

## FLUVIAL PROCESSES IN COMPOUND STRAIGHT CHANNELS: A LABORATORY INVESTIGATION

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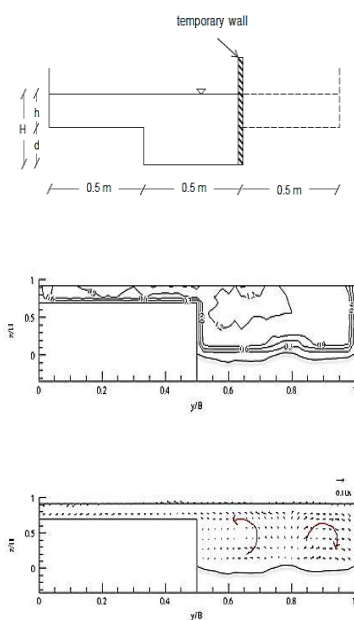
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### Graphical abstract



### Abstract

Floods are become frequent occurrence in every part of the world. The field of flood hydraulics has been keenly studied to enhance the understanding on its processes and impacts to the environment. The main impacts of frequent floods incidents are soil erosion phenomenon which leads to sedimentation problems in the drainage and river systems. It is extremely important to understand the sedimentation process and the flow behaviour patterns in the water course for post-flood events. Experimental investigations on the overbank flow in mobile bed straight channels have been undertaken. Significant changes on the bed morphology due to the changes in flow behaviour are studied. The findings on roughness coefficient, lateral distribution of stream-wise velocity, secondary currents, bed shear stress and bed formation are presented in this paper. Results show that the resistance coefficient increased with flow depth in the channel and the increments are about 32% and 42% for floodplain and main channel sections respectively.

**Keywords:** Straight compound channel, overbank flow, resistance coefficient, stream-wise velocity distribution, bed shear stress, bed morphology

### Abstrak

Banjir merupakan kejadian yang kerap berlaku di seluruh pelusuk dunia. Kajian banjir dalam bidang hidraulik telah dikaji dengan lebih mendalam untuk meningkatkan pemahaman terhadap proses dan kesan kepada alam sekitar. Hakisan tanah akibat kejadian banjir yang sering berlaku membawa kepada masalah pemendapan dalam sistem parit dan sungai. Ia adalah sangat penting untuk memahami proses pemendapan dan taburan aliran di dalam sistem aliran selepas banjir. Uji kaji pada aliran banjir di katil mudah alih saluran lurus telah dilaksanakan. Perubahan ketara pada pembentukan permukaan dasar adalah disebabkan oleh perubahan dalam pengedaran aliran. Hasil kajian seperti pekali kekasaran, pengedaran sisi halaju aliran, aliran sekunder, tegasan ricih sempadan dan pembentukan permukaan dasar dibentangkan dalam kertas ini. Hasil kajian menunjukkan bahawa pekali kekasaran meningkat dengan kedalaman aliran di dalam saluran dan peningkatan adalah kira-kira 32% dan 42% pada bahagian dataran banjir dan bahagian saluran utama.

**Kata kunci:** Saluran majmuk lurus, aliran banjir, pekali rintangan, halaju, tegasan ricih sempadan, pembentukan permukaan dasar

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## 1.0 INTRODUCTION

Flow in the compound open-channel is characterised by a complicated flow structure due to the interaction between the main channel and floodplain flows, lateral momentum transfer and secondary flows. The degree of flow complexity is intensified by erosion and sedimentation processes. Stream-wise velocities in straight open channels are controlled by water depth, bed properties and vegetation density. The movement of bed sediment along the channel by rolling, sliding or jumping refers to the bed load transport. It is absolutely dependent on the river morphological characteristics [1-2].

The transport of non-cohesive sediments during overbank flow is difficult to be described mathematically because of the interaction between floodplain flow and main channel flow [3]. The hydraulic geometry of channels is affected by flow conditions, sediment transport and distribution of channel roughness elements. The bed morphology that established forms additional roughness indirectly affects the velocity of water flow [4]. A variation in bed properties not only redistributes the flow locally but also can influence the flow as a whole because of lateral momentum transfer [5].

The contribution of secondary flow to the lateral momentum exchange in compound channels depends very much on the depth of the floodplains relative to the depth of the main channel and on the geometrical details of the interface [6-7]. The momentum exchange between the main channel and floodplain is due to both secondary circulations, in a vertical plane perpendicular to the main flow direction, and to large-scale vortices moving in the horizontal plane. The momentum exchange retards the main channel flow [8]. The size and position of secondary currents is largely dependent upon the channel geometry [9-10]. It is therefore important to analyse the strength and shape of the secondary circulation.

The boundary or bed shear stress is the main parameter that controls the erosion process in rivers which is directly related to the velocity in the channel. Many authors such as Guo and Julien and Babaeyan *et al.* have determined boundary shear stress to study the velocity profile [11-13]. The velocity in the main channel remained significantly faster compared with that on the floodplain, despite the increased roughness of the main channel bed [14]. In compound channels with mobile bed, the distribution of velocity changes due to the changes in the channel bed. Therefore, the bed shear stress also changes in the compound channels.

The present study intends to obtain the information on the influence of flow depth and discharge on the development of bed forms in compound channels. The bed forms, erosion and sedimentation processes are significantly influenced by the water velocity in the channel.

## 2.0 LABORATORY EXPERIMENT

The experiments are conducted in a 12 m long and 1.0 m wide channel constructed in laboratory. Figures 1 and 2 illustrate layout of experimental set-up and the cross-sectional configuration of the channel. The geometrical parameters are floodplain width,  $B_f$  and main channel width,  $B_m$  are equalled to 0.5 m. Meanwhile, main channel depth,  $d$  is 0.1 m. The total flow depth in the main channel is represented by  $H$ . The channel bed slope is set at 1/1000.

The main channel is filled with uniform graded sand with  $d_{50}$  of 0.8 mm as its bed material. A similar size of uniform sediments is used by Knight and Brown [4], Myers *et al.* [8], Knight *et al.* [14], Atabay *et al.* [15], Tang and Knight [16] and Bousmar *et al.* [17] in their laboratory investigation. In practice, it is hardly to found a river bed with a uniform size of sediment particles. Thus, the main reason for using uniform graded sand in this study is to minimise the influence of the “sheltering” and “hiding” effects. As bed forms propagate to the downstream, sediment moves from the crest of the bed forms to the trough. In the trough, the sediment is sheltered and overlaid by the advancing grains from the upstream bed forms [18].

A portable flow meter is installed to measure discharge in the channel. The water depth is controlled by an adjustable tailgate at downstream. The water depth and bed forms are measured using a digital point gauge attached on a special mobile carrier. The gauge gives the reading to the nearest of  $\pm 0.1$  mm. The effects of turbulence are minimized by using buffer install at the opening inlet of the channel.

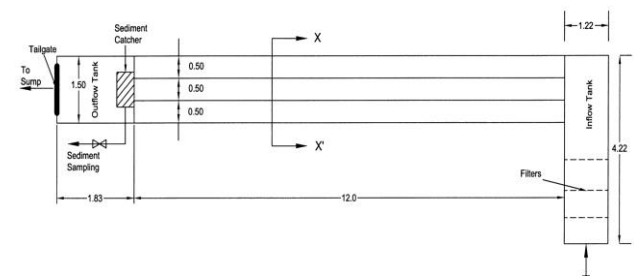


Figure 1 Layout of straight channel

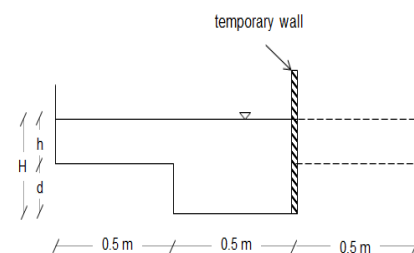


Figure 2 Cross-sectional view of an asymmetric compound channel

Flow velocities are measured using Nortek Vectrino+ ADV at a frequency of 100 Hz over 70 mm<sup>3</sup> sampling volume. The maximum sampling time at each nodal point is 2 minutes which is enough to collect an adequate of turbulence burst. Cao *et al.* stated that frequency of 50 Hz within 30.0 s is enough for acquisition of data velocity [19]. For most turbulent statistics, sufficient record length for measurement is 60 to 90 s [20]. The transverse interval distance for velocity measurement is 2 cm and varies vertically. For all relative depths, the calculated Reynolds number (Re) exceeds 2,000 and the Froude number (Fr) less than unity. Therefore, the regimes of flows are classified as sub-critical with turbulent condition. DR is the relative depth =  $(H - d)/H$ .

### 3.0 DISCUSSION OF RESULTS

The experimental investigations have been conducted under uniform flow condition in order to apply uniform flow theory in the analysis. The uniform flow has been achieved when the relative discrepancy between the slope of water surface ( $S_w$ ) and slope of channel bed ( $S_o$ ) are less than 5%. The analysis of experiment data for the flume is focused on the stream-wise velocity, flow resistance, secondary current and bed formation as discussed below:

#### 3.1 Resistance Coefficient

In order to understand the discharge characteristics and velocity in the compound channels, it is essential to look into flow resistance. The flow resistance in a channel is represented by the Manning's coefficient,  $n$  value for each interval of normalised longitudinal distance ( $x/L$ ) as shown in Figures 3 and 4.  $x$  is longitudinal distance and  $L$  is total length of the channel.  $n_{mc}$  is the Manning's  $n$  for main channel and  $n_{fp}$  is the Manning's  $n$  for floodplain.

As illustrated in Figure 3, the  $n_{mc}$  value ranged from 0.016 to 0.017 at DR = 0.30. Meanwhile, at DR = 0.50,  $n$  value ranged from 0.019 to 0.023. Figure 4 shows the  $n_{fp}$  values ranged from 0.012 to 0.014 at DR = 0.30 and from 0.016 to 0.018 at DR = 0.50. The values indicate that Manning's  $n$  increased with flow depth in the channel. The increments of Manning's  $n$  are about 32% and 42% for floodplain and main channel section respectively.

Manning's  $n$  is highly variable and depends on a number of factors [21]. From the observation of this experiment, the bed profile of the main channel creates additional resistance to flow hence contributing to higher Manning's  $n$ . The roughness of floodplain surface also can increase resistance of flow along the channel. A very similar result has been found to what van Rijn predicted on the roughness effects of the mobile bed [22-26].

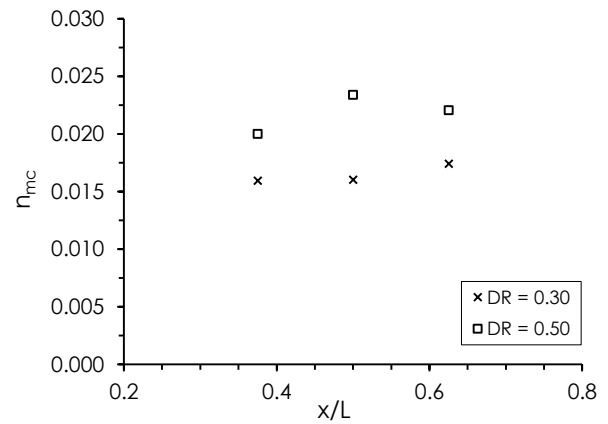


Figure 3 Resistance coefficient trend along the main channel section

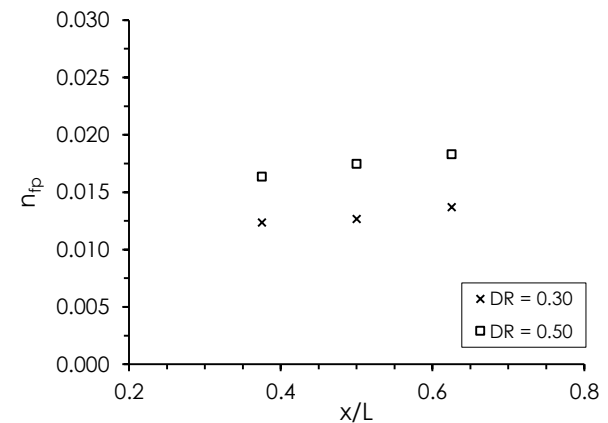


Figure 4 Resistance coefficient trend along the floodplain section

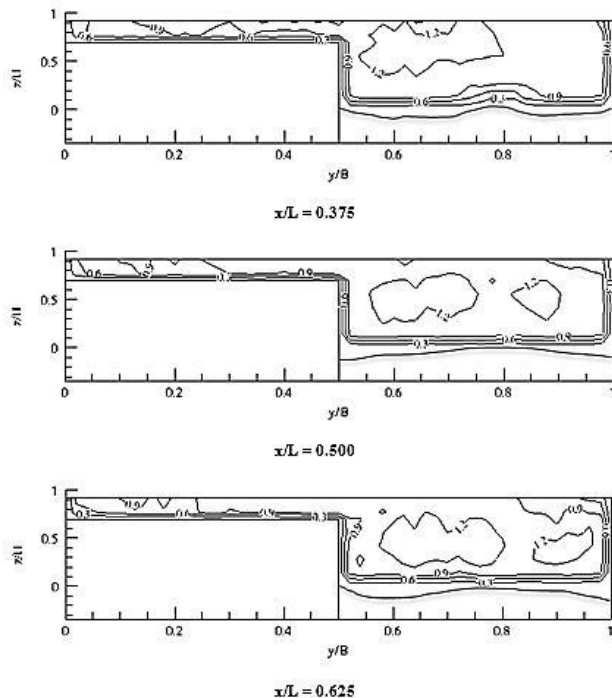
#### 3.2 Stream-wise Velocity Patterns

Measured stream-wise velocity components have been plotted in order to obtain the velocity distribution profiles. Plots are made based on the recorded stream-wise velocity,  $U$  is normalised by the mean sectional velocity,  $U_s$  for each interval of normalised longitudinal distance ( $x/L$ ). Figures 5 and 6 elaborate on the normalised  $U/U_s$  experimental results for relative flow depths of 0.30 and 0.50. The phenomenon of "velocity dip" in which a maximum velocity occurs below free surface does take place in the main channel.

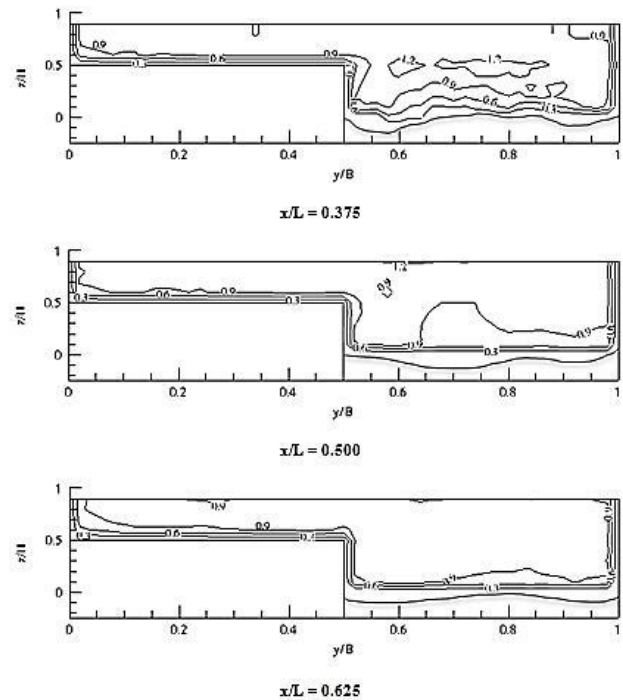
As illustrated in Figures 5 and 6, the velocity dip phenomenon can be clearly seen in the case of low relative depth. However, this phenomenon does not occur in the higher relative depth case. The maximum velocity cell is observed to be mostly in the main channel as shown in Figure 5. The maximum  $U/U_s$  for the DR = 0.30 case is 1.2. For the DR = 0.50 case in Figure 6, the maximum  $U/U_s$  is 0.9 which is smaller than the maximum  $U/U_s$  for DR = 0.30. It means that main channel flow is allowed to well-

dispersed between main channel and floodplain and resulting more uniform velocity distribution in the compound channel. When the overbank flow depth continues to rise, floodplain velocity will increase rapidly until the equalisation of main channel and floodplain velocities occurs [27]. This leads to a decrease in momentum transfer from main channel to floodplain and may lead to a reversal in direction of momentum transfer at larger flow depths.

In terms of the differences in stream-wise velocity distribution along the channel section, due to the different in depth and flow resistance which is caused by bed form profiles. Flow resistance in mobile bed material can be attributed into two sources which are grain resistance of channel bed material and form resistance or form drag due to the shape of channel bed forms [28]. Typical bed form profiles as normally expected that the deeper section appears along the upstream and the shallow section appears on the downstream due to erosion and sedimentation phenomenon. The higher velocity observed to be mostly in shallow section which appears on the downstream. The bed forms that established forms additional roughness indirectly reduces the velocity of water flow. The deep, fast flow within the main channel and the relatively shallow, slow flow over the floodplain take strong interactions. These interactions transfer longitudinal momentum between the two flow regions, decreasing flow velocity and boundary shear within the channel and increasing them over the floodplain [29].



**Figure 5** Cross-sectional distribution of stream-wise velocity at relative depth of 0.30



**Figure 6** Cross-sectional distribution of stream-wise velocity at relative depth of 0.50

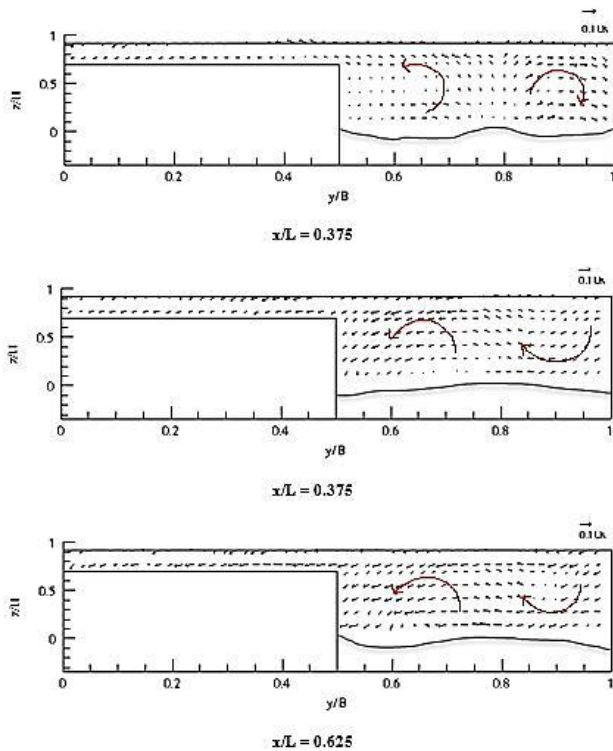
### 3.3 Vorticity

The secondary flow is generated by turbulence in the channel and the circulation vector is the resultant of transverse and vertical velocity components. Their characteristics are influenced by many factors, such as the channel cross-section geometry and aspect ratio, relative depth and turbulence activity [6]. To further understand the interaction between floodplain and main channel flows in this study, secondary flow or circulation patterns are plotted for shallow and deep relative depths. The secondary flow which is the resultant of  $V$  and  $W$  velocity components is normalised by the mean sectional stream-wise velocity,  $U_s$ . The direction of the flow is shown as positive or negative sign. The flow from main channel towards the floodplain is shown as a negative velocity.

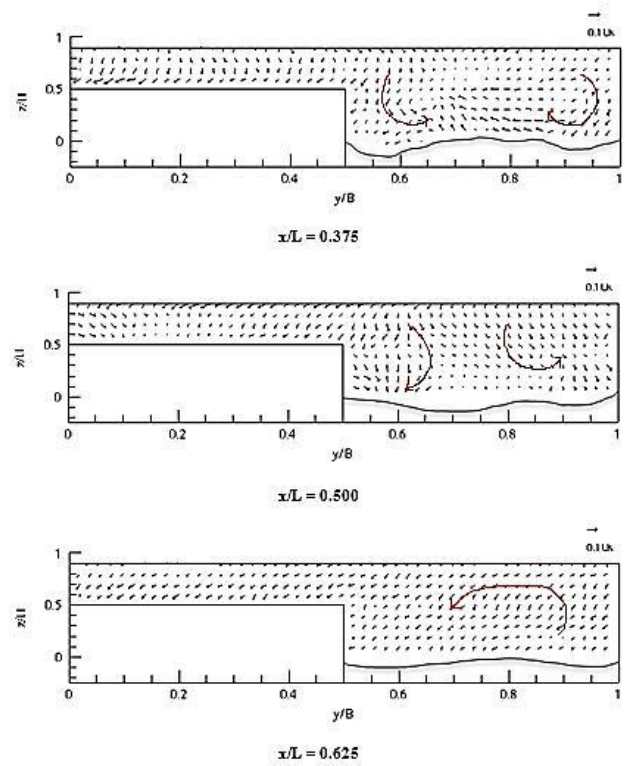
Figures 7 and 8 illustrate that water can flow freely between main channel and floodplain. There is also presence of bottom vortex at the corner of main channel which is the typical feature in rectangular open channels, as mentioned [30-31]. From the Figure 7, it seems in  $x/L = 0.325$ , the major vortex is observed in the central part of the main channel which is broken into smaller vortices rotating in opposite directions. The strength of right vortex appears to be sturdier than the left vortex. Meanwhile, the vortices in  $x/L = 0.500$  and  $x/L = 0.625$  are more or less of the same order of magnitude and direction. Thus, the strength of vortices was influenced by channel boundary or surface roughness. Also, due to the resistance effect, the

strength of secondary current on floodplain decreased.

A large anti-clockwise recirculation cell is observed in  $x/L = 0.625$  in Figure 8. This vortex called as the free surface vortex which has been generated due to the anisotropy of turbulence across the flume. In this case, the recirculation cell is similar as reported [32]. Meanwhile, a major vortex forms in the main channel and then shattered into smaller vortices rotating in opposite directions can be observed at the interface in the  $x/L = 0.325$  and  $x/L = 0.500$ . These vortices are more or less of the same order of magnitude. Thus, it is a strong evidence that larger and isolated bed roughness elements such as sand ridges may increase the strength of secondary flow [33].



**Figure 7** Distribution of secondary current along compound straight channel at DR = 0.30



**Figure 8** Distribution of secondary current along compound straight channel at DR = 0.50

### 3.4 Bed Shear Stress

Distribution of the boundary shear stress depends upon the shape of the cross-section, the structure of the secondary flow cells and lack of the uniformity in the boundary roughness. Boundary shear stress distribution is important in predicting flow resistance, sediment transport rate, channel erosion or deposition and cavitation [34]. The measured boundary shear stress,  $\tau_b$  has been normalised to the calculated mean shear stress,  $\tau_o$ .

Figures 9 and 10 present the normalised boundary shear stress difference  $(\tau_o - \tau_b)$  by mean shear stress  $(\tau_o)$  for relative depth of 0.30 and 0.50, respectively. It shows that boundary shear stress  $\tau_b$  depends on the velocity distribution in the channel where high velocity will result high shear stress. For high relative depth, the velocity is distributed more uniformly in main channel and floodplain. The maximum value for  $(\tau_o - \tau_b)/\tau_o$  in relative depth of 0.30 for  $x/L = 0.375, 0.500$  and  $0.625$  are 0.612, 0.576 and 0.576, respectively. Meanwhile, they are 0.576, 0.593 and 0.659 for  $x/L = 0.375, 0.500$  and  $0.625$  in relative depth of 0.50, respectively.

For a given relative depth, the value of  $\tau_b$  in the main channel decreases once overbank flow takes place. The reduction in the main channel shear stress is due to the presence of the interaction mechanism between the main channel and floodplain. It reduces the shear values due to the momentum transfer from the main channel to the floodplain. This

means that main channel flow is allowed to distributed freely between main channel and floodplain and resulting more uniform velocity distribution in the compound channel. The distribution of velocity and shear stress are dependent on the shape of the channel bed not its dimensions [35].

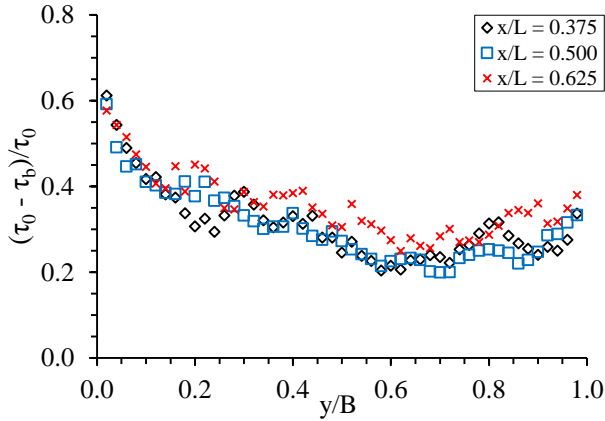


Figure 9 Boundary shear stress distribution at variance section along the channel for DR = 0.30

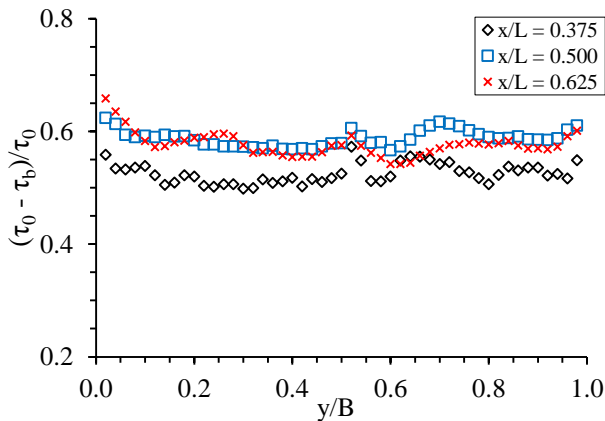


Figure 10 Boundary shear stress distribution at variance section along the channel for DR = 0.50

### 3.5 Bed Morphology

The main channel morphology is observed to visualise the flow behaviour on the bed channel. Sand erosion and sedimentation along the channel are completely affected by the environmental condition of the stream flow. The channel morphology is in many ways unique due to particle history of flow conditions, sediment transport and distribution of channel roughness elements as mentioned [36-37]. The scour depth is measured in mm as presented in Figures 11 and 12. A negative value indicates erosion while positive value represents sedimentation.

The bed morphology at the relative depths of 0.30 and 0.50 exhibits a typical profile as normally expected where the deeper section appears at the upstream channel and the shallow section slightly

occurs at the downstream channel due to the energy of the flow velocity in the channel. It also shows that the sand bed level at the downstream channel slightly higher due to deposition phenomenon. The greater flow velocity from the upstream to the downstream tends to influence the sediment transportation as well as occurrence of eroded and deposited of sand bed. The sand is covered with irregular bed forms consisting of ripples along the channel.

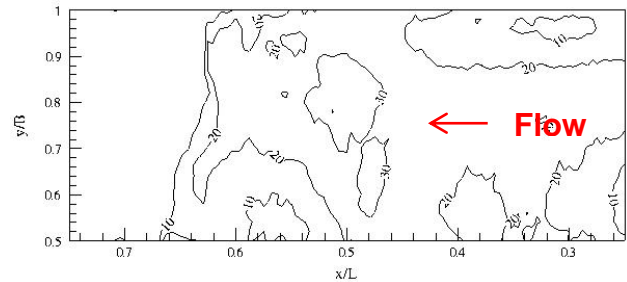


Figure 11 Plan view of bed profiles along the main channel at relative depth of 0.30

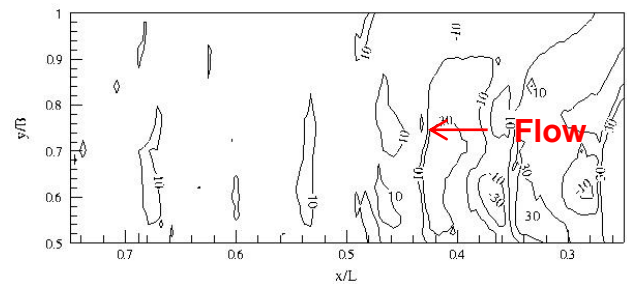


Figure 12 Plan view of bed profiles along the main channel at relative depth of 0.50

## 4.0 CONCLUSION

In the present study, the hydraulic characteristics in mobile bed straight channel have been investigated in the laboratory. The significant changes in the flow behaviour to the changes in bed formation, roughness coefficient, lateral distribution of stream-wise velocity and bed shear stress have been inspected in order to enhance knowledge on the fluvial river problem during flooding. The conclusion can be drawn from the findings are:

- i. A significant variation of bed morphology patterns creates a tendency for the main channel flow resistance increases with the increase of flow depth. The flows passing through this standing bed morphology create flow separation, which in turn induced a higher flow resistance.
- ii. At higher relative depth, the floodplain velocity increases rapidly until the equalisation of main channel and floodplain velocities occur. This leads to a decrease in momentum transfer processes

- from the main channel to the floodplain. It also may leads to a reversal in direction of momentum transfer at higher relative depths.
- iii. The size and position of secondary currents is largely dependent upon the channel geometry. The strength of vortices is also influenced by channel boundary or surface roughness.
  - iv. Boundary shear stress  $\tau_b$  depends on the velocity distribution in the channel. At high relative depth the velocity is distributed more uniformly in main channel and floodplain. It is due to the momentum transfer from the main channel to the floodplain and resulting more uniform velocity and boundary shear stress distribution in the compound channel.
  - v. The observation of the bed form changes showed that for higher flow depth, ripples were seen in the main channel. This indicates that the flow resistance becomes more homogeneous at the high overbank flow depth. A significant variation of bed form patterns in the main channel, which are totally influenced by sediment movement in the main channel.

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