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A COMPARISON STUDY OF FLOW FIELDS AT OPEN CHANNEL JUNCTION

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ABSTRACT

The present study focuses on comparison of the flow fields around the open channel junction region. In the vicinity the junction the velocity distribution along the channel cross-section changes sharply with discharge ratio in vertical direction towards the free surface. The magnitude of the bed shear stress varies in both the longitudinal and lateral direction of the flow and increases with a reduction in discharge ratio near the junction. Higher energy losses are exhibited in the compound channel in the near field when compared to a simple channel. Turbulence quantities associated with the shear layer is more predominant at the near field than far end of the channel. Reynolds shear stress component in a compound channel is found to be higher at the mixing region than that of simple channel. Results show that the strength of the time-averaged flow structures in a compound channel is higher than that of simple channel over a range of discharge ratios. The flow field in a compound channel junction is seen to be moderately different from that of simple channel junction. Overall, flow in a compound channel junction behaves similar to simple channel geometry except for small quantitative differences arising from a higher turbulence production.

1. INTRODUCTION

Flow in an open channel confluence has attracted increasing attention over the past few years in environmental and river engineering. The study of open channel confluences has a direct application in the design of networks in irrigation and drainage system. Many problems in water resources, river mechanics, and environmental hydraulics require description of the characteristic parameters of the flow regime in these open-channel networks. In real life applications, junction flows in compound channels are complicated for two reasons: first the effect of streamline curvature, and second, three dimensional effects arising from the orientation of the flow in the floodplains relative to that in the main channel. Recent work has focused on flow dynamics, turbulence characteristics and sediment transport patterns and their impact on hydraulic structures downstream of confluence in a simple channel. General conclusions regarding the change in water surface elevation, mean velocity profile

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and the turbulence phenomena near the confluence have been drawn. To the author's knowledge, limited research has been carried out on this important aspect of flow at the channel junction. The literature pertaining to these topics is reviewed in the following sections. To illustrate the application of junction flow in river engineering, an extensive number of experimental, analytical and numerical studies in combining open channel have been conducted.

Weber et al. (2001) provided important experimental data for junction flow. Three dimensional velocity and turbulence measurements were recorded by an acoustic Doppler velocimeter (ADV) in a horizontal fixed bed laboratory flume with 90^{o} junction and channel width of 0.91 m. The presence of one large helical cell, instead of two was reported. Weber et al. (2001) pointed out that the flow pattern near the bed and near the surface were very different. Simplified theoretical or numerical models were less capable of dealing with complex flow conditions such as secondary flow and separation. Huang et al. (2002) developed a 3D turbulence model to simulate 90° open-channel junction flows by using the test data of Weber et al. (2001). The effect of the junction angle on the flow characteristics was investigated. It was found that the 3D model was capable of reproducing important hydrodynamic characteristics of the junction flow, and the agreement with experimental data was favorable. Secondary flow existed for most flow fields and the strength of the secondary flow increased with the junction angle. Shabayek et al. (2002) derived a nonlinear model based on the theory that involved almost all the physical effects. The model is based on the momentum principle together with mass continuity for solving the conservation equations through the channel junction. Rhoads and Sukhodolov (2004) examined the spatial and temporal characteristics of turbulence structures within a shear layer at a stream confluence. Three-dimensional velocity measurements were recorded using two acoustic Doppler velocimeters spaced at various separation distances. The spatial-temporal pattern of maximum correlation was seen to reflect the extent to which discrete eddies maintain similarity along the shear layer. Kesserwani et al. (2008) described practical aspects of several combining flow models within the internal boundary of a junction. Attention was on the effect of steady and transient flows, high and low subcritical Froude number at the junction. Zhang et al. (2009) developed a 3D numerical model to investigate flow at a 90° open-channel junction. The results were validated using experimental data of Weber et al. (2001). The effect of discharge ratio on the flow characteristics was investigated for estimating the parameters needed in engineering applications. A comparison between the one-dimensional and two-dimensional numerical simulations of subcritical flow in open-channel networks was presented by Ghostine et al. (2010). Goudarzizadeh et al. (2010) analytically investigated the 3D flow pattern at a right angle confluence of two rectangular channels using Navier-Stokes equations based on Reynolds Stress Turbulence Model (RSM). The Shumate experimental finding (2001) were used to test the validity of data. Comparison of the simulation with experiments indicated a close agreement between the flow patterns of the two sets. Goudarzizadeh et al. (2011) investigated the effect of discharge ratio Q_r (ratio of side-channel to total discharge) and width ratio B_r (ratio of the side-channel to main-channel width) on the bed shear stress. Results indicated that the dimensions of the separation zone increased with the discharge ratio.

From the review of literature, it is clear that comprehensive data on flow in a simple channel junction are available. It is seen that the analysis of flow at a compound open channel junction has not been considered in the recent years. Such a study is important in the context of junction flow properties and related applications. Thus, there is a need to explore measurements in a physical model that can predict the flow features in a compound channel junction. To contribute to the present state of knowledge and understand the hydrodynamic flow features at the junction region, an experimental study on a laboratory model has been conducted under subcritical flow conditions. Results of the both channels around the channel junction are compared.

2. EXPERIMENTAL SETUP

The physical model is made of brick masonry and is used to generate subcritical flow under controlled condition over a smooth horizontal rigid bed. The combining compound channel consists of the main channel, tributary and floodplain, while the combining simple channel comprises of the main and lateral channels. The lengths of the main channel are 14.6 m and the lengths of the tributary and lateral channel are 3.75m, and 3.45m respectively. The width of the compound channel and simple channel are 0.20m, and 0.80m respectively. The bankfull height and each floodplain are 0.10m and 0.30m respectively. Water is discharged from two independent upstream constant head tanks which are controlled by valves in the pumping circuit. The flow depth at the outlet is controlled by an adjustable tailgate. The incoming flows are nearly uniform in the upstream portion of the approaching channel and mix at the channel junction. The experimental facility permits the measurement of flow velocity. Instantaneous velocities are measured by an acoustic Doppler velocimeter (ADV). The average velocity and turbulence quantities are calculated from the time series of velocities recorded at each location. The original ADV data are filtered in WinADV software to detect and remove spikes. In order to obtain the velocity distribution in each channel, the cross section is divided into five evenly spaced vertical profiles on main channel and nine evenly spaced vertical profiles on each floodplain. The locations of all velocity measurements are illustrated in Figure 1.

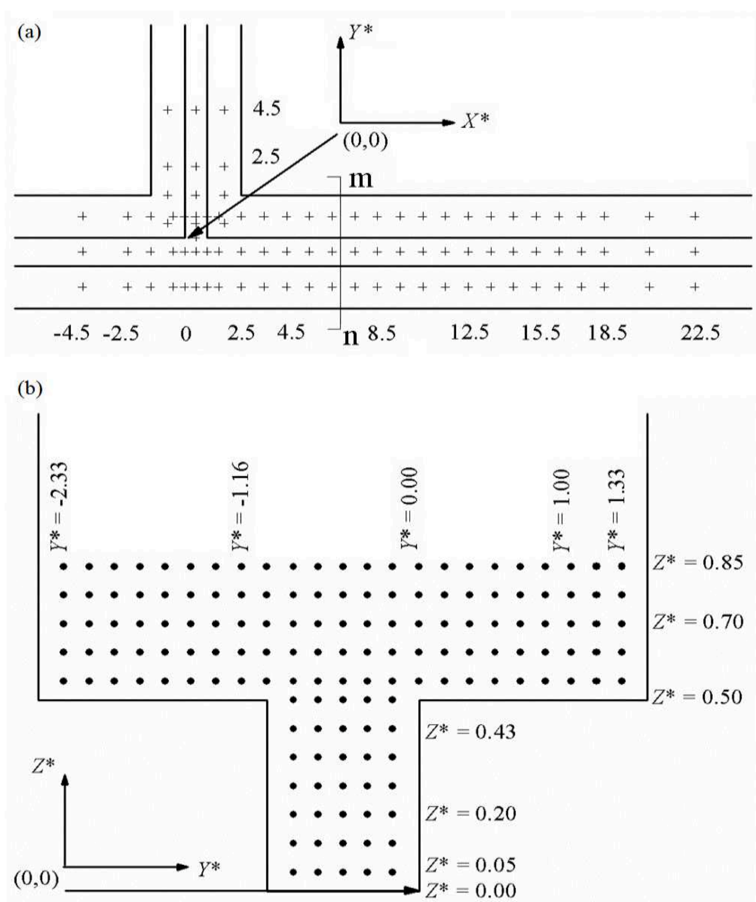

Figure 1 (a) Top view of the channel where locations of velocity measurements are shown by the + sign. Point O is the origin of the coordinate system. (b) Points of velocity measurement at section m-n of the combining compound open channel.

Vertical velocity profiles are taken 0.01m above the bed of the main channel and floodplains at 0.015m depth interval throughout the section. Velocity measurements upstream and far downstream from the junction are taken for 90s at a sampling rate of 50 Hz. However, for the flow data recorded near the junction region, the effect of combining flow is predominant and a sampling rate of 50 Hz is used for duration of 180s. The origin of the coordinate system is the bed at the upstream corner of the channel junction (Figure 1). The nondimensionalized coordinates X^*, Y^* and Z^* are X/B, Y/B and Z/B, respectively. Here, B is the bottom width of the tributary and main channel. The grid has 4,650 velocity measurement locations for each flow condition studied. In this experiment, the total combined flow Q_d = 0.016 m^3/s and flow depth h_d = 0.22 m are held constant. The hydraulic model is of equal width where a range of parameters such as Froude number (F = 0.12), Reynolds number (Re = 16108) and discharge ratios are possible. All experiments are conducted several times to ensure the repeatability of the flow measurements for the parameter range of interest. Careful measurements have been performed to reduce the errors involved in the experiments. The details of the experimental conditions and the ranges used for each relevant parameter are presented in Table 1

Table 1 Experimental parameters considered in the subcritical flow observation.

Open channel	Runs	Q_m (m^3s^{-1})	Q_l (m^3s^{-1})	Q_d (m^3s^{-1})	Q_r = (Q_m/Q_d)	h_d (m)	U_d (ms^{-1})
	1	0.004	0.012	0.016	0.250		
	2	0.008	0.008	0.016	0.500		
Compound	3	0.012	0.004	0.016	0.750	0.22	0.138
	1	0.004	0.012	0.016	0.250		
Simple	2	0.008	0.008	0.016	0.500	0.22	0.102

3. RESULTS AND DISCUSSION

3.1 Velocity distribution

Figure 2 shows the time-averaged velocity distribution on two planes, near the bed and one close to the free surface at a streamwise location of X^* = 4.5. These plots are shown as a function of the spanwise coordinate Y^*. Velocity is a maximum in the outer and is minimum in the inner portion of the main channel. Velocities closer to the surface are marginally higher than those below. Flow distribution downstream of the junction behaves like a simple rectangular channel without the presence of reverse flow. Figure 2b shows that the variation of velocity near the free surface in compound channel are slightly higher than a simple channel (Fig. 2a) for a discharge ratio of Q_r = 0.25. Velocity is a maximum in the outer bank of the main channel where a contraction region forms and is a minimum in the inner bank where a recirculation zone is formed. Velocities closer to the surface are marginally higher than those below.

[a]

[b]

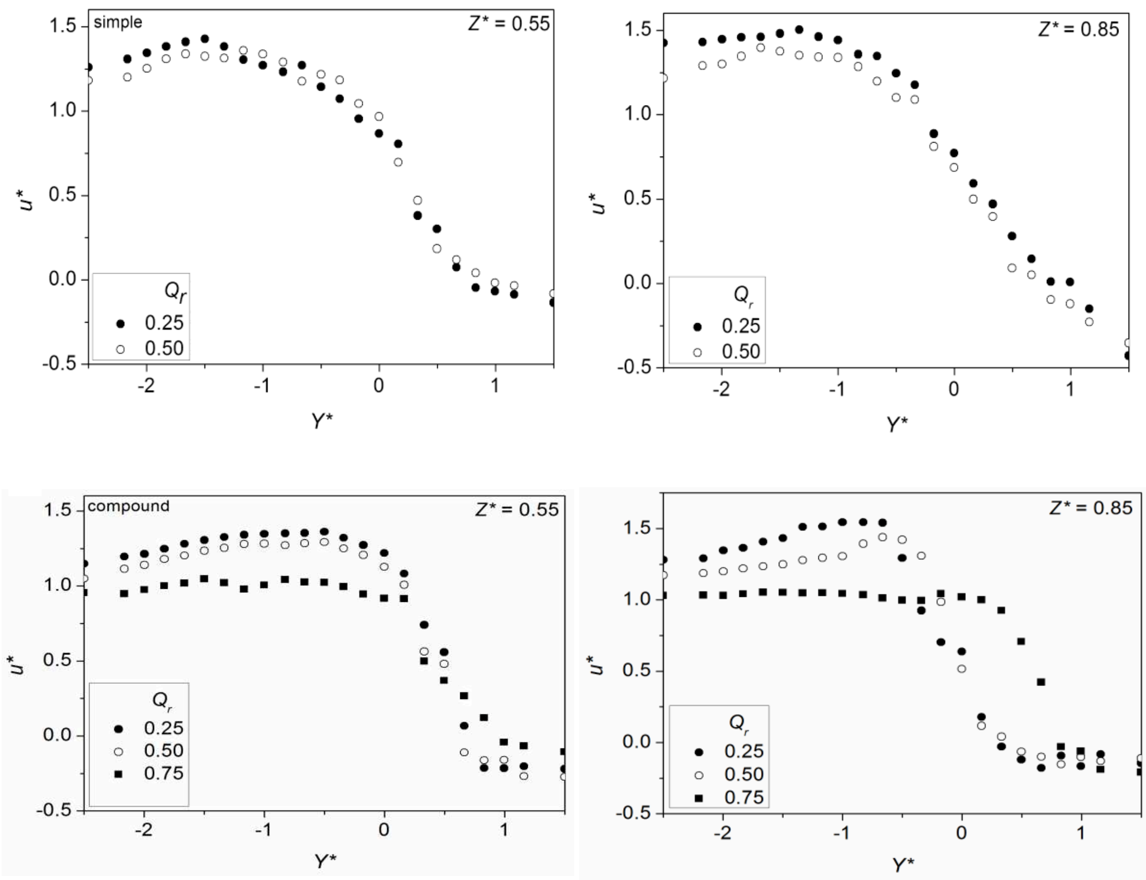

Figure 2 Time-averaged velocity distribution closer to the bed (Z^* = 0.55) and near the free surface (Z^* = 0.85) in a (a) simple (b) compound open channel junctions as a function of the spanwise coordinate Y^* at a stream wise location of X^* = 4.5

3.2 Bed shear Stress

Bed shear velocity is determined by fitting the near bed velocity profile to the logarithmic law applicable for turbulent velocity profiles in channel flow experiments (Nezu and Nakagawa, 1993). The friction velocity U_s is determined from the fully developed turbulent distribution of the velocity normal to the free surface, and is expressed as (Schlichting 1979):

Smooth surface

$$\frac{u}{U_s} = \frac{1}{\chi}\ln\left(\frac{Z_p U_s}{\upsilon}\right) + A, \qquad \frac{\varepsilon_S U_S}{\upsilon} \leq 5 \tag{1}$$

Here u = measured streamwise velocity; U_s = local friction velocity; χ = von Karman's constant; Z_p = distance from measurement point to the bed; and A_S = model constant (5.1 ~ 5.5) for smooth surface. The value of χ = 0.41 is universally applicable. Friction velocity U_s is derived from measurements (Z_p, u) from Equation 1. The relationship between shear velocitiy U_s and bed shear stress in dimensional form is given as

$$\tau_b = \rho U_s^2 \tag{2}$$

Here ρ = density of water. It is noted that channel slope is not provided in the present study and aspect ratio $\left(\frac{B}{H}\right)$ is constant. The variation of non-dimensional bed shear stress is plotted in Fig. 3 for two discharge ratios Q_r = 0.25 and 0.50 in a simple and compound channel junctions. It is normalized by the average of the square of shear velocity at the bed. Bed stress is evaluated using the Equation 1 at a height of 0.01 m above the base along the main channel at a location of Y^* = -0.5. The channel slope S_b = 0, and bed stress is calculated for constant relative depth h_r. It is clear from Figure 3 that bed stress increases with a reduction in discharge ratio near the junction. It attains a peak near the junction and falls gradually as one goes away from the junction along the tailwater channel. The peak coincides with the location of the maximum turbulent kinetic energy near the junction. Secondary flows have large effect on the boundary shear stress distribution in the near field. At the far end of the channel, bed shear stress is a function of Reynolds number and behaves like flow in a straight channel. Incoming flows from two different channels mix together and are deflected at the junction towards the tail water channel. This flow is accelerated over the entire contracted region and is turned gradually towards the inner region beyond the reattachment.

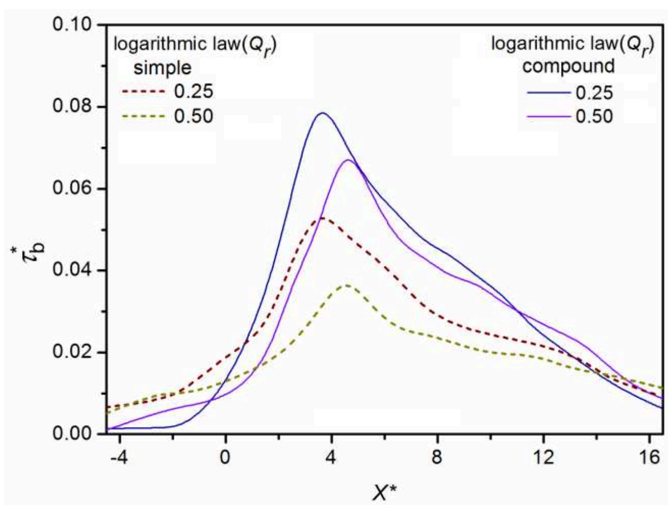

Figure 3 **V**ariation of dimensionless bed shear stress distribution with the streamwise coordinate for discharge ratios (Q_r = 0.25, and 0.50) at the center of the open channel junction.

3.3 Reynolds shear Stress

Reynolds stress components are calculated as

$$\tau_{ij} = -\rho \overline{u_i' v_j'} \tag{3}$$

Where u_1, u_2, and u_3 represent u, v and w in the laboratory frame of reference (X, Y, Z). Figure 4 shows the non-dimensional distribution of Reynolds stress and are normalized by square of the averaged velocity U_d^2 based on the total discharge. Reynolds shear stresses are generally related to gradients of the base flow and depend on transport of the turbulence fluctuations from the entire flow field. The time-averaged velocity gradient is responsible for generating turbulent shear stresses in the channel. Hence, the shear layer is a site for turbulence production but the distribution of Reynolds stresses becomes particularly complex due to effect of secondary currents. Secondary flows are dominant in the near field region due to larger influence of streamline curvature. The turbulence levels are large near the junction region and gradually fall towards tailwater regions. The formation of contraction and separation zones near the junction affects the distribution of Reynolds stresses. Here, two runs are chosen to illustrate the difference of the Reynolds stress distribution.

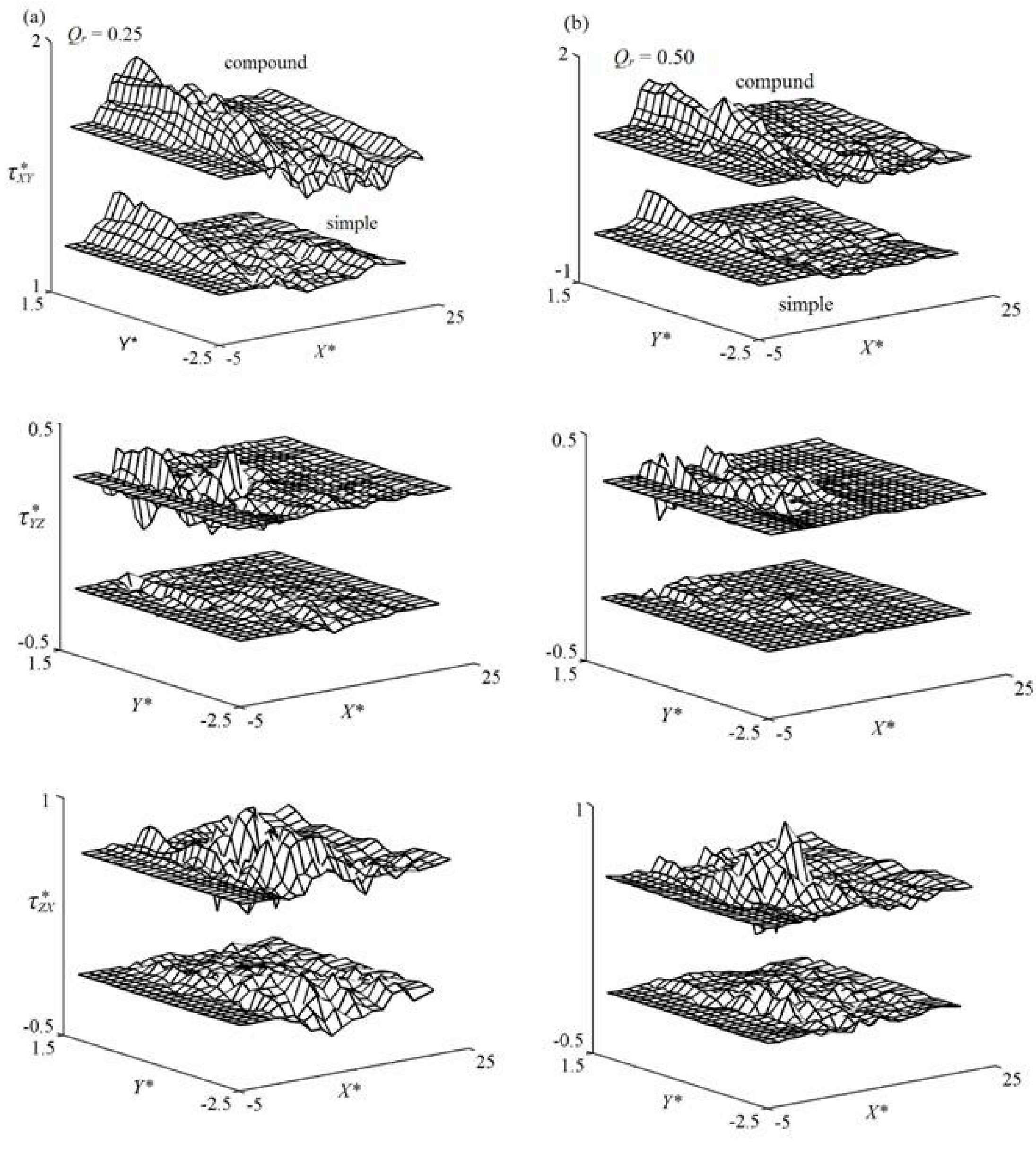

Figure 4 Distribution of the dimensionless turbulent shear stresses for two flow conditions (Q_r = 0.25-1st column and 0.50- 2nd column) in open channel junction near the water surface. The main flow direction is *X**, while the branch flow is oriented in the negative *Y** direction. The centrelines of the two channels meet at *X** = 0.5 and *Y** = -0.5.

It is noticeable that with the increase of the discharge ratio, the Reynolds stresses show a decrease. Velocity fluctuations and turbulent shear have a complex distribution at the near field region compared to the far end of the tailwater channel. The vertical gradients of $\tau_{ZX} = -\overline{w'u'}$ vary a great deal in the junction region and gradually level off at the far end of the channel. The distribution of $(-\overline{w'u'})$ in the shear layer describes the intensity of vertical mixing between two merging streams near the downstream of the junction. The characteristic feature here is the drastic change in the values near the junction, having a maximum in the shear layer formed near the junction. Values of Reynolds stresses on the cross-sections of the channel are found to depend on location, fluid density, and flow rate. As the flow is almost uniform and strength of secondary currents is negligible at the far end, the flow behaves more like one in a simple rectangular channel. The results show that the absolute values of two components of Reynolds stress τ^*_{YZ} and τ^*_{ZX} are small compared to $\tau^*_{XY} = -\overline{u'v'}$. Both longitudinal and vertical turbulent shear stresses within the mixing region of compound channel junction are generally greater than those observed for a simple junction.

4. CONCLUSIONS

This work presents ADV measurements of turbulence flow over a smooth bed in a compound channel junction. The experimental data obtained for a compound channel are compared to the simple channel for a range of discharge ratios. The main findings obtained in the present experimental study are as follows:

1. The flow velocity decreases with increase in discharge ratio in vertical direction towards the free surface.
2. Turbulence quantities associated with the shear layer is more predominant near the junction than far end of the channel. The distribution of turbulence shear depends on the strength of secondary flow which becomes stronger at lower discharge ratios.
3. The magnitude of the bed shear stress increases with a reduction in discharge ratio near the junction. Higher energy losses are exhibited in the compound channel in the near field when compared to a simple channel.
4. Reynolds shear stress component in a compound channel is found to be higher at the mixing region than that of simple channel.

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