Flood plain contribution to open channel flow structure

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Abstract Enhanced understanding of the role of flood plains in dictating open-channel flow is essential for environmental and ecological management of fluvial systems. This paper presents the field measurements and primary analysis of flood flow across a compound channel in the River Severn, England. A three-dimensional acoustic Doppler velocimeter in combination with a directional current meter is deployed to measure the velocity. The statistical flow structure is compared with existing analytical formulations derived for single channel flows. The existence of a vertically double-layer structure around the interface between the main channel and the flood plain is demonstrated, indicating (a) a vertical shear-dominated flow zone near the bed; and (b) away from the bed a transverse shear-dominated flow zone with enhanced turbulent mixing. This feature necessitates concurrent consideration of both the transverse and the vertical resolution in mathematical modelling. The measured data can be utilized to assess the performance of mathematical river models.

Key words fluvial system; flood plain; compound channel; turbulence; acoustic Doppler velocimeter (ADV); field measurement; open-channel flow; fluvial hydraulics; fluvial hydrology

INTRODUCTION

The turbulence characteristics in compound channels are of increasing interest to river scientists and engineers as they control flood conveyance, sediment movement, river morphological development as well as pollutant mixing and transport. Current understanding of compound channel turbulence is far from complete. Previous studies of compound channel flows have been largely limited to laboratory-scale experiments (Shiono & Knight, 1991; Shiono & Muto, 1998) and numerical simulation (Sofialidis & Prinos, 1999). In practice, river engineers are still reliant upon traditional one-dimensional (1-D) and depth-averaged two-dimensional (2-D) hydraulics approach to estimate the channel discharge capacity (Ervine *et al.*, 2000). One of the basic impediments to enhancing the understanding of compound channel flows is the lack of systematic detailed measured data at the field scale. Existing field measurement studies are limited to single channel weakly three-dimensional (3-D) flows (Nikora & Smart, 1997; Sukhodolov *et al.*, 1998).

This paper presents the 3-D ADV (acoustic Doppler velocimeter) and DCM (directional current meter) measurements and a basic analysis of the turbulent flow in the near-bank region of a natural compound river channel (River Severn, England).

The field measurements are first described, and then the mean flow and turbulence characteristics are analysed in comparison with existing formulations derived for single channel flows.

FIELD MEASUREMENT

The field measurements were carried out in the River Severn, England, during periods of overbank flow (1999–2001). The monitored reach consists of a roughly straight and deep channel downstream of a double-meandering channel bend. The true left bank of the river is a river terrace some 1 m higher than the surface on the right bank. The right bank surface is an active flood plain, the width of which is restricted by an artificial embankment. Whilst the terrace is rarely flooded, the active flood plain on the right bank is inundated by discharges in excess of approximately 100 $m^3 s^{-1}$. The main channel has a gravel bed whilst the steep river banks are predominately grass-covered gravels and silts. The flood plain surface consists of closely grazed pasture. Because the change in the flow conditions could not be controlled, the flow was strictly-speaking unsteady. Nevertheless, the data collected correspond to specific periods of time, in which the flow can be considered as quasi steady. The data presented and analysed in

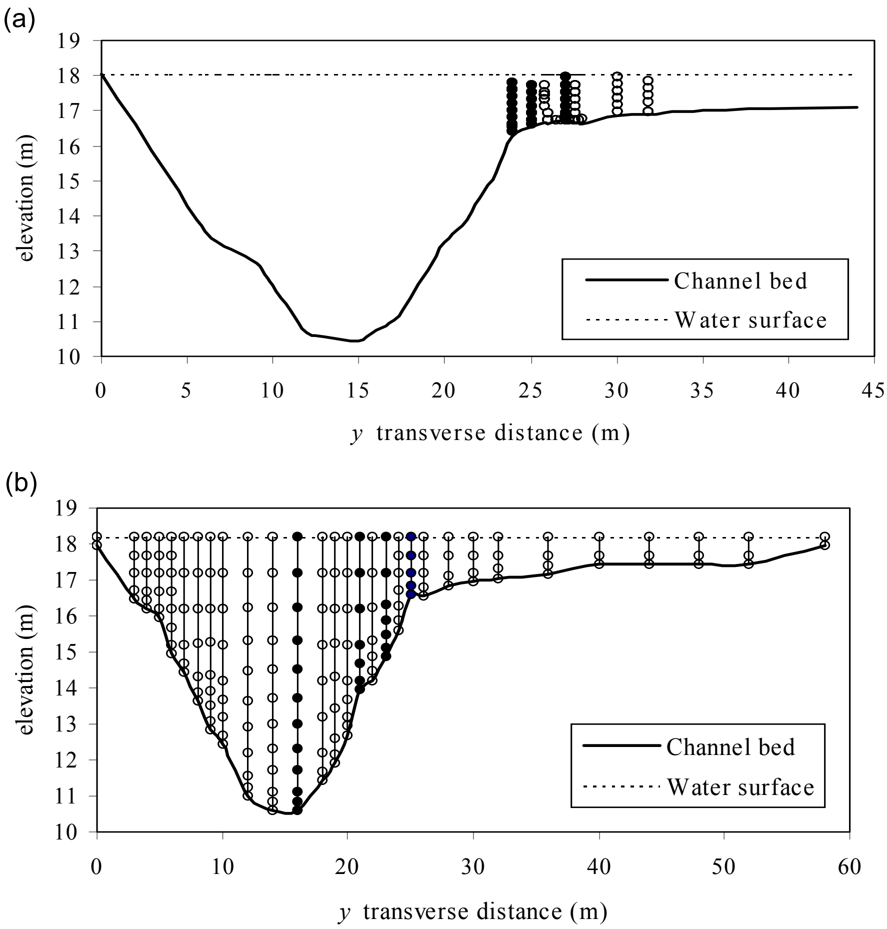

Fig. 1 (a) ADV probe locations; and (b) DCM probe locations. The solid symbols denote that the measured data are shown in the following figures.

the following are of this type. Recognizing the asynchronous nature of the measurements is vital for understanding the evident scatter of data points, as shown later.

The 3-D turbulence was measured using a 3-D ADV system (SonTek). Pseudo-synoptic velocity profiles were obtained in the vertical by raising the ADV sequentially. The ADV was mounted on a rigid steel scaffolding pole set within a guide rail on a specially constructed scaffold platform. Extending about 7.8 m onto the flood plain and also cantilevered out above the bankline, the platform allowed sampling on the flood plain and in the near-bank region of the channel (Fig. 1(a)). The sampling rate was 25 Hz, and the typical ADV sampling time period was 200 s. The ADV data were processed using the WinADV software, developed at the Water Resources Research Laboratory, US Bureau of Reclamation. Water depths of around 8 m in the main channel precluded deployment of the ADV in a controlled frame of spatial reference. Consequently velocity profiles were measured every 2 m across the full cross-section (Fig. 1(b)) using a DCM deployed from a boat. The position in the section was determined from metre markers on a taut rope stretched across the section and up to 12 readings were obtained in the vertical with more closely-spacing readings taken near the bed. Both streamwise and transverse mean velocity components were recorded. Note that the ADV and DCM cross-sections are slightly different.

MEAN FLOW

To expedite the description, it is necessary to define the coordinate system and notations. The streamwise direction x is defined as perpendicular to the cross-section, the transverse direction y as within the cross-section and being positive from the left towards the right bank (Fig. 1), and the vertical direction z being the distance from the bed, perpendicular to the xy plane and positive upwards. The corresponding mean velocity components are respectively denoted by U, V, W, and the fluctuating velocity components by u, v, w. For simplicity, the turbulent correlations between fluctuation velocity components are denoted by for example uw and uv with the commonly used overbar being eliminated. For convenient use of the data in potential mathematical river modelling, the data presented in the following are, where applicable, not non-dimensionalized.

Figures 2 and 3 show the measured mean velocities on selected verticals respectively from both ADV and DCM. The 3-D nature of the flow can be seen from the ADV profiles due to the non-zero transverse and vertical velocities. Also included in Figs 2 and 3 are the streamwise mean velocity profiles (solid lines) computed with the conventional log-wake formula for single channel flows, i.e.

$$\frac{U}{U_*} = \frac{1}{\kappa}\ln\frac{z}{z_0} + \frac{2\Pi}{\kappa}\sin^2\left(\frac{\pi z}{2h}\right) \tag{1}$$

where U_* = bed shear velocity; z_0 = hydrodynamic roughness; h = local flow depth; $\Pi = 0.2$, the wake strength parameter presumed herein because the Reynolds number $R_e = U_m h/\nu \propto 10^6$ (U_m = depth-averaged mean velocity, ν = kinematic viscosity of water, see Nezu & Nakagawa, 1993); and $\kappa = 0.41$, von Karman coefficient. For ADV data, the bed shear velocity in equation (1) is evaluated from the shear stress ($-uw$)

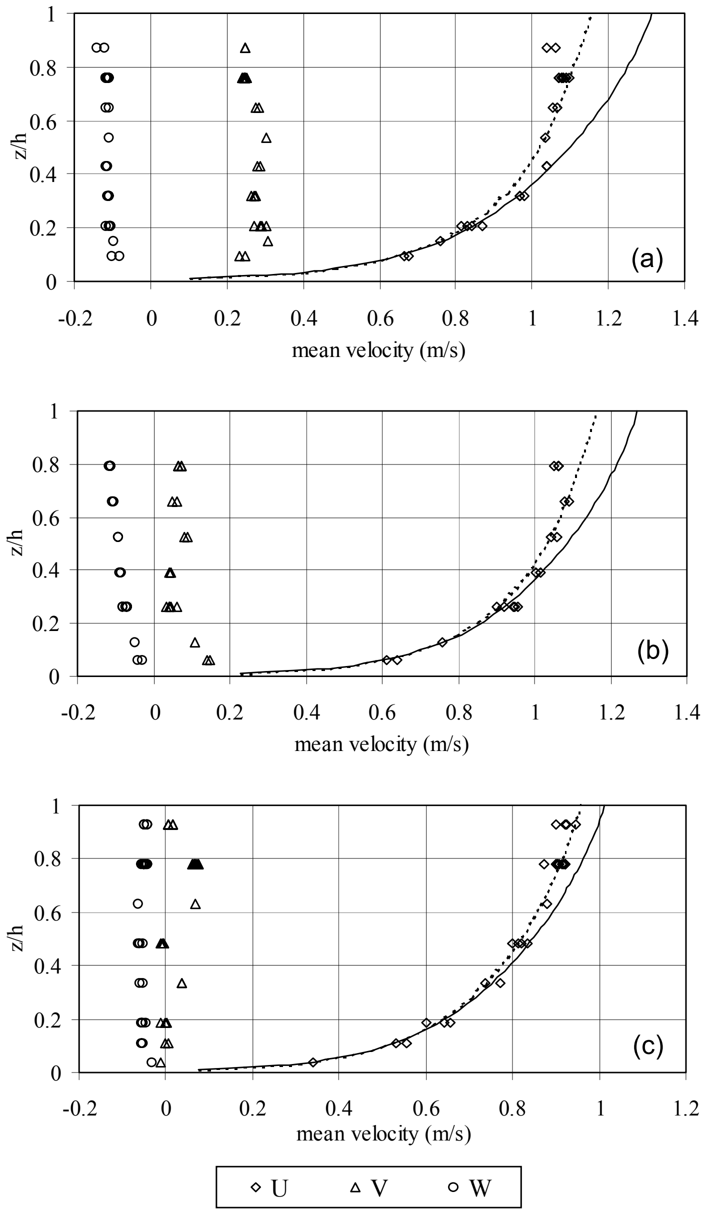

Fig. 2 ADV (symbols) and computed (lines) mean velocities. (a) $y = 23.95$ (m); (b) $y = 25.0$ (m); and (c) $y = 27.0$ (m). The solid lines correspond to $\Pi \equiv 0.2$, and for dashed lines Π is given in Table 1.

distribution near the bed (in the present case, within $z/h \leq 0.4$), as shown later in Fig. 5. Then the hydrodynamic roughness is estimated, using the method of least squares, by fitting equation (1) to the measured velocity profiles within approximately $z/h \leq 0.4$. For the DCM data, the turbulent Reynolds shear stresses are not available. Consequently both the bed shear velocity and hydrodynamic roughness are estimated using the method of least squares applied to velocity data points within the lower part of the flow depth. The flow depths, the values of bed shear velocity and hydrodynamic roughness values are listed in Table 1.

It is found in Figs 2 and 3 that, near the bed, there exists a log velocity zone in both the main channel and the flood plain, as is the case in single channel flows (the

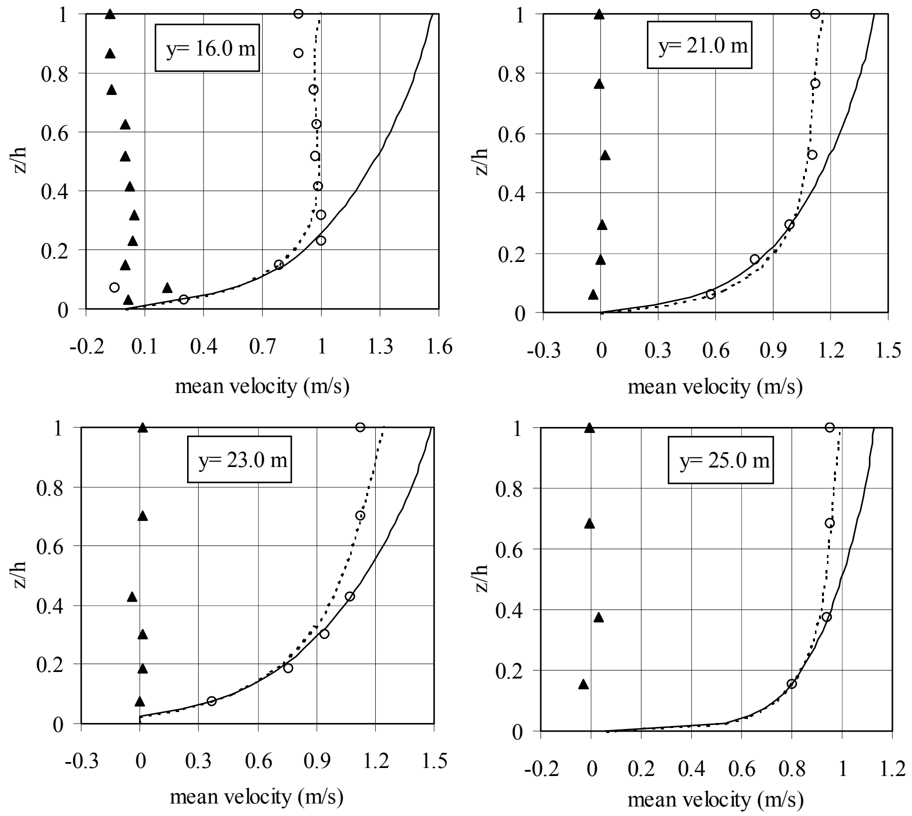

Fig. 3 DCM (symbols) and computed (lines) mean velocities on selected verticals. The solid lines correspond to $\Pi \equiv 0.2$, and for dashed lines Π is given in Table 1.

wake component is negligible near the bed). This result is related to the linear distribution of the Reynolds shear stress (–*uw*, Fig. 5) near the bed. Approaching the flood plain, the log velocity zone extends gradually towards the water surface (where the wake component becomes appreciable), as shown in Fig. 2. Within the main channel, the streamwise velocity near the free surface deviates considerably from the log-wake law, resulting from the strong transverse momentum exchange. Specifically, the transverse momentum exchange serves to slow down the water flow near the free surface so that the streamwise velocity is lower than what would otherwise be anticipated in single channel flows. This phenomenon has been found to exist close to

Table 1 Parameters for streamwise mean velocity profiles under log-wake law.

Location of verticals: Source	y (m)	Bed shear velocity U_* (cm s^{-1})	Hydrodynamic roughness z_0 (cm)	Flow depth h (m)	Wake strength parameter Π
ADV	23.95	9.93	1.18	1.8 ± 0.04	–0.13
	25.0	8.56	0.51	1.5 ± 0.09	–0.06
	27.0	7.68	0.90	1.35 ± 0.03	0.05
DCM	16.0	13.6	10.1	7.62	–0.67
	21.0	11.7	4.20	4.25	–0.40
	23.0	15.4	9.55	3.32	–0.13
	25.0	6.03	0.11	1.60	–0.30
	28.0	2.56	0.001	1.35	0.00

channel banks in single channel flows (Nezu & Nakagawa, 1993). The effect of hindered streamwise flow near the free surface must not be ignored. It is this retardation that gives rise to increased flow shearing near the bed, which subsequently results in the large values of hydrodynamic roughness z_0 in, and close to, the main channel (Table 1). Such large values of hydrodynamic roughness are not commonly seen in single natural channel flows (Nikora & Smart, 1997; Sukhodolov *et al.*, 1998).

As far as the isovels of the streamwise velocity are concerned (Fig. 4), the overall flow pattern is more complicated than that seen in laboratory symmetrical compound channels. Specifically, the flow pattern in the left-hand side of the cross-section (y < 16.0 m) is qualitatively similar to what would be seen close to a side bank in a single channel (Nezu & Nakagawa, 1993). The hindered velocity near the free surface immediately to the left of the cross-section centre (say, 8.0 < y < 16.0 m) is typical of straight prismatic channels of small aspect ratio (Flintham & Carling, 1988) without flood plains. This effect is also seen elsewhere in the River Severn during high flows (Carling, 1991; Beven & Carling, 1992). Nevertheless because of the asymmetrical geometry of the cross-section, the flow pattern in the right-hand side is quite different. The existence of the flood plain provides the space required for the flow to develop. The flow is clearly biased to the right, with the maximum velocity (flow core) being in the immediate vicinity of the interface between the main channel and the flood plain. More notably, the vertical variation of the flow structure is seen to be as substantial as

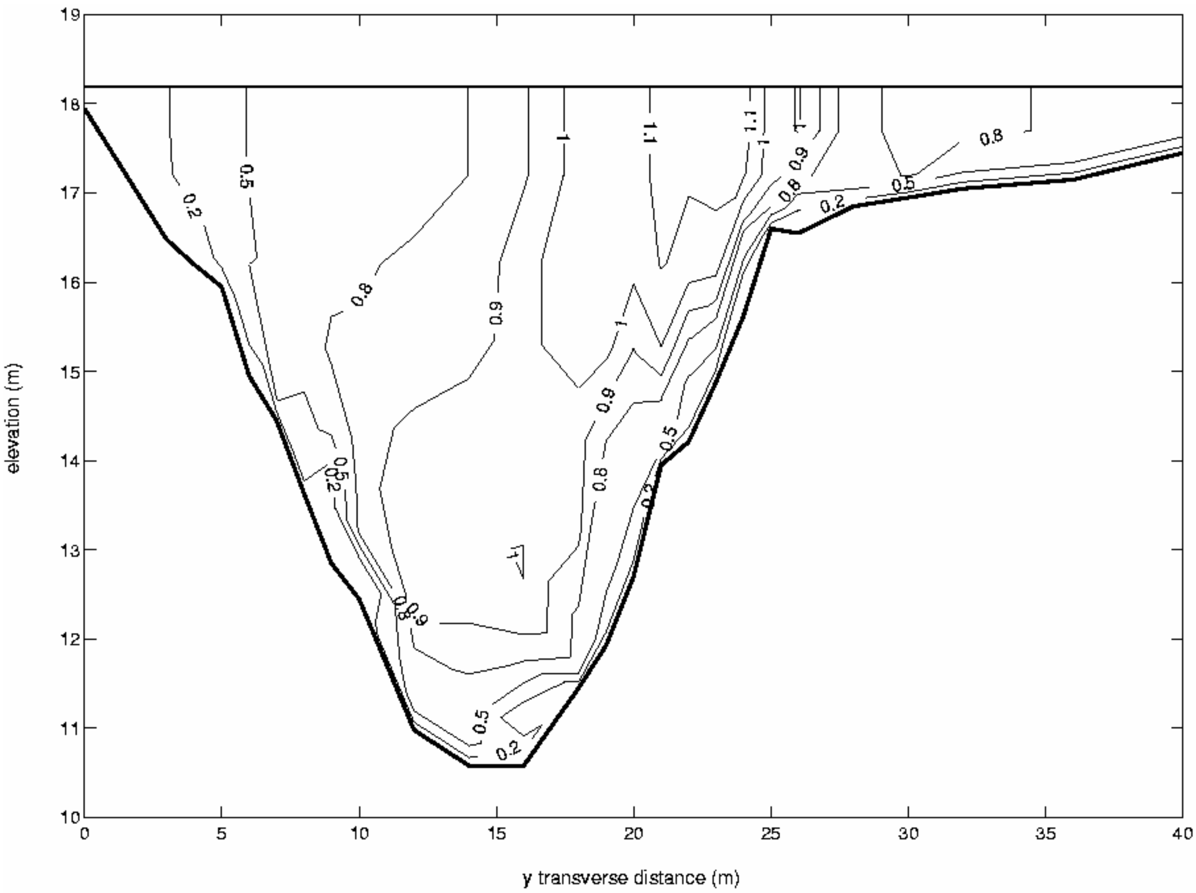

Fig. 4 Isovels of DCM streamwise velocity (m s^{-1}).

the transverse change. By this factor it is characterized that both the vertical and transverse resolution in model developments of compound channel flow requires close attention. Clearly the traditional 1-D model with a bulk roughness parameter (say the Manning roughness) is not fine enough for the complicated compound channel flow. This observation represents the most telling case for the need of more advanced modelling tools, which concurrently resolve the vertical and transverse structures.

A test of the applicability of the log-wake formula equation (1) to compound channel flows was made by tuning the wake strength parameter to get the optimal fit to the measured velocity in the sense of least squares. The tuned velocity profiles are also shown in Figs 2 and 3 (dashed lines). Qualitatively equation (1) can be fitted to the

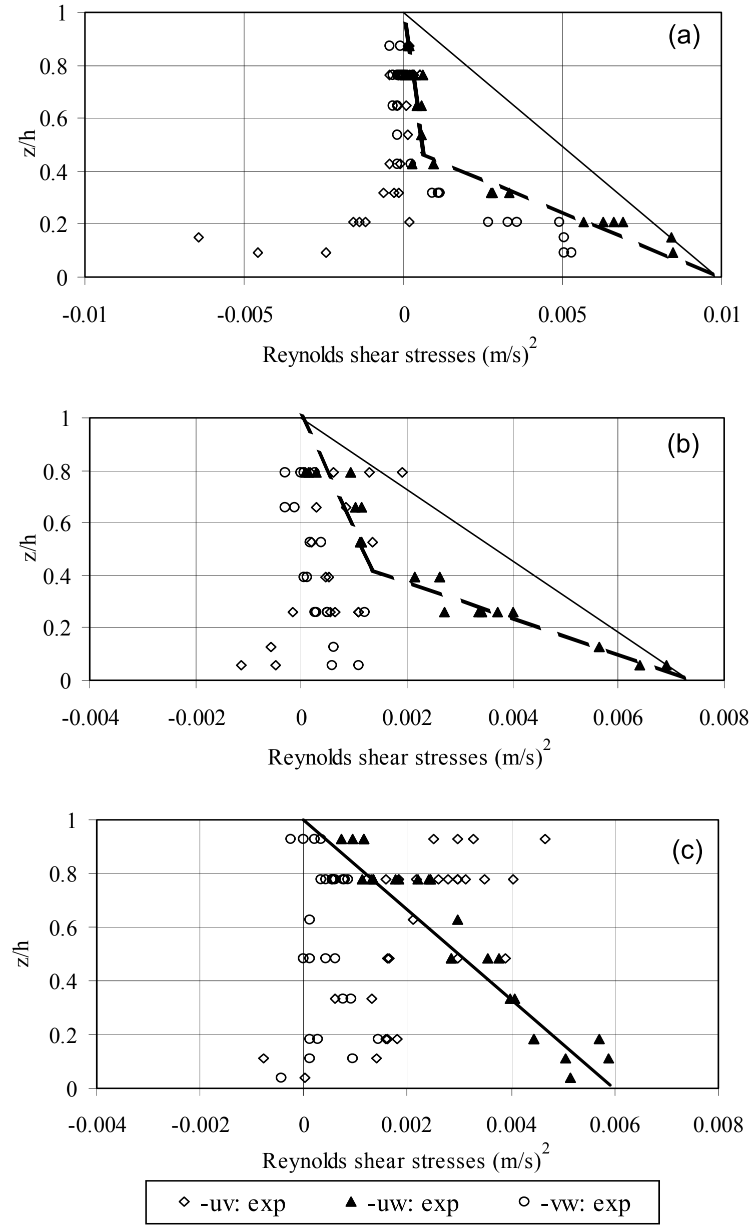

Fig. 5 Reynolds shear stress from ADV data. (a) y = 23.95 (m); (b) y = 25.0 (m); and (c) y = 27.0 (m). The dashed lines indicate the vertically double-layer flow structure, and the solid lines correspond to linear distributions valid for single channel flows.

measured velocities with reduced wake strength parameters (Table 1). However further work, using more measured data, is obviously required to determine an objective means of selecting the wake intensity parameter.

REYNOLDS SHEAR STRESS

Figure 5 shows the representative (ADV) Reynolds shear stresses for three verticals corresponding to the solid symbols in Fig. 1(a). Also shown is a linear profile (solid line) for $-uw$ based on the same bed shear velocity (Table 1), which is valid for straight single channel flow (Nezu & Nakagawa, 1993). It is seen from Fig. 5 that near the bed, $-uw$ follows approximately a linear profile as illustrated by the dashed lines (Fig. 5 (a) and (b)), which leads to a log velocity profile as shown in Figs 2 and 3. Physically this feature indicates the dominance of vertical flow shearing under the control of the wall, irrespective of the fact that the vertical gradient $|d(-uw)/dz|$ of the primary Reynolds shear stress $-uw$, is larger than that expected within a single channel flow as represented by the solid lines.

Echoing the mean velocity profiles shown in Figs 2 and 3, the shear stress near the free surface deviates substantially from the near-bed linear distribution. In particular, for verticals closer to the main channel (Fig. 5(a)), $-uw$ almost vanishes, which suggests considerably reduced vertical shearing and velocity gradient (Figs 2 and 3). The existence of the double-layer structure of the primary shear stress $-uw$ within the vertical is apparent. Away from the main channel and above the flood plain, this double-layer structure becomes less evident (Fig. 5(c)). Based on a comparison between the mean velocity profiles from ADV and DCM measurements (Figs 2 and 3), it can be inferred that the vertically double-layer structure will be more pronounced further approaching the main channel.

TURBULENT INTENSITIES

Figure 6 presents the turbulent intensities on three verticals corresponding to the solid symbols in Fig. 1(a). Turbulent energy is dependent on the three turbulent intensity components and thus not shown here. Existing formulations are limited to situations within single channels, which are derived on the basis of balance between turbulence production and dissipation. The following formulations (Nezu & Nakagawa, 1993) for 2-D steady and uniform open-channel flows are introduced to compare with the present ADV measurements,

$$\frac{u_{\mathrm{rms}}}{U_*} = D_{\mathrm{u}} \exp\left(\frac{-C_{\mathrm{k}} z}{h}\right) \tag{2a}$$

$$\frac{v_{\mathrm{rms}}}{U_*} = D_{\mathrm{v}} \exp\left(\frac{-C_{\mathrm{k}} z}{h}\right) \tag{2b}$$

$$\frac{w_{\mathrm{rms}}}{U_*} = D_{\mathrm{w}} \exp\left(\frac{-C_{\mathrm{k}} z}{h}\right) \tag{2c}$$

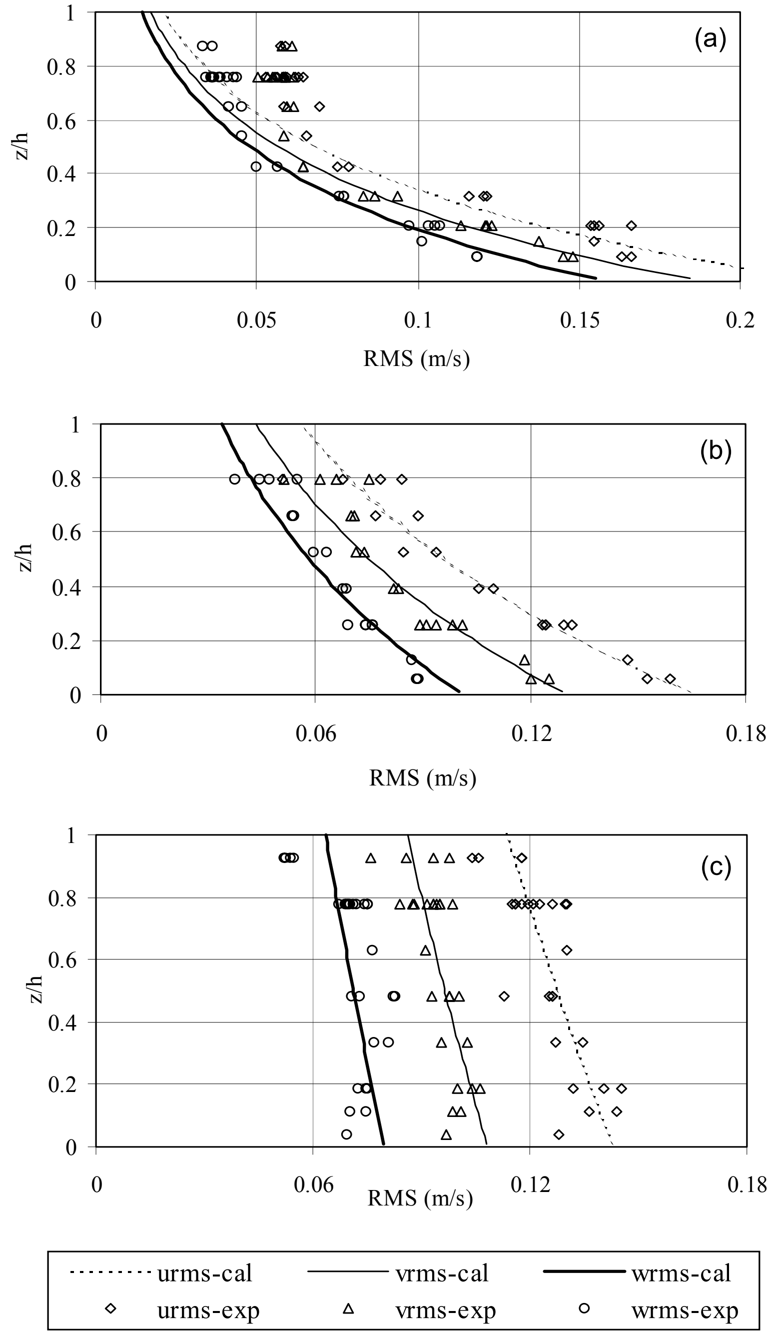

Fig. 6 Turbulent intensities from ADV data (symbols) and analytical formulations (lines). (a) $y = 23.95$ m; (b) $y = 25.0$ m; and (c) $y = 27.0$ m.

where D_u, D_v, D_w and C_k are empirical coefficients, and u_{rms}, v_{rms} and w_{rms} are respectively the root of mean square of the fluctuating velocity components u, v, w. For single channel flows, D_u, D_v, D_w and C_k are equal to 2.30, 1.63, 1.27, and 1.0 respectively (Nezu & Nakagawa, 1993). In the present case of compound channel flows, it is found that turbulent intensities can be represented reasonably well by equation (2) only with modified coefficients as listed in Table 2. These tuned coefficients are estimated by applying a least squares method to (2) using the ADV data within $z/h \leq 0.4$ in accord with the vertically double-layer structure demonstrated by the mean velocity and Reynolds shear stress (Figs 2 through 5). The use of modified coefficients in equation (2) has been reported by, for instance, Sukhodolov *et al.* (1998) for single natural channel flows. It is noted from Fig. 6(a) that on the measurement vertical closest to the main channel (y = 23.95 m), turbulent intensities and kinetic energy near the free surface are enhanced compared to those estimated by equation (2) with the modified coefficients for the near-bed fraction of flow ($z/h \leq 0.4$). This effect can be ascribed to the strong turbulent momentum exchange. Once again, this feature reveals the vertically double-layer structure for compound channel flows, although it becomes less pronounced approaching the flood plain (y = 25.0 m and 27.0 m in Fig. 6). Of further note are the values of C_k (C_k = 2.4 and 0.23 respectively for verticals at y = 23.95 m and 27.0 m, Table 2). These values are respectively larger, or smaller, than the value of unity applied to single channel flows (Nezu & Nakagawa, 1993; Sukhodolov *et al.*, 1998), which corresponds to a vertically suppressed (closest to the main channel and near the bed) or enhanced (on the flood plain) momentum exchange.

Table 2 Coefficients in equation (2) modified for ADV verticals.

Location of verticals y (m)	D_u	D_v	D_w	C_k
23.95	2.31	1.89	1.62	2.4
25.0	1.95	1.52	1.18	1.1
27.0	1.86	1.41	1.04	0.23

CONCLUSIONS

The ADV and DCM observations and basic features of flood flow across a natural compound channel are presented. A vertically double-layer structure around the main channel–flood plain interface is demonstrated. Near the channel bed, the wall-bounded vertical flow shearing dominates, whilst close to the free surface the transverse flow shearing dominates along with enhanced turbulent mixing. This double-layer structure results in large hydrodynamic roughness values that may not be commonly found in single channel flows. Existing formulations for single channel flows can be tuned to fit the measured mean velocity, turbulent intensities and kinetic energy profiles only within limited flow zones. The present finding necessitates more refined models for compound channel flows. In particular both the vertical and transverse structures merit concurrent resolution.

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