Visualization of Shear Layers in Compound Channel Flows

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Abstract This paper explains the process of visualizing shear layer formation by thermal video sequences captured at the interface between the main channel and the floodplain in a shallow flow compound channel. Hot water was added at the water surface using a small tube at ambient condition and at the interface between mainchannel and floodplain. A thermal camera (SC640) operating at 5Hz frequency and 640x480 pixels resolution was mounted vertically at 0.6m above a shallow flow compound channel at the interface between the main channel and the floodplain at a section where a fully developed flow had been achieved. This set-up enabled the capturing of the flow temperature differences at 5 locations longitudinally and at 3 locations transversely.

Flir's image processing software and Matlab were used to extract and analyse captured water surface temperature data. Image processing is done, first for five locations at the junction edge of the floodplain adjacent to the main channel with longitudinal overlaps between any two successive images, thus creating a part of the shear layer at the centre. The other five locations on either side of the centre were similarly carried with longitudinal overlaps to create the second and third parts of the shear layer. At the end three parts were creating that represent the entire shear layer. In order to visualize the final shear layer (from these three parts), a horizontal overlap was done for the left and the centre part firstly, and then overlap between the right and the centre parts was achieved secondly. The created shear layer image was then exported into Tec-plot software. The analysis showed that the shear layer at the interface between the main channel and the floodplain is well captured and quantified by this technique.

Keywords: Shear layer, Compound channel, Shallow flow, Image processing, Thermal technique

1 Introduction

Shallow flows are defined as open channel flows with transverse velocity gradient and is shallow because their mixing layer width larger than the water depth [1]. Shallow flow examples in nature are of different types such as lakes, bays, estuaries, lowland flows, and river confluences. Lowland rivers and their floodplain are examples of a compound channel quasi uniform flow which consists of main channel and one or two floodplains. Floodplains are usually rougher than main channels due to growing different types of vegetation in different alignment and configurations such as one line vegetation and wholly vegetated floodplain. When the flow exceeds the main channel, the faster flow in the main channel interacts with the slower flow velocity on the floodplain generates mixing shear layers (turbulent structures) near to the interface between the main channel and the floodplain which generates extra resistance. Mass and momentum transfer due to the velocity difference between the main channel and the floodplain(s). Shear layers were visualized experimentally by a number of authors using different techniques such as a dye tracer, Particle Image Velocimetry (PIV), Laser Doppler Anemometer (LDA) and numerically using such as large eddy simulations (LES). Sellin [2] injected aluminium powder on the water surface between the main channel and the floodplain in a straight compound channel flow. He visualized a strong vortex structure at the interface between the main channel and the floodplain. These vortices were recorded by a photography means. Pasche and Rouve [3] investigated experimentally the flow structures in compound channel flows with and without vegetated floodplain using Laser-Doppler Velocimetry (LDV) and Priston-tube techniques. They visualized the formation of eddies at the interface between the main channel and the floodplain. Tamai et al. [4] observed periodic large eddies (vortices) at the water surface at the interface between the main channel and the floodplain of a uniform compound channel flow using flow visualization method as hydrogen bubble method. These vortices generated by the local shear at the interface. Tominaga and Nezu [5] presented the interaction between the main-channel and floodplain flow in fully developed compound open channel flows using a fibre-optic laser Doppler anemometer. The contribution of secondary currents on momentum transport is very large near the junction, in which strong inclined secondary currents associated with a pair of longitudinal vortices on both sides of the inclined up-flow are generated from the junction edge toward the free surface. The effects of channel geometry and bed roughness on turbulent structure are examined. As the relative depth "which is defined as water depth on floodplain/ water depth in the main channel" decreases, strong vortices appear near the free surface of the floodplain, and the main channel

vortices expands in the span-wide direction. Nezu and Onitsuka [6] observed turbulent structures (vortices) generated at the edge of the vegetated channel flow located for half of the channel width using Laser Doppler Anemometer (LDA) and Particle Image Velocimetry (PIV). van Prooijen et al. [7] considered in their eddy viscosity model the transverse shear stress in mixing region responsible for momentum exchange between the main channel and the floodplain in a straight uniform compound channel flow. They assumed horizontal coherent structures movement dominate the mechanism for momentum exchange between the compound channel sections (the main channel and the floodplain) that results in lowering the total discharge capacity of the compound channel flow. Rummel et al. [8] emphasis experimentally on the shear layer forms at the water surface of a straight compound channel flow basing on PTV and PIV analysis of free surface velocities forms, especially on macro vortices and the horizontal flow mixing. White and Nepf [9] described the flow structures in a partially emergent vegetated single shallow open channel flow. They described the formation of shear layer with regular periodic oscillations vortex structures at the edge of the vegetation-main channel. The shear layer is asymmetric about the vegetation interface and has a two-layer structure. An inner region of maximum shear near the interface contains a velocity inflection point and establishes the penetration of momentum into the vegetation. An outer region, resembling a boundary layer, forms in the main channel, and establishes the scale of the vortices. The vortex structure shows strong cross flows with sweeps from the main channel and ejections from the emergent vegetation, which create significant momentum and mass fluxes across the interface. The sweeps maintain the coherent structures by enhancing shear and energy production at the interface. Nezu and Sanjou [10] investigated turbulence structures and coherent large-scale eddies in the vegetated canopy open channel flows based on LDA and PIV measurements. Coherent eddies such as sweeps and ejections in the mixing zone were highlighted on the basis of instantaneous contours of Reynolds stress and vorticity. Stocchino and Brocchini [11] investigated experimentally the generation and evolution of large-scale vortices in a straight compound channel under quasi-uniform flow conditions under shallow streams of different velocities using particle image velocimetry (PIV). Instantaneous measurements of the surface flow velocity are analysed by means of vortex identification and vorticity fields. Uijttewaal et al. [12] investigated experimentally the impact of bed level and bed roughness on the eddy formations between the main channel and the floodplain in compound shallow flows. The impact of transverse depth variation can be explained as the vertical compression will accelerate the flow towards the flood plain and decelerate the reverse flow leading to a deformation of the eddy structures. Jahra et al. [13] visualized "experimentally and simulated numerically" large-scale horizontal vortices along the interface of the main channel and the vegetated floodplain with three different cases of vegetation placement patterns on the floodplain under emergent condition. Jimenez et al. [14] have all noted that the coherent oscillations substantially increase the shear stress and scalar fluxes at the surface of permeable rough walls. These results suggest that shear instability leading to coherent oscillations may be a common feature of flows adjacent to rough or porous layers at sufficiently large Reynolds number. In these flows, the roughness layer is permeable but imposes resistance, combining to create strong velocity shear and an inflection point. Nezu and Sanjou [10] investigated turbulence structures and coherent motion in vegetated canopy open-channel flows using LES technique. They showed instantaneous vorticity in the non-wake plane at every 0.5 seconds. The present study aims to capture and evaluate the shear layers generated at the interface between the main channel and the floodplain of two cases (wholly vegetated floodplain with sparse density and non-vegetated floodplain) using a novel approach (thermal camera SC640). Image processing was also considered.

2 Experimental Setup and Methodology

The flume studies of a compound channel section were conducted in a 1.2m wide, 0.3m deep and 10m long slope-adjusted flume with glass sidewalls. A compound channel was designed with shallow flow conditions by attaching plastic sheets along one side of the flume, with a width of 76cm, a thickness of 2.4cm and channel side slope of 1(H):1(V). Aluminium sheets were used to carry out the channel side slope of 2mm thickness. Holes were made along the entire floodplain width with staggered arrangements with $a_x = a_y = 12.5$ cm, where ax and ay are the longitudinal and the lateral spacing respectively. The centre of the first row of the holes on the sheets bed adjacent to the clear channel is far a distance of about 2.5cm from the main channel-floodplain's interface. Wholly vegetated floodplain with vegetation density of 126.3 rods/ m^2 of a "Solid Volume Fraction, SVF=1.488%" and of diameter of D=1.25cm) was used as shown in figure (1) in comparison with non-vegetated floodplain case for a flow rate of 4.66l/s.



Fig. 1 Wholly vegetated floodplain of rod diameter D=1.25cm with vegetation density, SVF=1.488%

The flume was setup at a bed slope of 1/1000 using a graduated scale and then has to be checked and corrected using levelling. A thermal system was used that consists of a thermal camera of "30Hz image frequency and (640 x 480) pixels image resolution that collects the infrared radiation from objects in the scene and creates an electronic image based on information about the temperature differences", water tank with heater and thermostat, injected tube and computer with FLIR research IR software connects directly to FLIR thermal imaging cameras to acquire thermal snapshots or movies files that can be stored on the SD-card. Two moving rails across the compound channel section were used; at the first rail a thermal camera SC640 was mounted vertically above the water surface at a distance of about 60cm for high resolution purposes and at a section where the fully developed flow condition was achieved and a video capture rate of five frames per second was selected. An arrangement was also achieved across the moving rail to move the thermal system were fixed, in which the water tank connected to an injected tube, and the free end of the injection tube was fixed at the water surface at the junction edge between the main channel and the floodplain under fully developed flow condition (7.76m) from the up-stream end of the flume working section (see figure 2).



Fig. 2 IF infrared thermography system layout.

At the start, the flow runs under uniform flow condition, hot water releases from the water tank into the flume continuously via the injection tube with a considerable velocity equal to the velocity of the compound channel at the interface between the main channel and the floodplain. Because the thermal camera was fixed near to the water surface, the captured area is of a part of the whole shear layer area. The whole shear layer area was divided into 15 squares, five in the longitudinal direction and three squares in the transverse direction that checked before the actual runs. Thermal experiments were achieved in such a way that images have to be overlapped in two directions. To increase the number of image sequences that are used in the analysis, two videos were recorded for each square (part of the shear layer).

Lateral velocities across the compound channel flows (with vegetated and non-vegetated floodplain) at sections 4.76, 7.5 and 8.5m from the beginning of the flume working section were also achieved using Nixon probe velocimetry which performed the fully developed flow conditions at sections 7.5 and 8.5m. Velocity measurements were carried in the main channel, at two positions at $0.2H_{mc}$ and at $0.8H_{mc}$, which gives an averaged velocity of $V_{avg} = (0.2H_{mc} + 0.8H_{mc})/2$. Velocity measurements were performed at each 5 cm from the first position which is far 6.5 cm from the side-wall of the main channel and at each 1 cm for the last 10 cm near to the main channel- floodplain interface, while on the floodplain the averaged-velocity is measured at mid-depth of the floodplain water depth, i.e. $V_{avg} = 0.5h_{fp}$ at each 5 cm at each two positions between any two rods of equal distances across the floodplain for wholly vegetated floodplain. In the case of non-vegetated floodplain, velocity measurements were achieved at each 5 cm from the main channel-floodplain interface up to flume side-wall. The hydraulic characteristics of the experiments are shown in table (1).

Case study	Discharge Q (l/s)	Water depth <i>Hmc</i> (cm)	Water depth on the floodplain <i>hfp</i> (cm)	Bulk velocity Ub (cm/s)	Reynolds number Re = UbHmc/v	Froude number Fr=Ub/ √gHmc
Vegetated floodplain, D=1.25cm and SVF=1.488%	4.66	4.35	1.95	13.84	5985	0.211
Non- vegetated floodplain	4.66	3.96	1.56	16.07	6325	0.257

Table (1): The hydraulic characteristics of the experiments

3 Results

3.1 Image Processing Technique

At the end of recording video files, the next step is to exporting these sequences from the thermal camera into the FLIR software first, and then these sequences were transferred from the FLIR software to Matlab files. The information contained in Matlab files is not directly temperatures. The information is in another sort of scale which is called a colour code that should be converted into temperature values. When getting the images with FLIR, the user has to set up the maximum and minimum range for the temperature. In the Matlab files it is specified the maximum and minimum values for the colour code for getting out the relationship between the colour code values and temperature values. Knowing this fact it is able to transform the Matlab values into Celsius values. The average temperature calculation from a series of sequences of 187 images (640 x 480 pixels) was carried out for each part of the shear layer area. Because the recorded sequences were carried out for each part of the whole shear layer twice, an average temperature of each two recording videos was achieved for the entire shear layer parts. Then, a longitudinal overlapping for the entire shear layer parts at centre, left and right is required. Overlapping between the successive squares is down as follows; first between the first and the second images is achieved to get a new image. Then the new image overlaps with the third image and so on till the fifth image. Any overlap between any two successive images had to go through a trial and error process with high accuracy in order to select the most suitable overlap. At the end, three columns (centre, left and right) are being prepared for the second step. A horizontal overlapping is usually needed between the centre and the left and the centre and the right parts. In the present research two case studies of compound channel flows were examined as wholly vegetated floodplain of sparse density (SVF = 1.488%) and non-vegetated floodplain case. The results showed that the mean (187x2) row images of wholly vegetated floodplain were explained in figure (3). Figure (4) is showing the steps of the overlapping at centre location between the first and second squares as overlap1, and then between the result of the first overlap with the third square and so on to the end of squares. The other five locations on either side of the centre were similarly carried out with longitudinal overlaps to create the second and third parts of the shear layer as left and right (see figure 5).

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Fig. 3 Row images at five longitudinal locations for a wholly vegetated floodplain with rod diameter, D=1.25cm and flow rate, Q=4.66l/s. (a) Row image of the first square (b) Row image of the second square (c) Row image of the third square (d) Row image of the forth square (e) Row image of the fifth square. (All the dimensions in pixels).



Fig. 4 Image processing in the longitudinal direction for five squares for the case study of wholly vegetated floodplain with rod diameter, D=1.25cm and flow rate Q=4.66l/s. (a) Row images of the first and second squares (b) Overlap1 between the first and second row images (c) Overlap2 between the result of overlap1 and the third row image (d) Overlap3 between the result of overlap2 and the fourth image (e) Overlap4 between the result of overlap3 and the fourth image. (All the dimensions in pixels)

To extract the final shear layer (from the extracted 3 shear layer's parts), a horizontal overlapping was done for the left and the centre part of the shear layer first, and then between the right part and the centre part. The final results from Matlab of shear layer image were then exported into Tec plot software (see figure 6).



Fig. 5 Left and right parts of the shear layer resulted from the image processing technique in the longitudinal direction for five squares for the case study of wholly vegetated floodplain with rod diameter, D=1.25cm, and flow rate, Q=4.66l/s. (a) Left side part of the shear layer on the floodplain shows the rod diameters within the flow (b) Right side part of the shear layer on the main channel. (All the dimensions in pixels)



Fig. 6 Shear layer at the interface between the main channel and the floodplain for wholly vegetated floodplain with rod diameter of 1.25cm and flow rate of 4.66l/s. (Dimensions in pixels).

In a similar way the longitudinal overlap was done for a non-vegetated case study. There is no cause to do a horizontal overlap because the entire shear layer form is clear for the centreline shear layer part. Figure (7) shows the steps of carrying the longitudinal overlaps, while figure (8) shows the shear layer form conducting by Tec-plot software.



Fig. 7 Longitudinal overlaps (a) The first squares (b) overlap1 (c) overlap2 (d) overlap3 (e) overlap 4 for the shear layer at the interface between the main channel and the floodplain for the case of without vegetation on the floodplain for Q = 4.66 l/s. (All the dimensions in pixels).



Fig. 8 Shear layer form at the interface between the main channel and non-vegetated floodplain in a compound channel flow of a flow rate, Q = 4.66 l/s. (Dimensions in pixels).

Final shear layer images (figures 6 and 8) show the wake impact due to variation of roughness and water depth between the main channel and the floodplain. It is very clear that as the floodplain roughness is changed from non-vegetated to wholly vegetated floodplain with sparse density (SVF=1.488%) there is a clear shortened and a widened in the shear layer shape.

3.2 Lateral velocity profiles

Lateral velocity profiles of the compound channel flows with wholly vegetated floodplain and without vegetation are shown in figure (9). The lateral velocity profiles of these two experiments exhibit s-curve shape with strong gradients at the interface between the main channel and the floodplain. This transitional section is a hyperbolic tangent curve [9]. These velocity profiles showed a clear impact of the vegetation of the floodplain in comparison with the case of non-vegetated floodplain. The highest velocity gradients between the main channel and the floodplain is due to the roughness differences between the main channel and the floodplain sections causing the formation of shear mixing layer that cause to transfer of mass at the interface. It is seen that after implanting the vegetation over the floodplain, the depth averaged velocity over the floodplain decreases whereas it increases in the main channel. It is interesting to note that the impact of a sparse vegetation density exhibits a clear variation of velocity distribution over the floodplain.



Fig. 9 Lateral velocity gradients between the main channel and the floodplain of compound channel flows with Q=4.66 l/s for the case of non-vegetated floodplain and wholly vegetated floodplain of SVF=1.488%.

4 Conclusions

Using image processing technique together with Matlab software allows visualizing the shear layer that forms at the interface between main channel and floodplain of a compound channel. The shear layer at the interface of the vegetated floodplain was shown to be less elongated and wider than the non-vegetated case due to the drag impact by vegetation. Longitudinal overlaps for the centre line parts of the shear layer sometimes are enough to create the entire shear layer form with high resolution as shown in the case of non-vegetated floodplain. Mass and momentum transfer occurs between the main channel and the floodplain due to impact of the floodplain bed step and bed roughness variation which is shown in the lateral distribution of the depth averaged-velocity diagram.

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