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TURBULENT STRUCTURE IN COMPOUND OPEN CHANNEL FLOWS WITH VEGETATED FLOODPLAINS

Biswal, S.K [1], and Mohapatra, P.K [2]

***Abstract**: Understanding the hydraulics of flow in a compound channel with vegetated floodplains is very important for determining the stage- discharge curve and for supporting the management of fluvial processes. In this paper, the flow patterns over the vegetation are described based on an experimental observation. For vegetation on the floodplain, local grass is taken for model study. A 3D acoustic Doppler velocimeter (Vectrino) is used to measure the flow velocities for vegetation on the floodplain. In case of vegetated floodplains, all measured streamwise velocity distributions followed an S-shaped profile, exhibiting three zones related to flow depth and location, and the fluctuating velocity followed a normal distribution. The influence of vegetation on the distribution of secondary currents, turbulence intensities, and Reynolds shear stresses are also investigated.*

***Keywords**: Open-channel flow; Floodplains; Vegetation; Turbulence; Reynolds stress.*

INTRODUCTION

An investigation of three-dimensional (3D) turbulent structures in the compound open channel flows are a very important topic in hydraulic and river engineering, as well as in fluid mechanics. The turbulent structures in compound open channels are characterized by large shear layers generated due to the difference of velocity between main channel flow and floodplain flow. In this large shear layer region, not only vortices with vertical axis exit, but also vortices with longitudinal axis. The latter are the so-called secondary currents, which are driven by the anisotropy and inhomogeneity of turbulence. The secondary currents are found to influence the primary mean-velocity field in the same way as in square and rectangular channel (Bradshaw, 1987). Momentum transfer between the main channel and the floodplain generally decreases the discharge in the main channel, increases the discharge on the floodplain, and decreases the channel's total discharge capacity. This has been called the "kinematic effect". Along with the general trend of environmental river engineering and restoration, more variation of geomorphic and biological elements is allowed in rivers e.g. Irregular cross sections, floodplains and vegetation. The flow physics of nature, irregular and meandering channels with floodplains and vegetation differ remarkably from the ones of straightened and regular channels and thus, cause

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large problem in channel design. When the flow in a river channel rises above the bankfull stage and inundates the adjacent floodplain areas, momentum is transferred across the junction regions separating the deep and shallow zones. If the velocity gradient across the junction regions is large, this transfer mechanism will influence both velocity and boundary shear stress distributions and also the turbulence characteristics of the junction regions. Townsend (1968) studied momentum transfer phenomena in an asymmetrical compound channel and conducted for small floodplain depths, that both the streamwise and cross-stream turbulence intensities at the channel floodplain interface were significantly higher under interacting (compound channel) flow conditions than the corresponding values obtained for the equivalent isolated (separated channels) conditions. Myers and Elsawy (1975), and Knight and Demetriou (1983) focused on interaction between the main channel and the floodplain, and boundary shear stress distributions. Elsawy et al. (1983) used laser Doppler anemometry to measure turbulence characteristics in a compound channel and found that the measured normal stress $-\rho\overline{u}'^{2}$ at the interface was generally compatible with the apparent shear stress estimated from momentum balance considerations.

The characteristics of compound channel flows with vegetated floodplain are recognized in the mixing region between the main channel and the floodplain. The mean velocity fields are directly influenced by secondary currents, which are associated with pair of longitudinal vortices. A pair of secondary currents is recognized on the both sides of up flow at relative depths $D_{r,}$ is defined by Knight (1991) as the ratio of the depth of flow on floodplain to that in main channel, i.e., D_r= (H-h)/H. The vortex on the side of main channel is called “floodplain vortex”. Whereas the vortex on the main channel is known as “main channel vortex”. However, because of the influence of vegetation, the secondary flow structure is altered dramatically, with only some minor secondary currents on the vegetated floodplain.

In natural rivers, floodplains are often too many kinds of vegetation which generally increases the flow resistance, changes the velocity distribution, and affects the discharge capacity and sediment transport rate. Darby and Thorne (1996) developed a physically based method for predicting the impact of vegetation growth on flow resistance and flood capacity. Naot et al. (1996b) examined various numerical models for analyzing unstable patterns of overbank flow in partially vegetated channels. They compared predictions given by three algebraic stress models. Naot et al. (1996a) further discussed the hydrodynamic response of turbulent flow in a compound wide rectangular open channel, with specific vegetated domains. The experimental results of Huang et al. (1999) and Huang et al. (2002) showed that velocity in the main channel increased significantly after the floodplains were covered in vegetation. Thornton et al. (2000) experimentally examined the apparent shear stress at the interface between the main river channel and vegetated and nonvegetated floodplains. Shi (2002) deduced a formula defining the amount of flow in a vegetated floodplain coming into the main channel based on wake theory by experimental results. Kang and Choi (2004) used a Reynolds stress model, with a pressure-strain correlation term, to model overbank flow with vegetated floodplains, taking into account the anisotropy of the turbulence at the free surface. Yang et.al. (2005) analyzed the influence of different types of vegetation on the distribution of secondary currents, turbulence intensities and Reynolds shear stresses based on experimental study.

Since the hydraulic behavior of overbank flow with vegetated floodplains is so complex, experiments are undertaken herein with floodplain vegetation, such as grass, to elucidate the flow structure.

Experimental setup

The Experiments are carried out in a rectangular symmetrical compound channel, made of brick masonry with horizontal bed, located at Hydraulic laboratory of the Civil Engineering Department of Indian Institute of Technology Kanpur, India. The available compound channel is 11.8m long, 20cm wide and is of 10cm bankfull height. The width of floodplains on either side of the main channel is 30cm each. The top surface is plastered using 1:6 cement sand mortar and bed surface is smoothed by thin layer of concrete. Water is discharged from upstream constant head tank which is controlled by gate valve attached to the tank. Flow rates in the main channel are obtained from the rating curves which are calibrated by volumetric method. To represent vegetation on the floodplain, the author chooses local grass as model vegetation, and was planted on the floodplain over a length of 2.5m between 5 and 7.5m from the beginning of the compound channel at 50cm row spacing. The flume was operated under a uniform flow condition, and measurements of discharge and point velocity were taken. Water surface elevations are measured by a point gauge with an accuracy of 1.0mm.A fully developed uniform flow are established at test section 5m downstream from the channel inlet. A Vectrino (Nortek AS, Norway) acoustic Doppler velocimeter (ADV) is used to measure flow velocities for vegetation on the floodplain and secondary velocities at the test sections. The velocity measurements are taken at each data location for a 60 s at a sampling rate of 20Hz. The manufacturer's specifications stated that the measuring accuracy of the ADV is ± 0.5 % of the measured value ± 1mm/s. The time series of velocity at each sampling point is analyzed to produce a normalized average velocity and corresponding turbulence intensity. The tailwater depth in the downstream channel is controlled by an adjustable tailgate. "Fig. 1" illustrates the layout of compound channel and location of velocity distribution data on channel cross section, consisted of five evenly spaced vertical profiles on main river and eight evenly spaced vertical profiles on each floodplain. Vertical velocity profiles are taken 1cm above the main channel and floodplains bed at 1.5cm depth interval throughout the section for two different discharges, Q = 12 L/s and 20 L/s. It is fully recognized that the size of the experimental flume and the scale of the experimental setup are small, but the data were still obtained under turbulent flow conditions, although with small Reynolds numbers. Turbulent flow structures in compound channels tend to be similar in nature, regardless of scale and laboratory based experiments.

VELOCITY DISTRIBUTION

Time-Averaged Velocity Distributions

"Figs.2" illustrated, the vertical distributions of streamwise velocity at three different locations i.e. y = 0, 10, and 25cm for two different discharges Q= 12 and 20 l/s. These locations are at the centerline of the main channel, at the inner edge of the main channel and near the central line of the floodplain respectively. In each case, the relevant parameter has been nondimensionalized by the cross-sectional velocity, V_s. For fully developed 2D flow near the bed, the law of the wall is usually expressed as

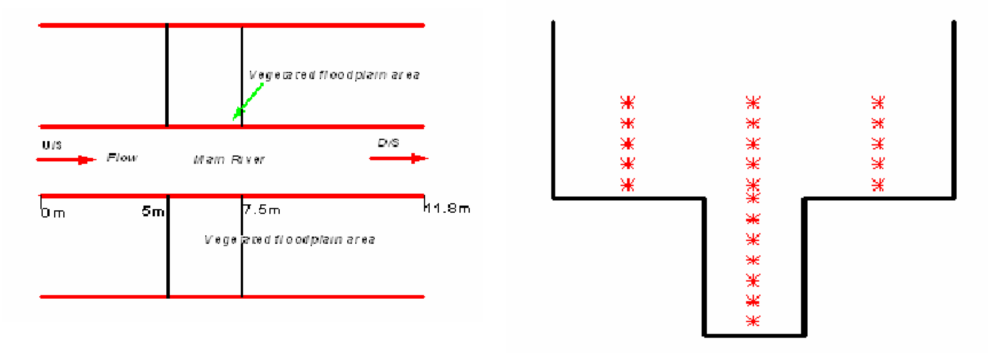


Fig.1. Layout of Compound channel and Cross-sectional view of flow measurement locations

$$\frac{U}{U^*}=\frac{1}{\kappa}\ln\left(\frac{zU^*}{\upsilon}\right)+c \tag{1}$$

Where U = streamwise velocity; U* = shear velocity; κ = Von Karman's constant, z = distance from measurement point to the bed; ν = kinematics viscosity; and c = constant.
Let U* = a(y) V_s, then Eq. (1) becomes

$$\frac{U}{a(y)Vs}=\frac{1}{\kappa}\ln\left\{\frac{za(y)Vs}{H(y)\upsilon}H(y)\right\}+c \tag{2}$$

Or

$$\frac{U}{Vs}=a(y)\frac{1}{\kappa}\ln\left\{\frac{z}{H(y)}\right\}+a(y)\frac{1}{\kappa}\ln\left\{\frac{a(y)Vs}{\upsilon}H(y)\right\}+a(y)c \tag{3}$$

Let $C=a(y)\frac{1}{\kappa}$, $D=a(y)\frac{1}{\kappa}\ln\left\{\frac{a(y)Vs}{\upsilon}H(y)\right\}+a(y)c$

Eq. (3) becomes

$$\frac{U}{Vs}=CLn(Hr)+D \tag{4}$$

Where Hr = z/H(y) is called the relative depth.

Hence, Eqs. (4) and (1) are equivalent. In other words, if the velocity satisfies the logarithmic distribution, then either Eq. (4) or Eq. (1) can describe the flow features. "Figs.2" shows that velocity in the main channel increases and that on the floodplain decreases, reflecting the resistance to the flow offered by the grass vegetation. "Fig. 2" also shows that for vegetation with Q = 20 L/s, the S-shaped distribution is very distinct. The S-shaped distribution divides the flow into three regions, with the extent of each region related to flow depth and the value of y. The vegetation top lies within the third region of flow in the present case. Furthermore, the velocity distribution is affected by two boundary layers, one at the bed and another at the top of the vegetation.

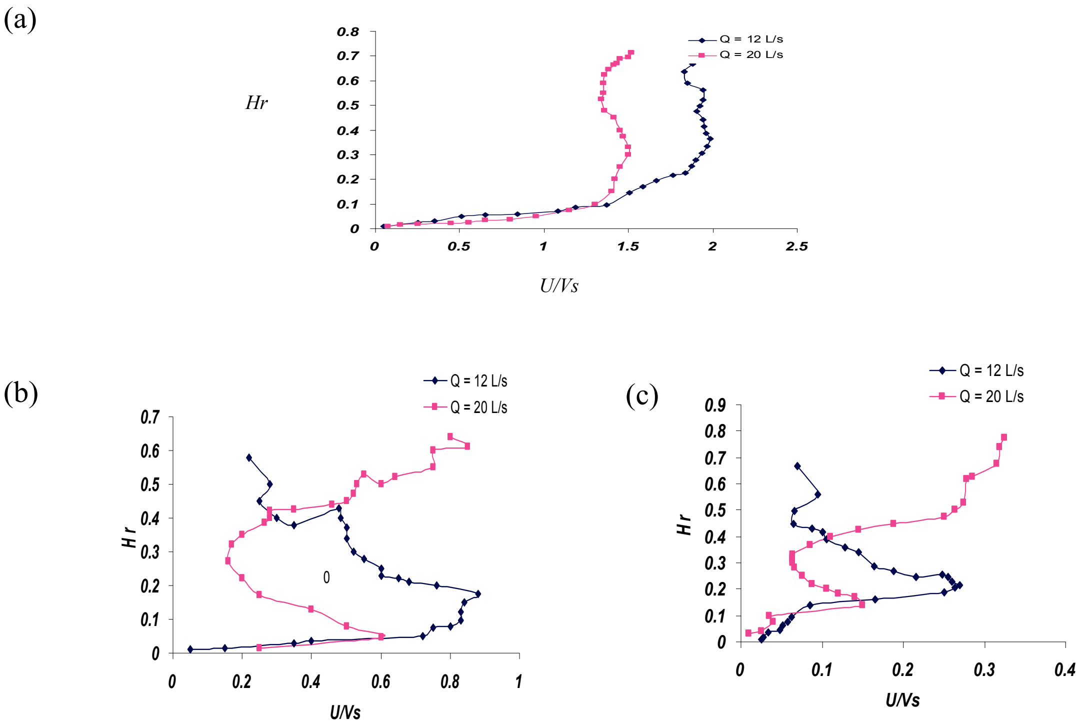


Fig.2. Vertical distributions of point velocity at main channel center, edge of main channel and near the centre of floodplain.

Fluctuating Velocities

The sediment transport rate and Reynolds shear stresses are both related to velocity fluctuations. Hence, from a theoretical or practical point of view, it is important to study the distributions of the velocity fluctuations. “Fig. 3” illustrates the temporal variation of turbulence data for u and v at the interface of main channel and floodplain, at z = 1cm, i.e., where the distance from the measurement point to the bed is 1cm. The turbulence intensity increases as a result of the presence of the vegetation.

A statistical analysis of the raw data in “Fig. 3” found that the distribution of the fluctuating velocities along three directions follow approximately normal distributions as shown in “Fig.4”However, when the fluctuating velocity approaches zero, the measured data depart somewhat from the full line. The full line in “Fig.4” is plotted according to the following equation.

$$f(u_i) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{u_i^2}{2\sigma_i^2}} \qquad (5)$$

Where f = probability density; u_i = fluctuating velocity in the i-direction, i.e., u, v and w; and σ_i= standard deviation of ui. Thus, σ_i actually reflects the intensity of the turbulence in the i-direction. The value of y for the point of intersection of the full line and the y axis can also reflect the intensity of the turbulence.

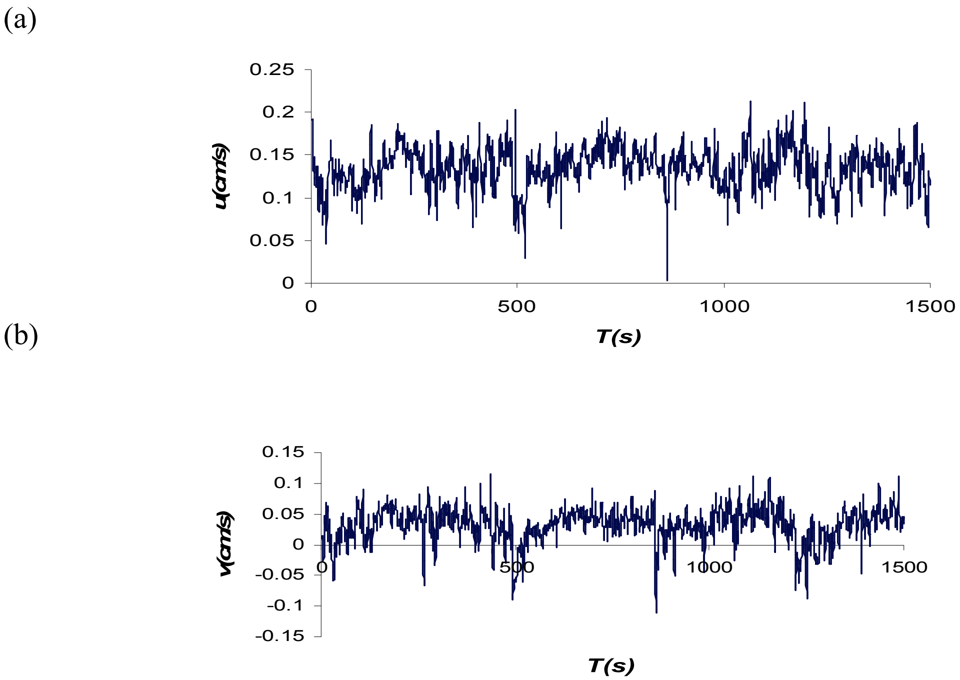
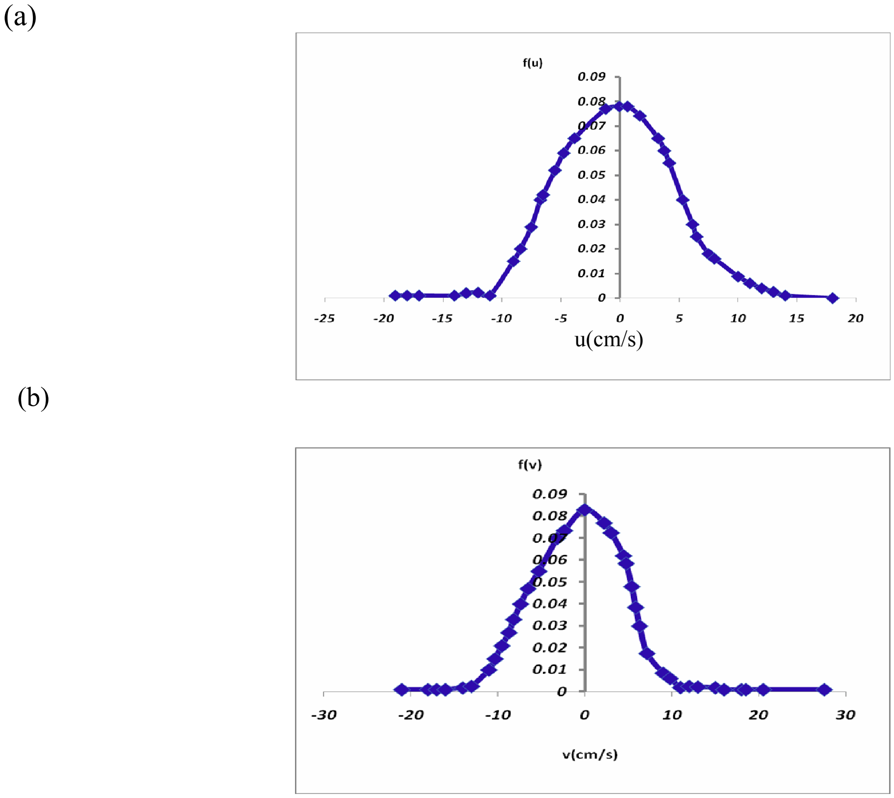


Fig. 3. Temporal variation of fluctuating velocities corresponding to streamwise and Spanwise direction.



(c)

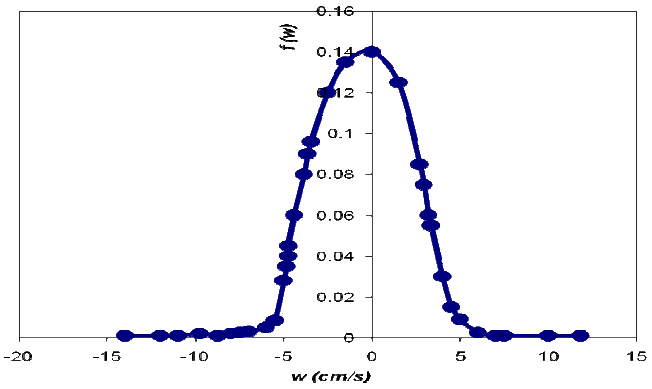


Fig. 4. Distribution of fluctuating velocities along streamwise, spanwise and vertical direction

Secondary Currents

At low relative depths, there are generally two major secondary current cells in the vicinity of the interface region. The relative depth, Dr, is defined by Knight as ratio of the depth of flow on the floodplain to that in the main channel, i.e., Dr = (H-h)/H. "Fig.5"shows that for a rigid bed at a relative depth, approaching 0.545, these secondary flow cells are not very strong. However, because of the influence of vegetation, the secondary flow structure is altered dramatically, with only some minor secondary current cells on the vegetated floodplain. In the mixing region between the main channel and floodplain, the pattern of secondary currents is extremely complex, causing the distribution of lateral velocity also to be complex

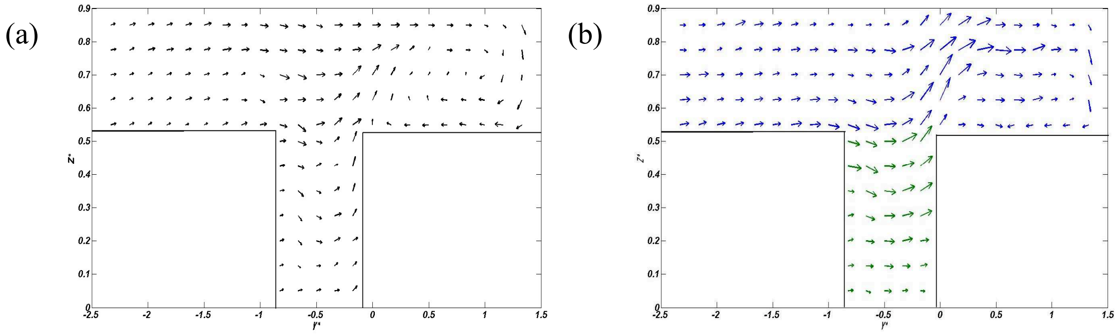


Fig.5. Secondary current vectors for (a) Q =12 L/s and (b) Q =20 L/s

Turbulence Intensities

The raw data were sampled at 20 Hz over a period of 60 s at each sampling location within the cross section. The time series of velocity at each data point was analyzed to produce a normalized average velocity and corresponding turbulence intensity. The turbulence intensity, σ_i in i- direction, was calculated from the velocity data according to

$$\sigma_i = \sqrt{\overline{u}_i^2} \tag{6}$$

However, many authors prefer the relative turbulence intensity, σ_{ir}, given by

$$\sigma_{ir} = \frac{\sqrt{\overline{u_i^2}}}{V_s} \tag{7}$$

The variations in the streamwise and lateral vertical turbulence intensities over the depth are shown in "Fig. 6" for two location i.e., at inner edge of the main channel and at interface between main channel and floodplain. These variations corresponding to the vertical distributions of streamwise point velocity, in that the vertical distributions of streamwise and lateral turbulence intensities are also S-shaped for the cases of vegetated floodplains. However, the vertical turbulence intensity does not follow the same kind of distribution. By comparing the distributions in three directions, it was found that the streamwise and lateral intensities are approximately equal.

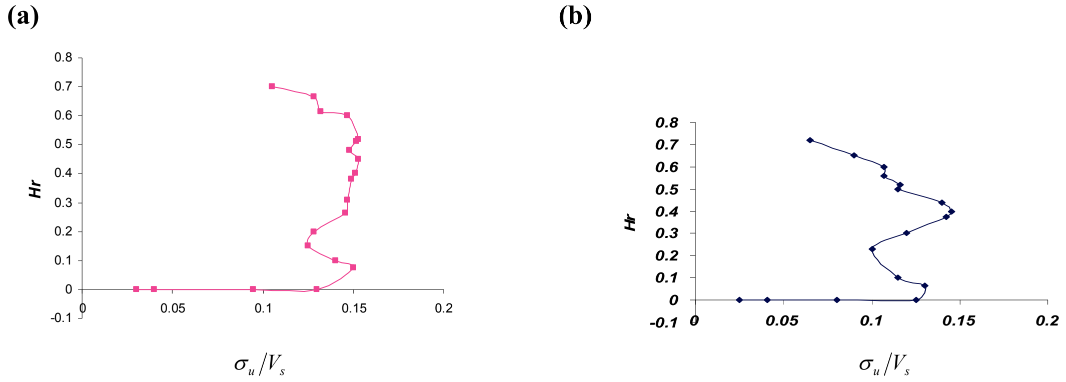


Fig. 6. Vertical variation of turbulence intensity for (a) streamwise and (b) spanwise for Q = 20 L/s

Reynolds Shear Stresses

The Reynolds shear stresses were calculated from the raw turbulent data using the equation $\tau_{ij} = -\rho\overline{u_i u_j}$. Because the water in the main channel generally moves faster than water on the vegetated floodplains, a shear layer is created in the interaction region between the main channel and the floodplain. From "Fig.7" it is clear that the vegetation on the floodplain affects

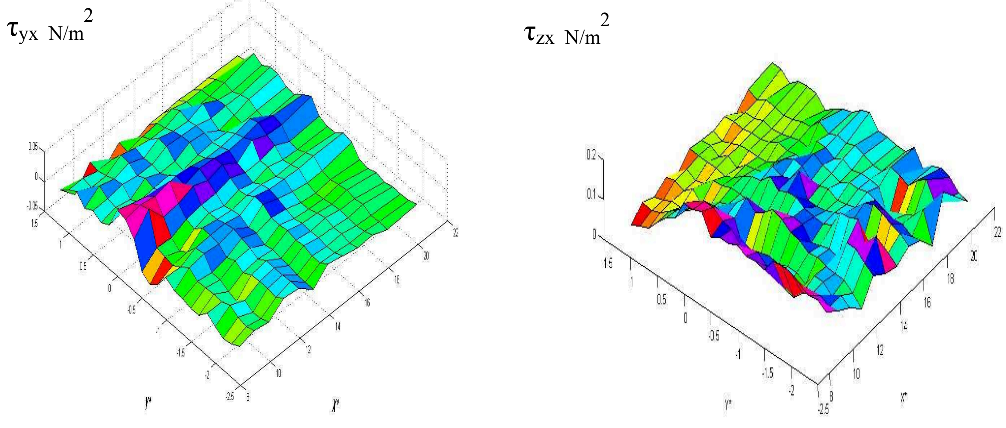


Fig. 7. Reynolds shear stresses τ_{yx} and τ_{zx} for Q=20L/s

the floodplain/main channel boundary. For vegetated cases, the vertical gradients of τ_{yx} in the main channel are approximately equal to zero, whereas the vertical gradients of τ_{zx} vary a great deal in the near bed flow region and are approximately equal to zero at other locations. This is probably because the main channel behaves more like a single channel after its floodplain is vegetated. On the floodplain, the flow below the secondary boundary layer is almost laminar, owing to the low Reynolds numbers.

CONCLUSIONS

These experiments indicate that the distribution of streamwise time-averaged velocity for vegetated floodplain follows an S-shaped curve. The vertical distribution of streamwise and lateral turbulence intensities are S-shaped for vegetated floodplains, similar to the distributions of streamwise point velocity. The vertical turbulence intensity, however, does not follow the same kind of distribution. The streamwise and lateral turbulence intensities are approximately equal. The vertical turbulence intensity is the weakest. The vegetation on the floodplain affects the spatial distribution of Reynolds stresses, especially near the interface. For vegetated cases, the vertical gradients of τ_{yx} are approximately equal to zero in the main channel, while the vertical gradient gradients of τ_{zx} vary a great deal, especially in the near-bed flow region. On the floodplain, the low velocity between the first and second boundary layers causes the lateral and vertical shear stresses to approach zero.

Notations

The following symbols are used in this paper:
a (y) = ratio of local shear velocity at y to cross-sectional velocity;
B= width of compound channel;
b = bed width of main channel;
C= constant in Eq. (1);
C and D = coefficient in Eq. (4);
D_r = relative depth, ratio of depth on floodplain to that in main channel;
f = probability density;
H = depth in main channel;
h = bankfull depth;
H_r = relative height, ratio of Z_p to H(y);
Q = total discharge through compound channel;
U* = local shear velocity;
U, V = time-averaged velocities in {x, y} direction;
u_i = fluctuating velocity in i-direction;
u, v, w = turbulent fluctuating velocities in {x, y, z} direction;
Vs = cross-sectional velocity;
Z_p = distance from measurement point to bed surface;
ν = kinematic viscosity;
ρ = flow density;
σ_i = turbulence intensity in i-direction;
τ_{yx} = Reynolds shear stress in x-direction on plane perpendicular to y- direction;
τ_{zx} = Reynolds shear stress in x-direction on plane perpendicular to z- direction.

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