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FLOOD FLOW CHARACTERISTICS AND BED LOAD TRANSPORT IN NON-VEGETATED COMPOUND STRAIGHT CHANNELS

Mazlin Jumain, Zulkiflee Ibrahim*, Zulhilmi Ismail, Mohd Fuad Samsudin, Muhd Zubair Tajol Anuar, Sobri Harun, Md Ridzuan Makhtar, Mohd Suhaimi Abd Rahman

Department of Hydraulics and Hydrology, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

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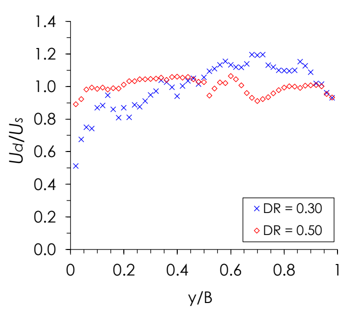
*Corresponding author
zulkfe@utm.my

Graphical abstract



Abstract

Floods are the most common natural disasters in Malaysia and have damaged structures, infrastructures, crops and even causes fatalities. It may also lead to erosion and sedimentation in rivers and this will result to complex river behaviour. A hydraulic laboratory experimental study was carried out. Also, flood flow and sediment transport in straight compound channels involving flow resistance, distribution of depth-averaged velocity, stream-wise vorticity patterns, channel bed morphology and bed load transport rate in non-vegetated compound straight mobile bed channels were investigated. The finding showed that the Darcy Weisbach friction factor f increased by 40% and 54% for floodplain and main channel, respectively when relative flood flow depth increase from 0.30 to 0.50. The small bed load transport rates of 0.09 g/s and 0.03 g/s for shallow and deep overbank flows, respectively were measured due to effect of very gentle or mild channel bed slope which was fixed at a gradient of 0.1%.

Keywords: Compound straight channel; flow resistance; velocities distributions; channel bed morphology

Abstrak

Banjir merupakan bencana alam yang paling biasa berlaku di Malaysia dan telah merosakan struktur, infrastruktur, tanaman dan juga menyebabkan kematian. Ia juga boleh membawa kepada hakisan dan pemendapan di sungai dan menjadikan aliran sungai menjadi lebih kompleks. Kajian ekperimen hidraulik dijalankan di makmal. Juga, aliran banjir dan pengangkutan sedimen di saluran kompaun lurus tanpa tumbuhan melibatkan pekali kekasaran, taburan halaju aliran, arus sekunder dan pembentukan dasar telah dikaji. Hasil kajian menunjukkan bahawa factor geseran Darcy *Weisbach f* meningkat sebanyak 40% dan 54% pada dataran banjir dan saluran utama dengan kenaikan relative kedalaman aliran banjir dari 0.30 kepada 0.50. Kadar pengangkutan sedimen yang kecil iaitu 0.09 g/s untuk aliran cetek dan 0.03 g/s untuk aliran dalam kerana kesan kecerunan terlalu mendatar yang telah ditetapkan pada kecerunan 0.1%.

Kata kunci: Saluran majmuk lurus; pekali kekasaran; taburan halaju aliran; morfologi permukaan dasar

1.0 INTRODUCTION

Floods are frequent natural disasters occur in Malaysia and damaged the structures, infrastructures, crops and even causes deaths. Deforestation activities and rapid development such as land clearing for the purpose of agriculture or housing development on the floodplains have been pointed out as one of the contributing factors to the severity of damages. Flow in a compound channel is characterised by a complex flow structure due to the interaction between the main channel and floodplain, lateral momentum transfer and secondary flows. The interaction between the floodplain and main mobile bed channel in overbank flow condition is considerably more complex than in non-erodible bed channels [1]. The degree of flow complexity is intensified by erosion and sedimentation processes. The presence of the bed forms lead to much greater variability in water surface slope, energy dissipation, bed load transport rate and channel dimensions than anticipated [2]. Overbank flow hydraulics in mobile bed channels had been studied by investigators including Myers *et al*. [3], Valentine *et al*. [4], Atabay *et al*. [5] and Tang and Knight [6].

The hydraulic characteristics in mobile bed channels are affected by various parameters. It is unique due to influences of flow conditions, sediment transport, bed morphology and distribution of channel roughness elements. The transport of non-cohesive sediments during overbank flow is difficult to be described mathematically due to the interaction between floodplain flow and main channel flow [7]. Knight and Brown reported that the bed will deform under the action of flow, changing its roughness, and then affecting the flow itself [8].

Zhang *et al*. [9] and Ali *et al.* [10] also stated that the roughness of non-mobile beds is noticeably less than those of mobile beds. The approach proposed by van Rijn gave very good predictions of the roughness effects of the mobile bed [11 - 13]. The present study intends to understand better on the influence of flow depth and discharge on the development of bed profiles in compound channels.

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 [14, 15]. 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 plain. The momentum exchange retards the main channel flow [3]. The size and position of secondary currents is largely dependent upon the channel geometry [16, 17]. Khademishamami *et al*. [18] conclude that the secondary currents play an important role which causes a lateral migration of trapped sediment particles along the channel. It is therefore important to analyse the strength and shape of the secondary circulation.

Yang [19] reported that sediment particles along an alluvial bed channel will start to move when the flow conditions satisfy or exceed the criteria for incipient motion. The bed load transport is said to occur when the motion of sediment particles rolling, sliding or sometimes jumping along the bed of a stream and absolutely dependent on the river morphological characteristics [20, 21]. The movement of bed load plays important role in forming and maintaining channel geometry [22, 23]. Ackers [24] predicted that the sediment transport would increase in most rivers up to bankfull discharge, but the sediment transportation process might diminish with further increase in discharge and roughness on overbank condition. Atabay *et al*. [5], Ayyoubzadeh [25] and Tang and Knight [26] found that similar results to Ackers's prediction.

Experimental investigations on the flood flow and sediment transport in non-vegetated compound straight channels had been undertaken. The focus was given to flow resistance, stream-wise velocity distribution, vorticity patterns, main channel bed morphology and bed load transport rate in the channels. The study is limited to asymmetric non-vegetated compound straight mobile bed channel and the flume experiments were conducted in the Hydraulics Laboratory in Universiti Teknologi Malaysia (UTM). The study involves shallow and deep flood flow conditions.

2.0 METHODOLOGY

The experiments were conducted in a 12 m long and 1.0 m wide flume. Figures 1 and 2 illustrate the layout of experimental set-up and the flume cross-sectional configuration. The geometrical parameters; floodplain width, B_f and main channel width, B_m were equalled to 0.5 m. Meanwhile, main channel depth, d was 0.1 m. The total flow depth in the main channel was represented by H. The channel bed slope was set at a gradient of 0.1%.

The main channel was filled with uniform graded sand with d_{50} of 0.8 mm as bed material. A similar size of uniform sediments was used by Knight *et al*. [1], Myers *et al*. [3], Atabay *et al*. [5], Knight and Brown [8], Tang and Knight [26] and Bousmar *et al*. [27] in their laboratory investigations. In practice, it is difficult to find a river bed with a uniform size of sediment particles. Thus, the main reason for using uniform graded sand in this study was to minimise the influence of the "sheltering" and "hiding" effects as mentioned by Ismail [28]. As bed forms propagate to the downstream, sediment moves from the crest of the bed forms to the trough. In the trough, the sediment was sheltered and overlaid by the advancing grains from the upstream bed forms.

A portable flow meter was installed to measure discharge in the channel and the water depth was controlled by an adjustable tailgate at downstream. The water depth and bed forms were measured using a digital point gauge attached on a special mobile carrier. The gauge gave readings to the nearest of ± 0.1 mm. The effects of turbulence were minimized by using buffer installed at the opening inlet of the channel.

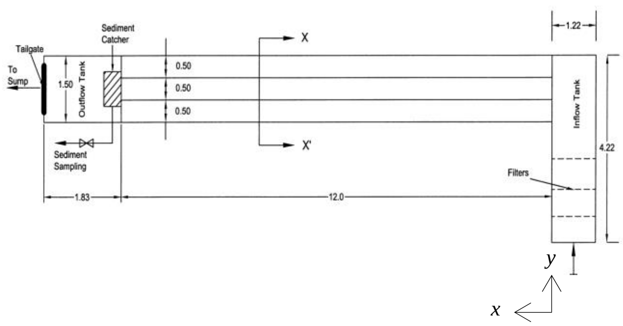


Figure 1 Plan view of experimental flume

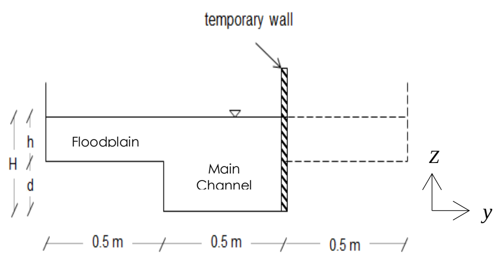


Figure 2 Cross-sectional view of experimental flume

The experiment was left to run continuously for more than 24 hours and the water surface level was checked regularly until representative bed forms developed. At higher flow depth, it was quite difficult to ensure that the flow was uniform due to fluctuations of the water level. Additionally, the development of bed forms varied dramatically with time; taking sometimes of longer time scales [28, 29].

Flow velocities were measured using *Nortek Vectrino+ ADV* at a frequency of 100 *Hz* over 70 mm^3 sampling volume. The maximum sampling time at each nodal point was 120 s, enough to collect an adequate of turbulence burst. Cao *et al*. [1] stated that frequency of 50 *Hz* within 30.0 s was sufficient for acquisition of data velocity. For most turbulent statistics, sufficient record length for measurement is 60 s to 90 s [30]. The interval distance for velocity measurement was 2 cm in transverse and vertical directions. For all relative depths, the calculated Reynolds number (*Re*) exceeded 2,000 and the Froude number (*Fr*) less than unity. Thus, the regimes of flows were classified as sub-critical and turbulent.

The relative flood flow depth *DR* in an open channel was computed using Equation (1):

$$DR = \frac{(H - d)}{H} \tag{1}$$

where *H* represents the total flow depth in main channel; and *d* is the depth of main channel.

The common parameters which express the flow resistance in open channel hydraulics were Darcy Weisbach friction factor *f* and Manning's roughness coefficient *n*. The Darcy's *f* for open channel flows was calculated using the Equation (2):

$$f = \frac{8gRS_o}{{U_s}^2} \tag{2}$$

where *g* is gravitational acceleration, *R* is hydraulic radius; S_o is channel bed slope; and U_s is mean longitudinal (stream-wise) velocity.

The depth-averaged or depth-mean velocity U_d was computed using Equation (3):

$$U_d = \frac{1}{H(y)} \int_0^{H(y)} U dz \tag{3}$$

where *U* is stream-wise velocity and *H* is the flood flow depth.

Meanwhile, Equation (4) was used to determine the bed load transport rate in this study:

$$q_b = \frac{m_s}{t} \tag{4}$$

where q_b represents the bed load transport rate; while m_s is mass of sediment transported and *t* is sampling time.

3.0 RESULTS AND DISCUSSION

The experimental investigations were carried out under uniform flow condition to apply its theory in the analysis. The uniform flow achieved when the relative discrepancy between the slope of water surface (S_w) and slope of channel bed (S_o) were less than 5%. Shallow and deep relative flood flow depths *DR* of 0.30 and 0.50, respectively were investigated. The selected relative depths represent shallow and deep overbank flows in the compound channels.

3.1 Darcy-Weisbach Friction Factor, *f*

The flow resistance in an open channel was represented by the Darcy-Weisbach friction factor, *f* value for each interval of normalised longitudinal distance (*x*/*L*) as shown in Figure 3. *x* is longitudinal distance and *L* is total length of the channel. f_{mc} is the friction factor for main channel and f_{fp} is the friction factor for floodplain.

As illustrated in Figure 3, the f_{mc} values ranged from 0.046 to 0.057 at *DR* = 0.30. Meanwhile, at *DR* = 0.50, the f_{mc} values ranged from 0.066 to 0.086. Figure 4 shown the f_{fp} values ranged from 0.035 to 0.044 at *DR* = 0.30 and from 0.048 to 0.060 at *DR* = 0.50. The values indicate that Darcy's friction factor increased with higher flood depth in the channel. The mean increments of the Darcy's friction factor were about 40% and 54% for floodplain and main channel, respectively.

Chow [31] stated that the flow resistance was highly variable and influenced by a number of factors. From the observation in this experiment, it was found that the bed morphology of the main channel created additional resistance to flow which contributed to higher Darcy's friction factor. The rough floodplain surface also increases the flow resistance along the channel. Zhang *et al*. [9] and Ali *et al.* [10] investigated and found very similar results to van Rijn's [11 - 13] predictions on the roughness changes on variation of bed geometry in erodible bed channel.

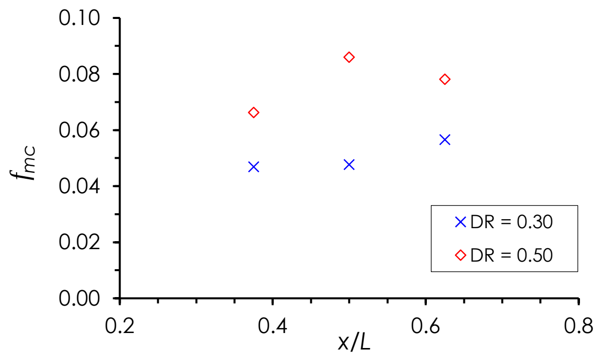


Figure 3 Main channel Darcy's friction factor profiles along the channel

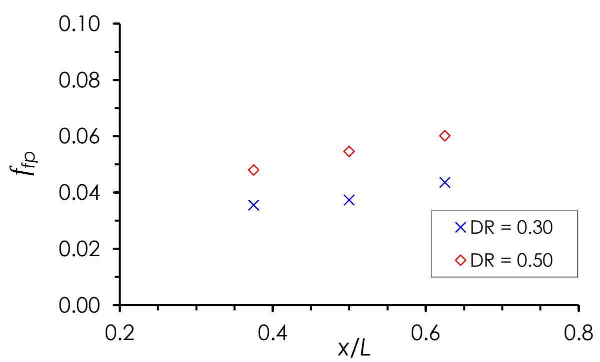


Figure 4 Floodplain Darcy's friction factor profiles along the channel

3.2 Depth-Averaged Velocity Distribution

The transverse distributions across each section were plotted based on the depth-averaged velocity components. The depth-averaged velocity U_d was normalised by the mean sectional velocity, U_s. Figures 5, 6 and 7 illustrate the transverse distribution (*y*/*B*) of normalised U_d/U_s in non-vegetated compound straight channel for shallow (*DR* = 0.30) and deep (*DR* = 0.50) overbank flows at different sections. *y* represents transverse distance and *B* is total channel width. The floodplain is located between *y*/*B* = 0 to 0.5, while main channel is located between *y*/*B* = 0.50 to 1.00. Therefore, *y*/*B* = 0.50 is the interface of main channel and floodplain.

The main channel depth-averaged velocities were different from the floodplain due to different hydraulic conditions. It was noted that the U_d/U_s on the floodplain was less than U_d/U_s in the main channel for shallow relative depth of 0.30. Meanwhile, the distribution of velocity was more uniform between main channel and floodplain when the relative flow depth increased to 0.50. The flow velocities between main channel and floodplain were well-dispersed for higher flood flow depth. This means that the effect of interaction between main channel and floodplain flows was also reduced. The velocity decreased from the upstream to the downstream of the channel.

The maximum U_d/U_s was observed mostly in the main channel for shallow relative depth. The maximum values of U_d/U_s occurred at *y*/*B* = 0.56, 0.72 and 0.62 for the longitudinal distances of *x*/*L* = 0.375, 0.500 and 0.625, respectively. For the relative depth of 0.50, the maximum U_d/U_s was found to be 1.10; which was smaller than the maximum U_d/U_s for relative depth of 0.30 with 1.21 which occurred at the similar longitudinal distances of *x*/*L* = 0.625.

The changes in normalised U_d/U_s distribution patterns between main channel and floodplain at each section were smaller compared to shallow relative depth of 0.30. This means that the water in the main channel flows freely into the floodplain for deep relative depth. Lai *et al*. [32] stated that when the overbank flow depth continues to rise, floodplain velocity will increase rapidly until the equalisation of main channel and floodplain velocities occurs. 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.

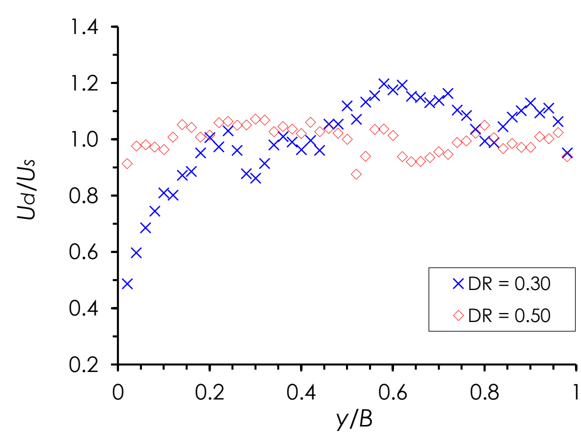


Figure 5 Transverse distribution of U_d/U_s at longitudinal distance of *x*/*L* = 0.375

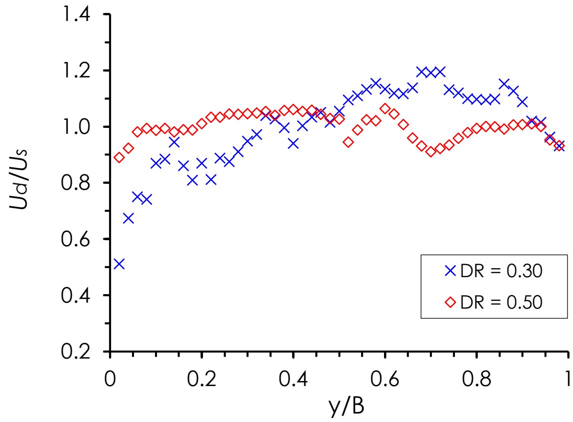


Figure 6 Transverse distribution of U_d/U_s at longitudinal distance of x/L = 0.500

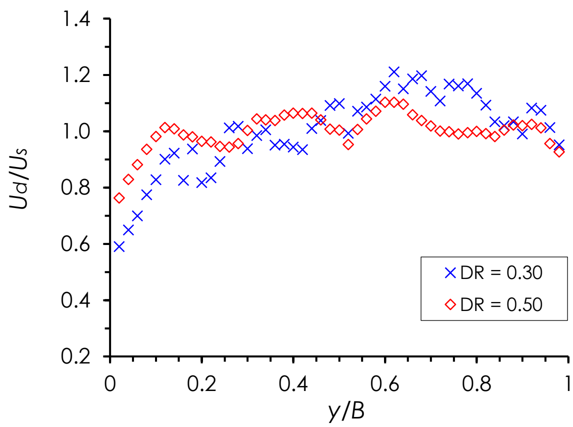


Figure 7 Transverse distribution of experimental normalised depth-averaged velocity, U_d/U_s at longitudinal distance of x/L = 0.625

3.3 Stream-Wise Vorticity

The horizontal secondary flow or circulation is also known as "stream-wise vorticity" [33, 34]. The stream-wise vorticities are important in altering the pattern of stream-wise velocity, bed shear stress, turbulence structures and sediment transport. The secondary flow is the resultant of V and W velocity components in the y and z directions which are normalised by the mean sectional stream-wise velocity, U_s. Figures 8 and 9 illustrate that the water in the main channel flows freely into the floodplain. The presence of bottom vortex also observed at the corner of main channel which was the typical feature in rectangular open channels, as mentioned by Naot and Rodi [35] in Rodriguez and Garcia [36].

For normalised longitudinal distance of x/L = 0.375 in Figure 7, the major vortex was found in the central part of the main channel and then broken into smaller vortices rotating in opposite directions. The strength of right vortex appears to be stronger than the left vortex. Meanwhile, the vortices at x/L = 0.500 and x/L = 0.625 are the same order in both magnitude and direction. Thus, the strength of vortices was influenced by channel boundary or surface roughness as mentioned by Guo and Julien [37]. In addition, the strength of secondary currents on floodplain decreased due to the resistance effect of surface roughness as explained in section 3.1.

A large anti-clockwise recirculation cell was found at x/L = 0.625 in Figure 9. This free surface vortex is generated due to the anisotropy of turbulence across the flume. In this case, the recirculation cell was similar as reported by Tominaga and Nezu [16] and Hamidifar and Omid [38]. Meanwhile, a major vortex forms in the main channel, then shattered into smaller vortices rotating in opposite directions as observed at the interfaces of x/L = 0.375 and x/L = 0.500. These vortices are about the same order in magnitude. It was proven that larger and isolated bed roughness elements such as sand ridges might increase the strength of secondary flow [39].

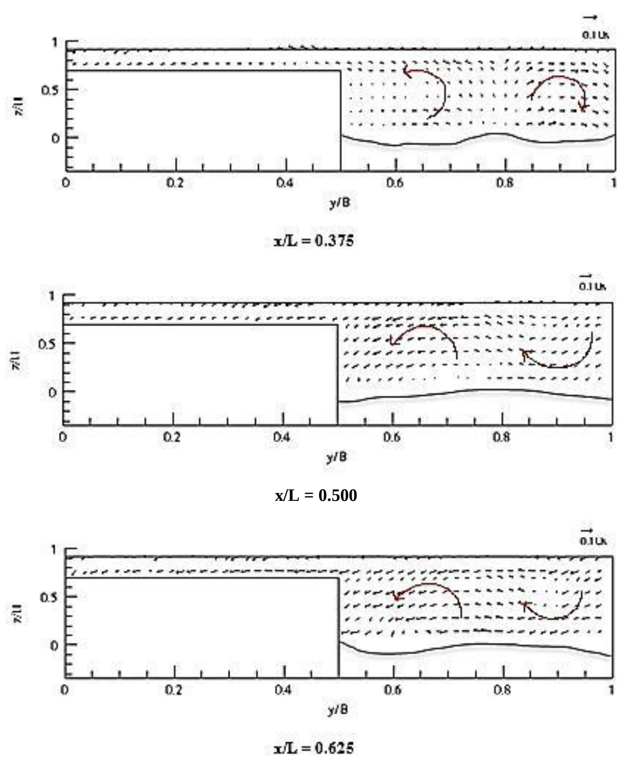


Figure 8 Distribution of secondary current along compound straight channel for shallow overbank flow

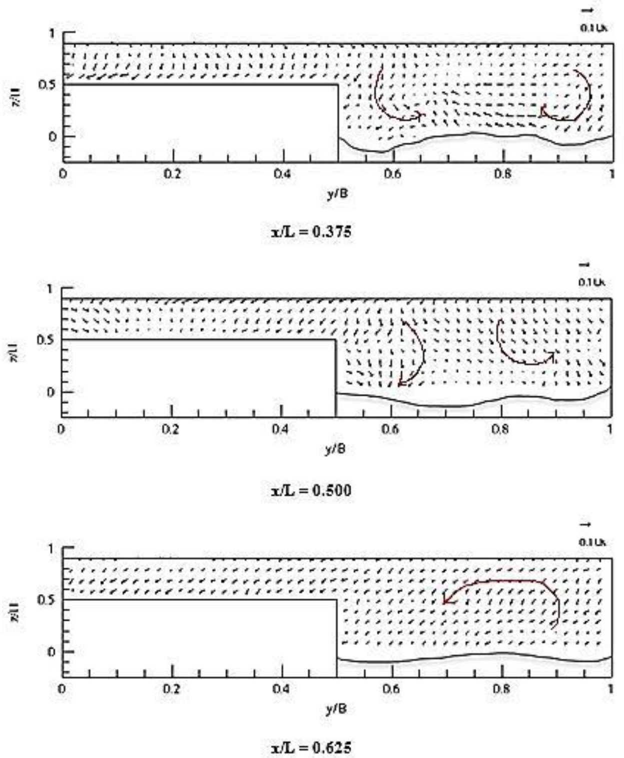


Figure 9 Distribution of secondary current along compound straight channel for deep overbank flow

3.4 Main Channel Bed Morphology

The main channel morphology was observed at the end of the experiment to understand the flow behaviour on the bed channel. Sand erosion and deposition along the channel were completely affected by the hydrodynamic condition of the stream flow. The channel morphology was in many ways unique due to particle history of flow conditions, sediment transport and distribution of channel roughness elements as mentioned by Beschta and Platts [40] in Sirdari *et al.* [41]. The visualisations of main channel morphology were plotted as illustrated in Figures 10 and 11. The scour depths were measured in mm. A negative value indicates erosion while a positive value represents deposition.

The main channel morphology in shallow and deep overbank flows exhibit a typical bed profile as normally expected where the deeper section appeared at the upstream and the shallow section was slightly occurred at the downstream of the channel due to the energy of the flow velocity in the channel. The bed forms in Figure 10 shows that deposition obviously occurred at most of part along the main channel due to the energy of the flow in the channel. The flow energy in the channel was influenced by channel bed slope which was dissipated due to the transportation of sediment along the channel [10]. The levels of deposition sand bed obtained were in ranged of 10 to 30 mm.

While the bed forms for deep overbank flow in Figure 11 shows a different trend where at the similar distance of x/L = 0.250 to x/L = 0.400, the deepest section due to erosion of sand bed was observed; while the deposition of sand bed appeared for shallow overbank flow case. The greater flow velocity from the upstream to the downstream of the channel transported the sediment with erosion and deposition of sand bed. The maximum eroded sand bed levels obtained was 30 mm. The sand levels observed in downstream section seemed to be covered with irregular bed forms consisting of small ripples. It shows that the sand bed level at the downstream of the channel was 10 mm higher than initial bed form due to deposition phenomenon. The bed formations for both flows were classified as ripples. Ripples are small bed forms with heights less than 50 mm and the profiles are approximately triangular, with long gentle upstream slopes and short, steep downstream slope [19].

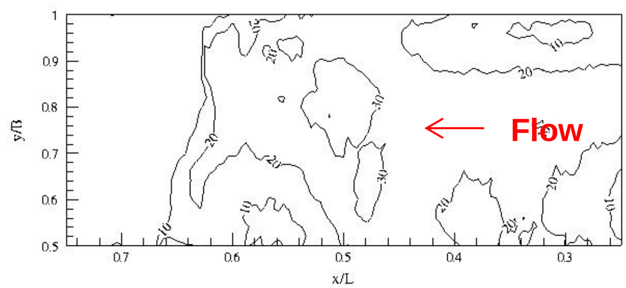


Figure 10 Plan view of bed profiles along the main channel in shallow overbank flow

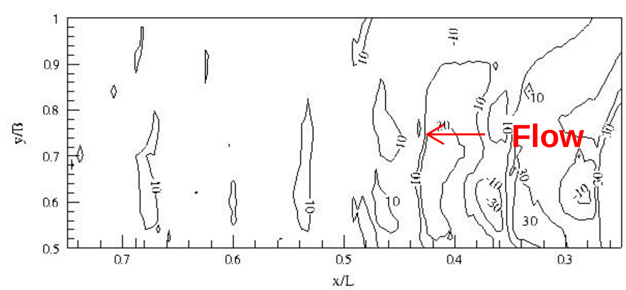


Figure 11 Plan view of bed profiles along the main channel in deep overbank flow

3.5 Bed Load Transport Rate

Figure 12 displays the temporal patterns of bed load transport rate in shallow (DR = 0.30) and deep (DR = 0.50) overbank flows. The transported of sediment were collected and weighted every 15 minutes for duration of 6 hours. The bed load transport rate was computed using Equation (3) as explained in section 2.0. It showed that the bed load transport rates fluctuate, against the mean values for each relative depth. The fluctuations of bed load transport rate arose from the change in bed elevation caused by the bed forms and dune mitigation rate. The maximum and minimum of bed load transport rate obtained for shallow relative depth were 0.12 g/s and 0.06 g/s. Meanwhile, for higher relative depth, the maximum and minimum bed load transport rates were 0.04 g/s and 0.02 g/s, respectively. This indicated that the sediment transport was maintained reasonably well in the equilibrium condition. A similar result was reported by Knight and Brown [8].

The mean bed load transport rates were 0.09 g/s and 0.03 g/s for DR = 0.30 and 0.50, respectively. It showed that the bed load transport rates were small for both relative flood flow depths. However, the change was about 67% decrease as the flood flow depth rose in the channel. The reduction of the bed load transport rate with increased of relative flood flow depth was due to significant influence of the interaction between main channel and floodplain flows. As the flood depth increase, more main channel flow was allowed to move into floodplain and achieving an equilibrium flow condition. It resulted to a reduction of flow velocity in the main channel. The sediment transport rate is directly related to the velocity of the flow in the channel, as it is the energy of the flow that determines the transportation of the sediment [42]. Tang and Knight [6] stated that the sediment transport rate decreases even further as the roughness of the channel increase.

Thus, the experimental results revealed that the slope gradient has a stronger impact on the sediment transport capacity than unit discharge and mean flow velocity in the channel as mentioned by Ali *et al*. [10]. This was due to the fact that the flow energy of a particular discharge substantially increases with the slope, but a major part of the flow energy was dissipated for detachment and transport of sediment instead of increasing the flow velocity [10, 43].

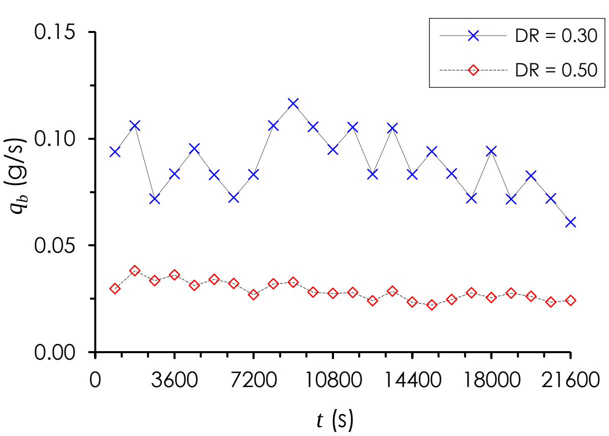


Figure 12 Temporal pattern of bed load transport rate for *DR* = 0.30 and *DR* = 0.50 overbank flows

4.0 CONCLUSION

The hydraulics of non-vegetated mobile bed straight channel for shallow and deep overbank flows were investigated through flume experiments in the laboratory. The findings of the study were: (i) a significant variation of bed morphology patterns created a tendency for the main channel flow resistance increase with the increase of flow depth, (ii) at higher relative depth, the floodplain velocity increased rapidly until the equalisation of main channel and floodplain velocities occurred, (iii) the size and position of secondary currents were largely dependent upon the channel geometry, (iv) variations of bed form patterns in the main channel were totally influenced by sediment movement due to the flow velocity in the channel and (v) the bed load transport rate decreases as flood flow depth increase, due to significant influence of the interaction effect between main channel and floodplain flows in higher flood depth.

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