either within the watercourse or on stream corridor plays an important role because it is closely related to stream ecology of aquatic habitats. Thus, the hydraulic engineers tend to pay more attention to the water flows through vegetation than ever.

Numerical modeling of vegetated open-channel flows is challenging because of the complicatedness of flow. The flow structure of vegetated open-channel flows is different from that of plain open-channel flows. The difference is pronounced if the vegetation height affects the flow (Nepf and Vivoni, 2000). In such case, the mean flow and turbulence statistics are totally different from those of plain open-channel flows Flexibility of vegetation and non-homogeneous distribution of vegetation add extra complexity of flow.

Regarding vegetative resistance, previous concern in hydraulic engineering is how to assess the additional roughness by vegetation. For this, many handbooks or textbooks present tables of roughness coefficients for various vegetative conditions. However, since the range of roughness coefficient is too wide in some cases, the resulting change in the flow depends heavily on the engineers' judgment.

Recent advance in computer technology enables the hydraulic engineers to model the detailed structures of vegetated open-channel flows using CFD. At the same time, the detailed mean flow and turbulence statistics are being disclosed due to high technology in laboratory measurement. In limited cases, both simulated and measured flow structures were compared, and the results indicated that the CFD models predict the flow structures successfully.

The purpose of this paper is to review the state of the art of the applications of CFD to vegetated open-channel flows and to suggest a prospect on future researches. For this, we briefly review the physics of vegetated flows found through the laboratory experiments. Then, the reviews of 1D vertical structure, partly vegetated flows, compound open-channel flows with floodplain vegetation, and fully 3D numerical simulations are given.

2. PHYSICS OF VEGETATED CHANNEL FLOWS

2.1 Classification of vegetated flows

In general, vegetated open-channel flows are classified into three types depending upon the relative height of vegetation (h_p) to the total water depth (H), namely terrestrial canopy flows ($h_p/H \approx 0$), flows with submerged vegetation ($0 < h_p/H < 1$), and flows with emergent vegetation ($1 < h_p/H$) (Nepf and Vivoni, 2002; Murato et al., 1984). The terrestrial canopy flows are extremely similar to flows over very rough bed, and the flows with emergent vegetation are confined type flows. The flows with submerged vegetation take an in-between feature of these two flows.

2.2 Organized vortex

The streamwise mean velocity profile has an inflection point, which makes the flow susceptible to Kelvin-Helmholtz instability (Ikeda and Kanazawa, 1996; Ghisalberti and Nepf, 2002). This instability generates large, coherent vortices within the mixing layer. Ikeda and Kanazawa called this "organized vortex," downstream advection of which creates the progressive, coherent waving of vegetation known as monami (see Figure 1). Due to the monami, the turbulent vertical transport of momentum is enhanced.

2.3 Mixing layer concept

Ghisalberti and Nepf (2002) found that the mean velocity distribution qualitatively resembles the typical hyperbolic tangent profile of a mixing layer. They showed the collapse of mean velocity data obtained from various experimental conditions (see Figure 2).

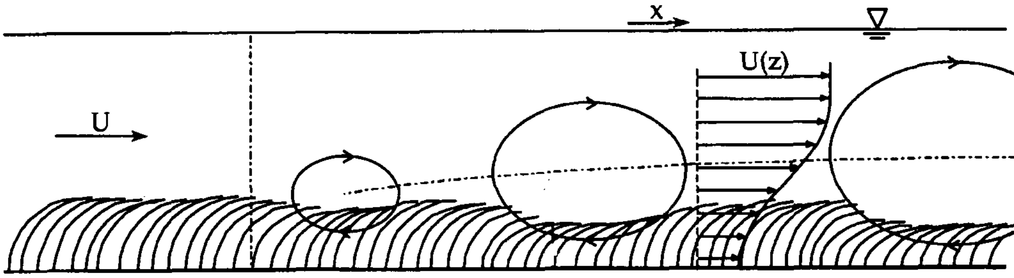


Figure 1. Enhancement of vertical momentum transport due to organized vortex (Ghisalberti and Nepf, 2002)

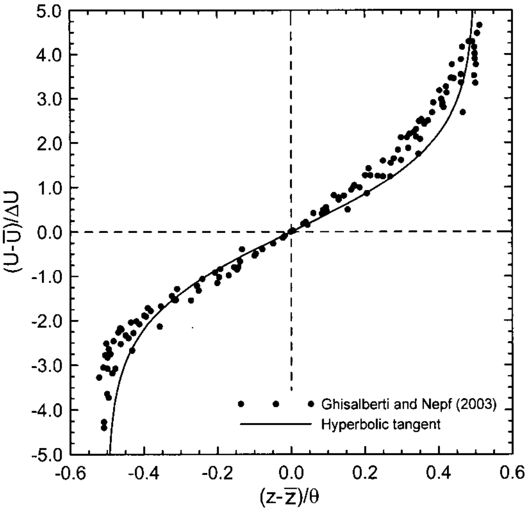


Figure 2. Collapse of mean velocity

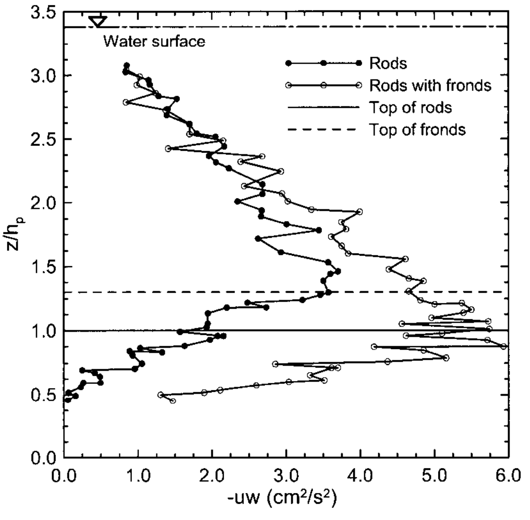


Figure 3. Impact of fronds on Reynolds stress

2.4 Impact of fronds

Wilson et al. (2003) carried out experiments of vegetated open-channel flows with and without the fronds on rods. They observed that the velocity distribution does not follow the standard log law within canopy region. They also found that the drag due to the fronds retards the velocity and turbulence production diminishes due to decreased momentum exchange between vegetation layer and free surface region.

3. NUMERICAL MODELINGS OF VEGETATED FLOW STRUCTURES

3.1 1D vertical structure

For vegetation canopy flows in the atmospheric boundary layers, Wilson and Shaw (1977) and Raupach and Shaw (1982) recognized the necessity of averaging the governing equations over time and space and introduced averaging schemes for transport equations of the momentum and turbulent kinetic energy.

Many of previous researches were performed by using the $k-\varepsilon$ turbulence closure. The transport equations for turbulence kinetic energy (k) and its dissipation rate (ε) are given by, respectively,

$$\frac{\partial k}{\partial t}=\frac{\partial}{\partial x_3}\left[\left(\frac{\nu_t}{\sigma_k}+\nu\right)\frac{\partial k}{\partial x_3}\right]+P_k-\varepsilon+C_{fk}f_{x_1}\langle u_1\rangle \qquad (1)$$

$$\frac{\partial \varepsilon}{\partial t}=\frac{\partial}{\partial x_3}\left[\left(\frac{\nu_T}{\sigma_k}+\nu\right)\frac{\partial \varepsilon}{\partial x_3}\right]+\frac{\varepsilon}{\kappa}\left[C_1(P_k+C_{f\varepsilon}f_{x_1}\langle u_1\rangle\right] \qquad (2)$$

where σ_x = the Prandtl-Schmidt number, $P_k=\nu_T\left(\partial\langle u_1\rangle/\partial x_3\right)^2$, $f_{x_1}=\frac{1}{2}C_D a<u_1>\sqrt{<u_1>^2}$, and $\nu_T=C_\mu k^2/\varepsilon$.

Bulke and Stolzenbach (1983) proposed a two-equation turbulence model ($k-\varepsilon$ type) to simulate vegetated flows. Although Bulke and Stolzenbach found a good agreement between computed and measured data, they recognized the lack of knowledge about the drag coefficients due to vegetation.

Shimizu and Tsujimoto (1994) computed vertical structures of open-channel flows with submerged vegetation using the $k-\varepsilon$ model.

They simulated the vegetated flow developing in the streamwise direction. Shimizu and Tsujimoto compared the computed results (mean velocity and Reynolds stress) with measured data, finding a good agreement.

According to Burke and Stolzenbach (1983), theoretical values of drag-related weighting coefficients in Eqs. (1) and (2) are C_{fk} = 1.0 and $C_{f\varepsilon}$ = 1.33, respectively. However, smaller values for the coefficients have been used in previous modelings, for example, C_{fk} = 0.07 and $C_{f\varepsilon}$ = 0.16 by Tsujimoto et al. (1991), and C_{fk} = $C_{f\varepsilon}$ = 0.0 by Fischer-Antze et al. (2001). These values were obtained from the fitting turbulence intensity profiles with measured data. Lopez and Garcia (2001) showed that the use of C_{fk} = 1.0 and $C_{f\varepsilon}$ = 1.33 overestimates turbulence intensity (see Figure 4(b)). This is because the total turbulent kinetic energy is composed of turbulent kinetic energy due to temporal fluctuations ($\langle\overline{u_i'u_i'}\rangle$) and that due to spatial fluctuations ($\langle\overline{u_i}''\overline{u_i}''\rangle$). That is,

$$\langle u''u''\rangle=\langle\overline{u_i'u_i'}\rangle+\langle\overline{u_i}''\overline{u_i}''\rangle \tag{3}$$

where the second term on the right hand side of Eq. (3), turbulent kinetic energy due to spatial fluctuations, is extremely difficult to obtain through laboratory experiments. Thus the weight coefficients were obtained by fitting the simulated profile to the data corresponding to $\langle\overline{u_i'u_i'}\rangle$ (see Figure 4(a)). This explains why very small weighting coefficients in the drag-related source terms for k and ε equations yield very good predictions of turbulence intensities in such type of flows.

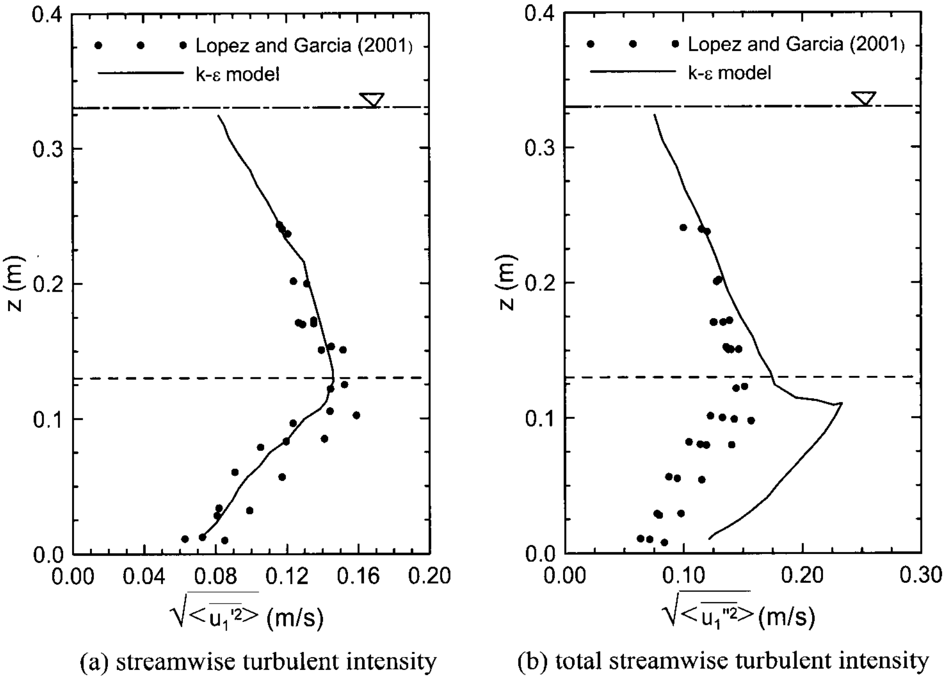
Choi and Kang (2004) simulated the vegetated open-channel flows for submerged and emergent conditions by using three different turbulence models. They found that the Reynolds stress model (RSM) predicts the mean flow and turbulence structures of the open-channel flows with submerged vegetation better than the algebraic stress model (ASM) or the standard $k-\varepsilon$ model (see Figure 5). Choi and Kang also indicated that the isotropic turbulence model may underestimate the suspended sediment load seriously.

3.2 Flexible vegetation

Tsujimoto and Kitamura (1998) proposed a numerical model based on the $k-\varepsilon$ turbulence closure to simulate open-channel flows over flexible vegetation. They estimated the height of inclined vegetation by using the cantilever beam theory. In order to consider the flexibility of vegetation, they first assume the inclined height of vegetation. Then, the flow equations are solved, and the resulting vegetation height is obtained and compared with the assumed value. The computations are repeated until the assumed and calculated values are close enough. They also presented the following simple relationship for inclined height of vegetation:

$$\frac{l}{l_0}=1-0.89\exp\left(-4.66\frac{\gamma EI}{\rho u_{*0}^2 l_0^4}\right) \tag{4}$$

where l and l_o are the inclined and the vertical heights of the stem, respectively. Using the above relationship, one can estimate the inclined vegetation height by using the flexural rigidity (EI) of the stem and shear velocity (u_{*0}) estimated for vertical (or non-inclined) vegetation. Eq. (4) was verified against experimental data sets by Tsujimoto et al. (1991) and by Murota and Fukuhara (1984) (see Figure 6).



(a) streamwise turbulent intensity (b) total streamwise turbulent intensity

Figure 4. Observed and predicted turbulent intensity (Lopez and Garcia, 2001)

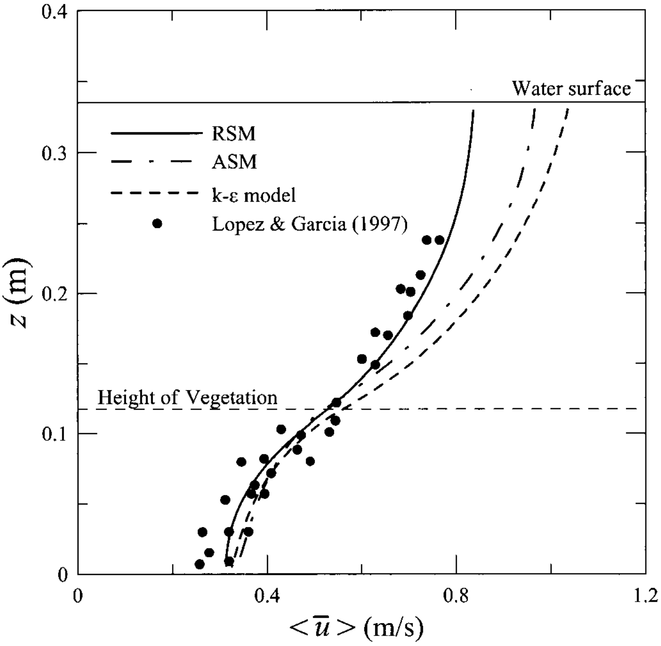


Figure 5. Mean velocity of open-channel flows with submerged vegetation (Choi and Kang, 2004)

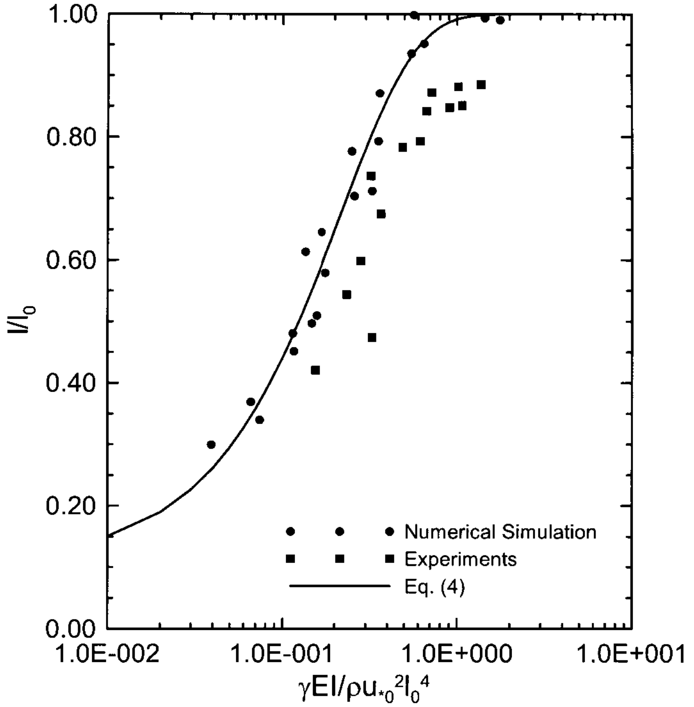


Figure 6. Hydraulic resistance of flow with flexible vegetation (Tsujimoto and Kitamura, 1998)

Velasco et al. (2005) suggested a simple scheme for calculating the velocity and the shear stress profiles of the flow with flexible vegetation. The mixing length model was used to close the flow equations. To take into account of the shear balance, they divided the flow profile into four zones, i.e., laminar zone, shear-less zone (below the penetration depth), internal zone (from the penetration depth to the vegetation height), and external zone (above vegetation) depending on the distance from the bottom. They estimated the height of flexible vegetation from the cantilever beam theory similar to the approach proposed by Tsujimoto and Kitamura (1998), but they found that the analytical expression of deformation on beams was not valid because of the large deformation. Velasco et al. insisted that the additional bending by the second order moment should be taken into account. They showed that the zoning approach reproduces the velocity and Reynolds stress profiles of open-channel flows with vegetation quite well.

3.3 Partly-vegetated flows

Shimizu and Tsujimoto (1993) investigated the similarity and difference in flow structure between the partly-vegetated corner flow and compound open-channel flow. They used the ASM for the turbulence closure. They compared the stage discharge relationship of such flows (see Figure 7) and found that vegetated corner flows show higher resistance because of the momentum transfer between plain and vegetated zones.

Naot et al. (1996) simulated numerically partly vegetated open-channel flows using the ASM. In limited cases, they attempted to validate the

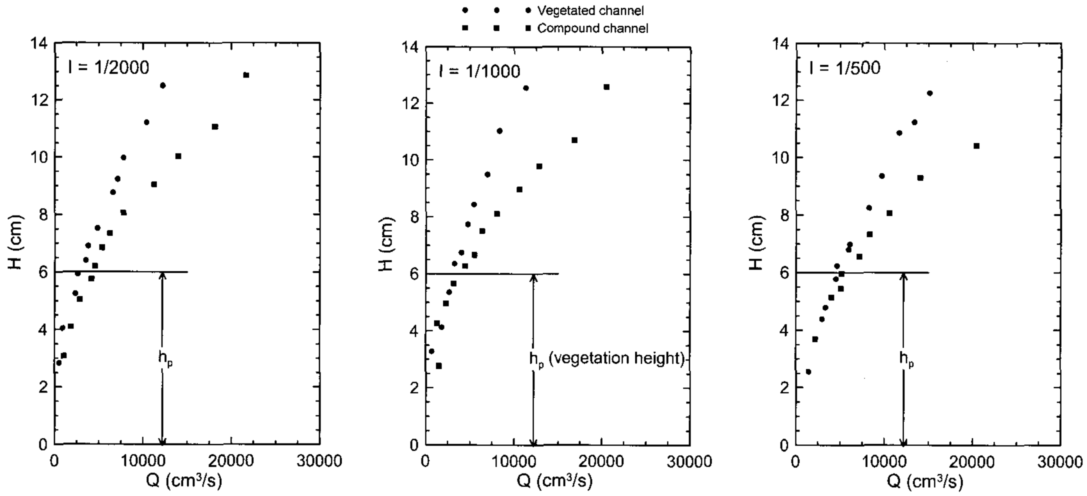


Figure 7. Stage-discharge relationships of partly vegetated corner flow and compound open-channel flow (Shimizu and Tsujimoto, 1993)

model by comparing the computed results with measured data and found qualitative agreement (see Figure 8). However, the velocity dip phenomenon was not observed in the mean flow and detailed flow structures such as turbulence statistics were not reported.

Choi and Kang (2005) conducted 3D numerical simulation of partly-vegetated open-channel flows using the RSM. Comparisons were made with Nezu and Onitsuka's (2001) measurement data, showing a moderate agreement. In the simulated streamwise mean velocity, the velocity dip phenomenon could be clearly observed (see Figure 9). Moreover, it was found that the point of the maximum of the streamwise mean velocity is deepened and moves to the other side of the vegetated zone as vegetation density increases. This implies that the vertical component of the Reynolds stress is negative near the free surface in the non-vegetated zone.

Figure 10 shows the RSM results of the depth-averaged velocity distribution by Choi and Kang (2005) with observed data by Shimizu and Tsujimoto (1993). The overall agreement between simulated and measured profiles appears to be good. In the non-vegetated zone, it is seen that the depth-averaged velocity increases rapidly from the left sidewall, reaching a maximum, and then gradually decreasing. The depth-averaged velocity in the vegetated zone is seen to be nearly uniform.

3.4 Compound open-channel flows with vegetated floodplain

Naot et al. (1996) simulated numerically compound open-channel flows with vegetated floodplain. The ASM was used for turbulence closure. They showed that the flow in the floodplain is weakened considerably with vegetation density.

Kang and Choi (2005) simulated the same type of flows with the RSM. They compared the simulated results with ASM data by Naot et al. (1996) due to the lack of experimental data. As can be seen in Figure 11, velocity dip is clearly

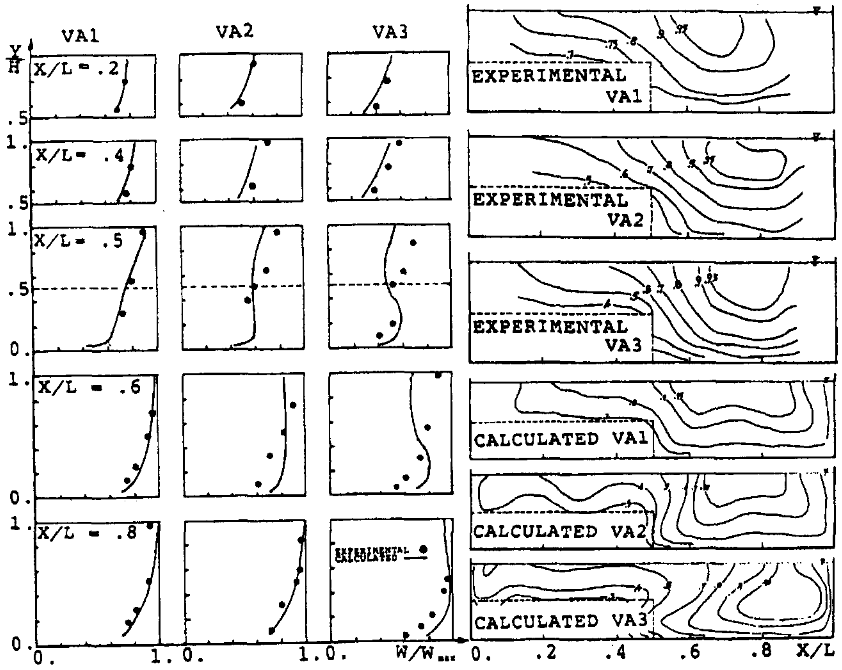
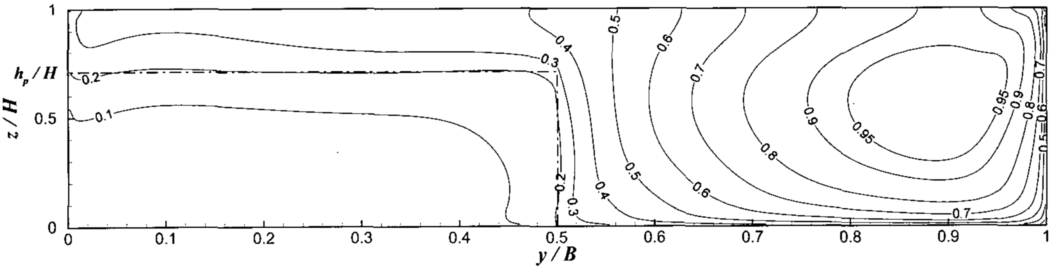
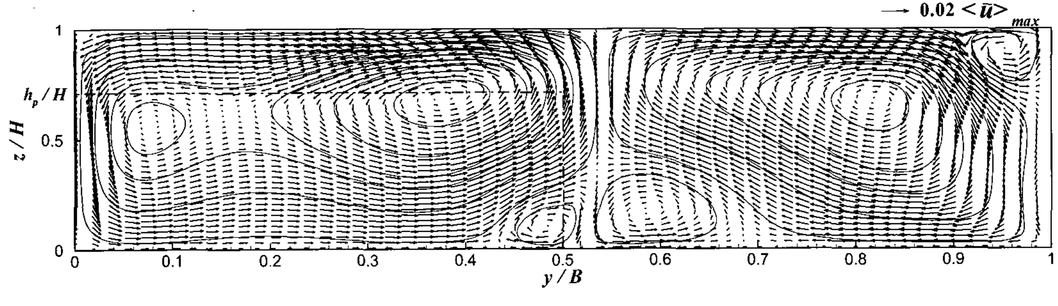


Figure 8. Rectangular open-channel flow with vegetated corner (Naot et al., 1996)



(a) Streamwise mean velocity



(b) Secondary currents and vorticity

Figure 9. RSM results of partly vegetated open-channel (Choi and Kang, 2005)

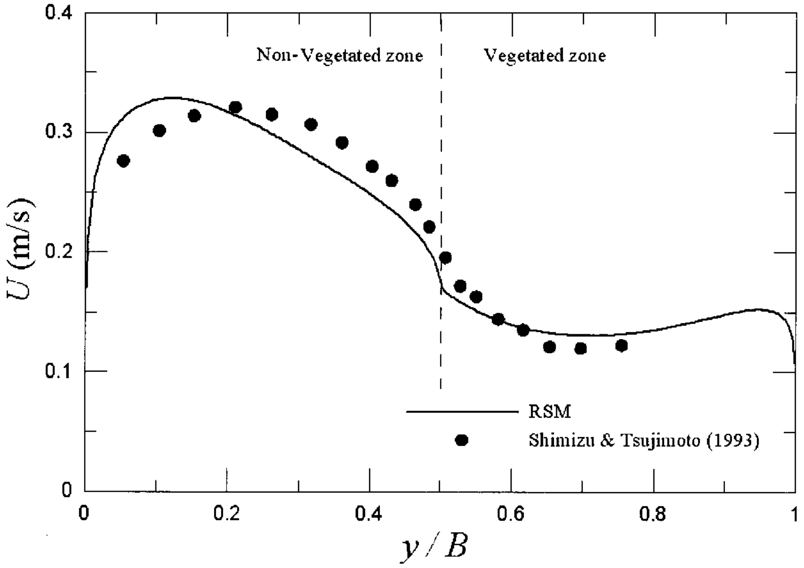


Figure 10. Depth-averaged velocity by RSM (Choi and Kang, 2005)

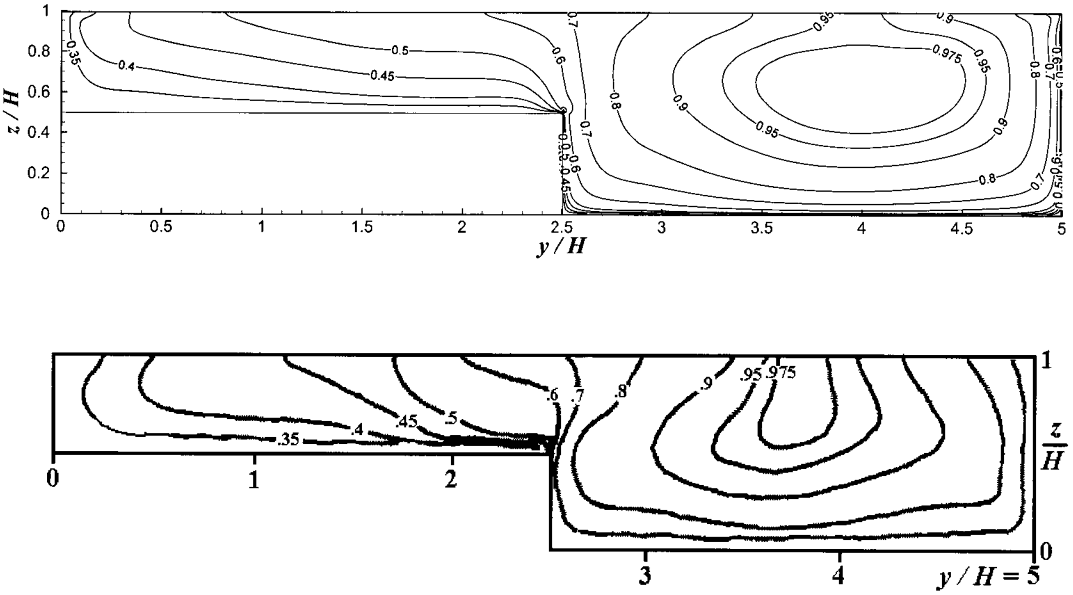


Figure 11. Mean velocity of compound open-channel flow with vegetated floodplain for $a=0.25m^{-1}$ [top: RSM, down: ASM by Naot et al. (1996)] (Kang and Choi, 2005)

observed in the streamwise mean velocity simulated by the RSM. However, it appears that the ASM is unable to reproduce such phenomenon. Kang and Choi also observed that streamwise mean velocity in the floodplain decreases and the location of the maximum velocity moves away from the floodplain as vegetation density increases. The lateral shift is related with the secondary currents in the main channel, the strength of which increases with vegetation density.

3.5 Fully 3D numerical Simulation

Xiaohui and Li (2002) developed a large eddy simulation (LES) model to simulate 3D partly vegetated open-channel flows. The k-l model was used for modeling the sub-grid scale turbulence. They showed that large eddies are generated at the interface between the vegetated and non-vegetated zones where significant mass and momentum exchanges occur.

Nadaoka and Yagi (1998) developed the sub-depth scale 2D model to simulate open-channel flows with submerged vegetation. Using the developed model, they investigated the evolution of horizontal large-scale eddies in shallow water (see Figure 12). Nadaoka and Yagi found that the bottom friction and vegetation drag, acting as sinks of vorticity, play a key role in the development of the horizontal large-scale eddies and in the generation of the Reynolds stress. Also, Nadaoka and Yagi found that the horizontal large-scale eddies dominate horizontal momentum mixing.

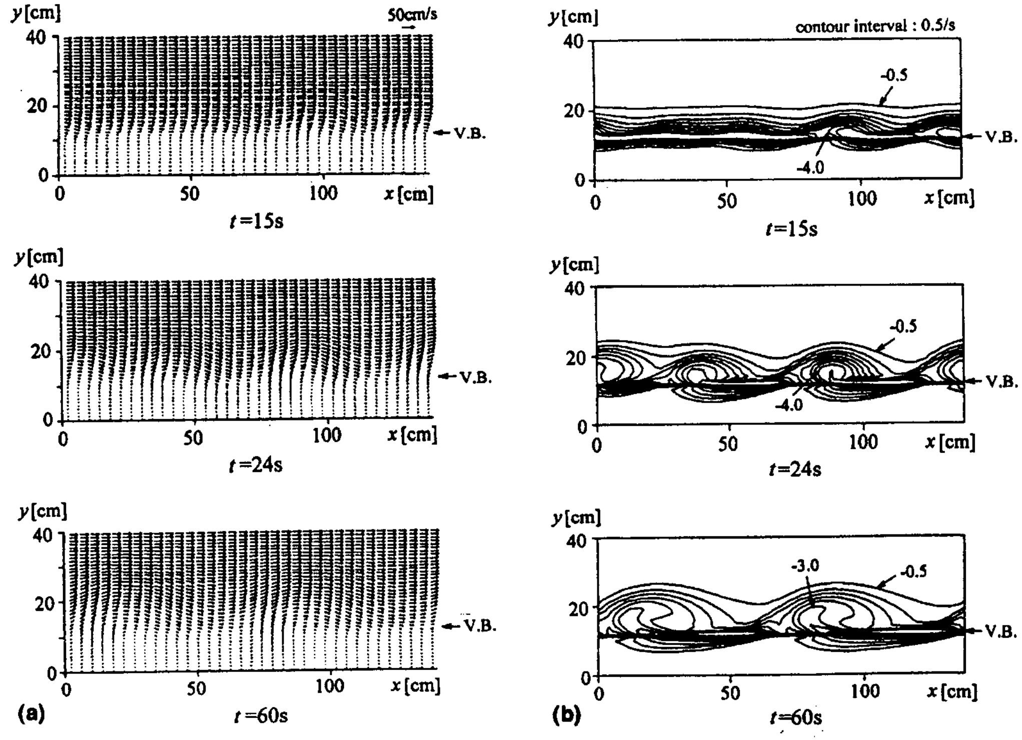


Figure 12. Plan view of horizontal large scale eddies: (a) velocity; (b) vorticity (Nadaoka and Yagi, 1998)

4. CONCLUSIONS

This paper presented a state-of-the-art of applications of CFD to open-channel flows with vegetation. The numerical models were based upon the governing equations averaged over time and space as proposed by Wilson and Shaw (1977) and Raupach and Shaw (1982). Various turbulence models from two-equation model to LES have been used in simulating the mean flow and turbulence statistics. Measurement data sets from laboratory experiments with ADV or LDV were used for comparisons with simulated flow structures. Results indicated that current status of numerical modelings of vegetated open-channel flows is successful. Future challenges lie in the modelings of such flows with vegetation close to reality. This is possible by solving the problems of relationship between the resistance and flexural rigidity and additional drag due to foliages. Also, knowledge accumulated in the experience of CFD applications should be melted into the depth-averaged modeling of flow and sediment or solute transport which is more attractive to engineers in charge of stream management.

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Associate Professor, School of Civil and Environmental Engineering, Yonsei University, Seoul, Korea
(E-mail: schoi@yonsei.ac.kr)

Ph.D. Student, School of Civil and Environmental Engineering, Yonsei University, Seoul, Korea
(E-mail: pulip@yonsei.ac.kr)