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EFFECTS OF FLOODPLAIN VEGETATION ON FLOW RESISTANCE AND LARGE HORIZONTAL VORTICES

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ABSTRACT

The arrangement of vegetation over the floodplains of the rivers affects the flow resistance as well as the flow structures. Large horizontal vortices are evolved near the plant-water interface and play significant role in mass and momentum transfer. The objective of this study is to gain the insight of the flow resistance and the change in flow structure in presence of floodplain vegetation with the change of vegetation placement patterns. The flume experiments have been carried out with three different vegetation layouts along with the unsteady three-dimensional numerical simulations with a non-linear k-ε model, coupled with a vegetation model. The mean velocity distributions in the case studies are reasonably reproduced by the numerical model together with successful calculation of large horizontal vortices along the plant-water interface. It is found that removal of vegetation from floodplain in form of vegetation belt reduces the momentum transfer from main channel to floodplain and enhances the flow resistance on the floodplain.

1. INTRODUCTION

Vegetation has a great influence on the aquatic flows and has been considered as a key factor for aquatic ecosystem and river management. Natural rivers usually consist of a deep main channel and flanked by relatively shallow vegetated floodplains. It can affect the transport of water, sediment and nutrients both within the channel and to or between the riparian zones. Riparian vegetation plays significant role in altering the flow structure and eventually the geometry of the rivers. It acts as a flow resistance and frequently removed from the river side to increase the flood carrying capacity. On the contrary under river restoration and river bank stabilization schemes vegetation is planted to control the erosion and deposition and has been considered as one of the most important technical issues in river engineering. Thus an in-depth understanding of flow characteristics in the presence of vegetation is indispensible for the better management of riparian vegetation for flood control and environmental protection.

Compound channel flows are characterized by complex flow structure due to the presence of shear layer at the junction between main channel and floodplain (Kang and Choi, 2006). The flow phenomena become more complex in the presence of vegetation. The arrangement of vegetation

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over the floodplain affects the flow resistance as well as flow structures. In-depth understanding and accurate prediction of the flow structure in a compound channel with vegetated floodplain has been intensively pursued through laboratory experiments and numerical computations over the last three decades. Previous studies (Nagao and Tominaga (1995), Tsujimoto (1999), Okada and Fukuoka (2004)) have demonstrated that a row of large vortices with vertical axes are formed along the interface between a main channel and a floodplain when the vegetation on the floodplain is emergent, and that the vortices transport high momentum and suspended sediment towards the floodplain. Many investigations have also revealed the effects of vegetation on flow mechanisms and resistance in compound channels with vegetated floodplains, e.g. Pasche and Rouve (1985), Naot et al. (1996), Bennett (2002), Kang and Choi (2006), Rameshwaran and Shiono (2007). However, there remain many unknowns with respect to flow vegetation interaction.

The aim of this study is to gain the insight of the flow resistance and the change in flow structure in presence of floodplain vegetation with the change of vegetation placement patterns. Along with physical experiments unsteady three-dimensional numerical simulations have been carried out with a non-linear *k-ε* model, coupled with a vegetation model. It is found that the mean velocity distributions in the three cases are reasonably reproduced by the numerical model together with successful calculation of large horizontal vortices along the interface. It is found that removal of vegetation from floodplain in form of vegetation belt reduces the momentum transfer from main channel to floodplain and enhances the flow resistance on the floodplain. The flow pattern as well as vertical voriticity show complex structure in case of patched vegetation. This study summarizes the effects of floodplain vegetation on large horizontal vortices, flow resistance and primary flow pattern.

2. MATHEMATICAL MODEL FORMULATION

The numerical calculations have been conducted using a RANS model with a non-linear *k-ε* model. The computer code calculates hydrodynamics for three dimensional geometry. The Navier-Stokes equations are temporally and spatially averaged (double averaged) to capture the effects of vegetation on turbulent flows. The computational grid size is larger than the diameter of vegetation elements, as discussed by Raupach and Shaw (1982) and recently by Nikora et al. (2007).

$$\frac{\partial U_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial U_i}{\partial t}+\frac{\partial U_iU_j}{\partial x_j}=g_i-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\nu\frac{\partial^2 U_i}{\partial x_j\partial x_j}-\frac{\partial \overline{u_i'u_j'}}{\partial x_j}-F_i \tag{2}$$

$$F_i=\frac{1}{2}C_D\lambda U_i\sqrt{U_jU_j} \tag{3}$$

where, C_D = drag coefficient (= 1.0 for Case C1 and 0.8 for Case C2) and λ = vegetation density. The term consisting of the Reynolds stress and the velocity correlation in Eq. (2) has been modeled as:

$$-\overline{u_i' v_j'} = -\frac{2}{3}k\delta_{ij} + \nu_t S_{ij} - \frac{k}{\varepsilon}\nu_t \sum_{\beta=1}^{3} C_\beta \left(S_{\beta ij} - \frac{1}{3} S_{\beta\alpha\alpha}\delta_{ij} \right) \tag{4}$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

$$S_{ij} = \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}, \quad S_{1ij} = \frac{\partial U_i}{\partial x_m}\frac{\partial U_j}{\partial x_m}, \quad S_{2ij} = \frac{1}{2}\left(\frac{\partial U_m}{\partial x_i}\frac{\partial U_j}{\partial x_m} + \frac{\partial U_i}{\partial x_m}\frac{\partial U_m}{\partial x_j} \right), \quad S_{3ij} = \frac{\partial U_m}{\partial x_i}\frac{\partial U_m}{\partial x_j} \tag{6}$$

The transport equations for turbulent kinetic energy k and its dissipation rate ε are written as:

$$\frac{\partial k}{\partial t} + \frac{\partial U_j k}{\partial x_j} = \frac{\partial}{\partial x_m}\left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_m} \right] + P_{rod} + S_k - \varepsilon \tag{7}$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial U_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_m}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_m} \right] + \frac{\varepsilon}{k} C_{\varepsilon 1} P_{rod} + S_\varepsilon - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{8}$$

$$P_{rod} = -\overline{u_i' u_j'}\frac{\partial U_i}{\partial x_j} \tag{9}$$

The source/sink terms of the transport equations for k and ε are S_k and S_ε:

$$S_k = F_i U_i - 2C_D \lambda \sqrt{U_i U_i}\, k \tag{10}$$

$$S_\varepsilon = \frac{3}{2}\frac{\varepsilon}{k} F_i U_i - 1.4 C_D \lambda \sqrt{U_i U_i}\, \varepsilon \tag{11}$$

$$\sigma_k = 1.0, \ \sigma_\varepsilon = 1.3, \ C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92 \tag{12}$$

Along the bottom and the side walls "wall function" technique has been applied. Near free surface turbulent dissipation rate is specified as follows:

$$\varepsilon_s = C_\mu^{3/4} k_s^{3/2} \Big/ (0.4\Delta z_s) \tag{13}$$

The suffix s indicates the value at the point adjacent to the free surface and Δz_s = normal distance from the free surface. The CFD code was developed in house. The basic equations were discretized by Finite volume method with a fully implicit scheme for unsteady terms and SIMPLE algorithm was used. The QUICK scheme was applied to the convection terms in the momentum equations whereas Power-law scheme was used for the transport equations for k and ε.

3. EXPERIMENTAL SETUP

The flow measurements in a compound channel were conducted by Jahra et al. (2011) and Hasegawa et al. (2011). Experiments were conducted in a straight channel whose length, width and slope are 2200 cm, 182 cm and 1/500, respectively. Floodplains have been constructed along both sides of the channel. The height and width of the flood plain are 4 cm and 45.5 cm, respectively. Three types of vegetation zone were prepared on a floodplain of one side of the channel (Figure 1) in an aligned arrangement: (i) case C1: floodplain fully covered by model vegetation, (ii) case C2: vegetation belt of 9cm width, 1280 cm long, located along the interface of the main channel and floodplain, and (iii) case C3: patched vegetation, each of which is 9 cm wide and 90 cm long placed along the main channel-floodplain interface. The vegetation is idealized with wooden rigid cylinders of 3 mm diameter and 5 cm height. The distance between the adjacent vegetation stems is 3 cm in both the streamwise and spanwise directions. For all the cases the discharge is 30 l/s and the vegetation density is 0.033/cm. Three mean velocity components were measured by two-component electromagnetic current meters (both L-type and I-type). The flow conditions are summarized in Table 1.

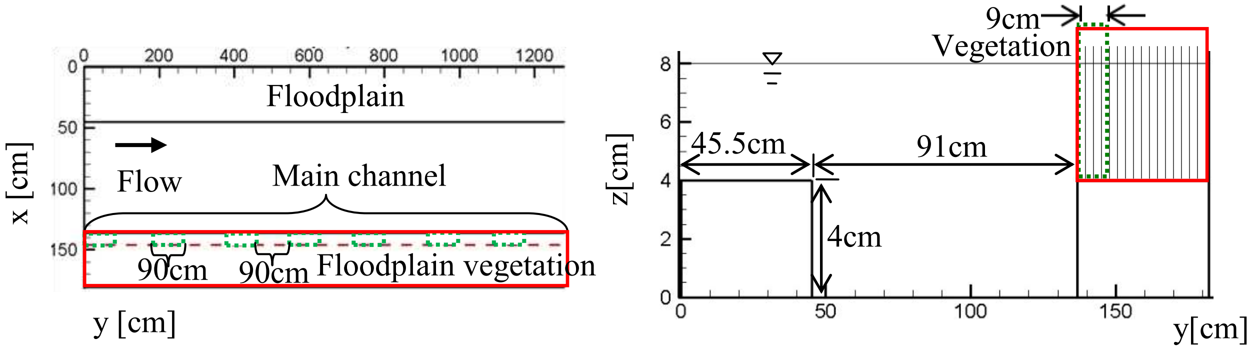


Figure 1 Sectional view of the channel with different vegetation lay-outs.

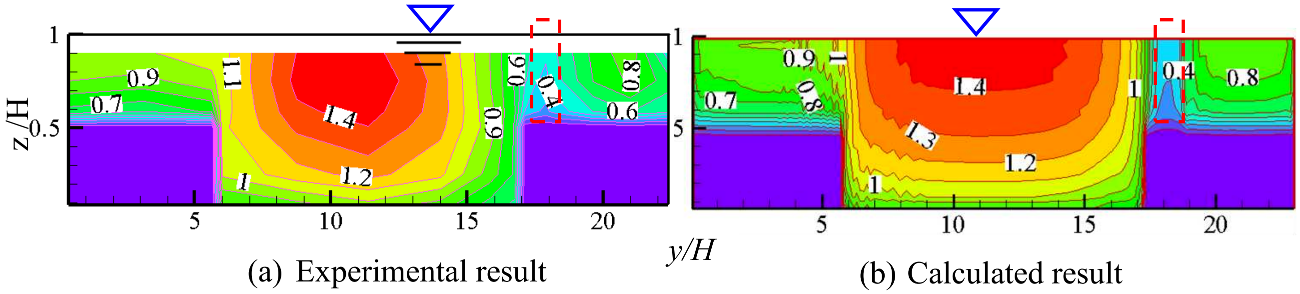
Table 1 Flow condition for compound channel

Case	Bed slope	Discharge	Water depth	Average velocity	Vegetation density	Vegetation placement
	I_b	Q [l/s]	H [cm]	U_m [cm/s]	λ [1/cm]	
C1	1/500	30	8.0	27.5	0.0333	Floodplain fully covered by vegetation (length 1280 cm)
C2			7.9	33.6		Vegetation belt (length 1280 cm, width 9 cm)
C3			7.3	40.5		Patched vegetated area (length 90 cm, width 9 cm, each)

4. RESULTS AND DISCUSSION

4.1 Mean velocity

The present non-linear linear k-ε model (Navier-Stokes equations are both temporally and spatially averaged), coupled with a vegetation model reproduces the mean velocity quantities reasonably well. Figure 2 shows the U/U_m-velocity contour for both the experimental and calculated results at section x=1000 cm of case C2 where 9 cm wide vegetation belt is located along the interface of the main channel and the floodplain. It gives both qualitative and quantitative view of the cross sectional flow structure. It has been found that the experimental result is reproduced by the simulated result quite satisfactorily. Present model also shows reasonable agreement with the other two experimental cases. Secondary currents (V and W velocity) are also well reproduced by the present model. Vegetation significantly reduces the U-velocity within the vegetated area. At the rare side of the vegetation belt velocity had increased abruptly producing strong shear layer along the interface of the vegetation belt and the non-vegetated area on the floodplain. This contributes in generating large vortices along the rare side of the vegetation belt.



(a) Experimental result (b) Calculated result

Figure 2 U/U_m-velocity contours at x=1000 cm in Case C2.

4.2 Flow visualization

Flow visualization was carried out for all the three case studies. Through flow visualization large horizontal vortices have been perceived along the interface of the main channel and the floodplain vegetation for all the three cases. The vortices take complex pattern in case C2 and C3 (Photo 1) attributing effect on mass, momentum transfer. Figure 3 shows the calculated result of instantaneous distribution of horizontal velocity vectors of case C1 and C2 (exactly speaking $U-\overline{U}_{\text{interface}}$ and V velocity vectors where $\overline{U}_{\text{interface}}$ is the mean velocity at the interface). It is apparent that the

numerical model successfully reproduces the size and shape of large vortices passing along the interface of the main channel and floodplain vegetation. Spectrum analysis also agrees with this fact. Removal of vegetation from the floodplain generates large vortices on the both side of the vegetation belt leaving significant effect on mass and momentum transfer.

Photo 1 Flow visualization; left: case C1 and right: case C2.

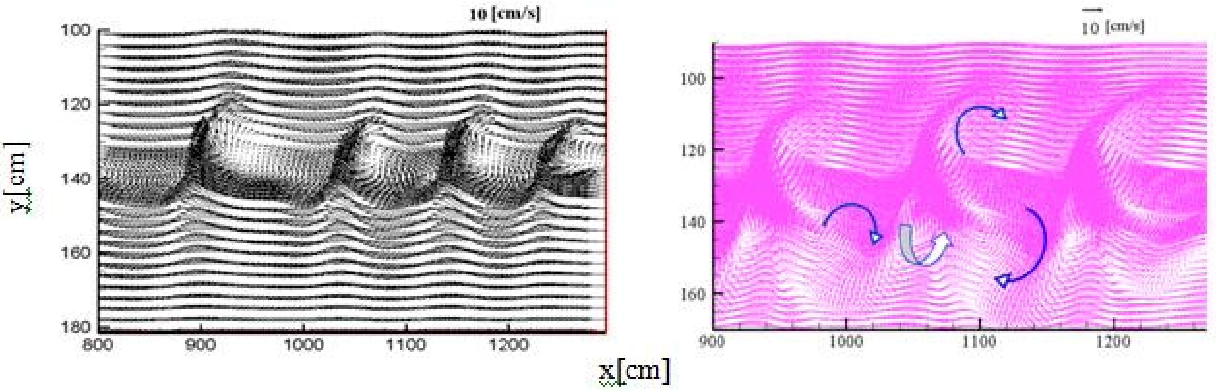


Figure 3 Velocity vectors, left: case C1 and right: case C2.

4.3 Lateral momentum transfer and flow resistance

Momentum exchange process in the compound channel becomes complex in the presence of localized vegetation. Figure 4 shows the streamwie distribution of momentum transfer. It has been found in Figure 4(a) that higher momentum is transferring from main channel to the fully covered vegetated floodplain (at y=137 cm) compared to the floodplain with vegetation belt (case C2). Removal of vegetation in form of vegetation belt suppresses main channel to floodplain momentum transfer. At the rare side of the vegetation belt (y=147 cm) vegetated floodplain to main channel momentum transfer has been perceived which enhances the flow resistance over the floodplain. The momentum transfer abruptly increases behind each patched vegetation belt and flood carrying capacity increases compared to the long vegetation belt (Figure 4(b)). It has been found that momentum transfer in the cases of vegetation belt and patched vegetation belt is turbulence dominant, whereas convection is dominant for fully covered vegetated floodplain. From these results, for the cutting of vegetation on the riverbank or channel floodplain is reconfirmed that careful consideration is required.

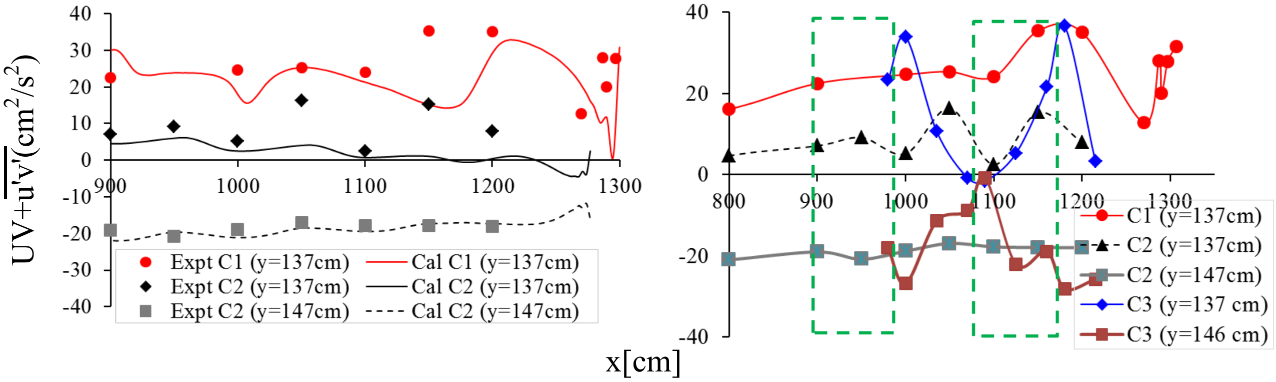


Figure 4 Streamwise distribution of lateral momentum transfer (a) comparison between experiment and calculation-case C1 and C2; (b) experimental result-case C1, C2 and C3, z=6cm).

5. CONCLUSIONS

Flume experiments were carried out for turbulent open channel flows in the presence of fully covered vegetated floodplain as well as localized vegetation over floodplains under emergent conditions. Numerical simulations were also performed with a non-linear k-ε model with a vegetation model in the transport equations for k and ε. The findings are mentioned below:

- The present nonlinear k-ε model can reproduce the mean velocity field fairly well under different vegetation layouts.
- The present model produces the large vortices along the interface between the main channel and the vegetation zone.
- Removal of vegetation from floodplain in form of vegetation belt reduces the momentum transfer from main channel to floodplain and enhances the flow resistance on the floodplain.

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